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Research article

An imbalance fault detection method based on data normalization and EMD for marine current turbines

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ABSTRACT

This paper proposes an imbalance fault detection method based on data normalization and Empirical Mode Decomposition (EMD) for variable speed direct-drive Marine Current Turbine (MCT) system. The method is based on the MCT stator current under the condition of wave and turbulence. The goal of this method is to extract blade imbalance fault feature, which is concealed by the supply frequency and the environment noise. First, a Generalized Likelihood Ratio Test (GLRT) detector is developed and the monitoring variable is selected by analyzing the relationship between the variables. Then, the selected monitoring variable is converted into a time series through data normalization, which makes the imbalance fault characteristic frequency into a constant. At the end, the monitoring variable is filtered out by EMD method to eliminate the effect of turbulence. The experiments show that the proposed method is robust against turbulence through comparing the different fault severities and the different turbulence intensities. Comparison with other methods, the experimental results indicate the feasibility and efficacy of the proposed method.

1. Introduction

With the advantages of high power potential of marine tidal current and high predictability of the marine tides, the Marine Current Turbine (MCT) system are increasingly developed [1,2]. However, an MCT works in a harsh marine environment where its availability and reliability are highly desired [3]. Devices installed in the sea could become artificial reefs because of marine species [4,5]. Attached to the moving parts of system, the growth of marine organisms or marine pollutants could cause blade imbalance [6]. This blade imbalance reduces overall performances. It may damage the structure of blade or even lead to an interruption of power generation [7]. In order to ensure the system safety and reliability, researches on fault detection for MCT system are extremely important [8]. However, the MCT can produce 800–900 times more power compared to an equivalent wind turbine of similar size due to the higher density of seawater [9,10]. Thus, the shaft speed fluctuates with water velocity [11,12]. The hydrodynamic asymmetry causes the instability of the system, which makes it a challenge for the imbalance fault detection [13].

Several studies have been focused on imbalance fault diagnosis. In [14,15], the method is based on vibration and spectrum analysis. In [16], wind turbine shaft torque and spectrum analysis is used for blade imbalance fault detection. Other methods like temperature monitoring and acoustic emission monitoring have been developed in [17,18]. However, fault detection based on stator current has several advantages since it is a non-invasive technique and avoids the use of additional sensors [19,20]. The most used tools to extract a fault indicator are demodulation techniques. The current is sinusoidal and its frequency and/or amplitude is (are) modulated when a fault occurs [21,22]. In order to perform current demodulation, several authors have employed classical demodulation techniques such as the synchronous demodulator [23,24], the Hilbert transform [25–27], or time-frequency distributions [28,29]. In [30] and [31], the electric power and modulus of the stator current are used respectively to realize the imbalance fault detection under constant shaft speed condition. These aforementioned methods can identify imbalance faults at steady state. However, the velocity of the seawater keeps changing all the time resulting in frequent variation of the shaft speed and inducing various forms for the fault feature [8]. Synchronous sampling is a potential candidate to transform the variable fault characteristic frequency into a constant one before the spectral analysis is applied [8]. However, these methods require extracting fault features

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of stator current's harmonic components. The amplitudes of harmonic components are much less compared with the amplitude of the fundamental frequency and environmental noise in practice, which may cause some difficulties for the above-mentioned technique.

In this paper, an imbalance fault detection method is proposed based on data normalization and Empirical Mode Decomposition (EMD) for MCT system under the condition of wave and turbulence. Influenced by imbalance fault and hydraulic moment, the characteristics of the generator stator current signal are first analyzed. Then, a Generalized Likelihood Ratio Test (GLRT) detector is developed and the monitoring variable is selected by analyzing the relationships between the variables in the detector. After that the selected monitoring variable is converted into a time series through data normalization, which makes the imbalance fault characteristic frequency constant. Finally, the monitoring variable is filtered out by EMD to eliminate the effect of turbulence. As a consequence, the fault characteristic frequency component can be reflected adequately in the power spectrum. The experimental results show that the proposed method is robust against different turbulence intensity by direct-drive horizontal-axis Permanent Magnet Synchronous Generator (PMSG) MCT system.

The paper is organized as follows: In Section 2, the detection problem is described by analyzing the output torque and stator current of MCT under different situation. In Section 3, the fault feature is selected based on GLRT. In Section 4, to solve the problem of fault feature extraction under the condition of fundamental frequency variation, an imbalance fault detection method is proposed. In Section 5, the test bed is presented and experimental results are analyzed.

2. Problem description

Marine current system harnesses energy from tidal flow, which converts the kinetic energy into the motion of a turbine and then drives an electrical generator [32–34]. The torque is modeled as a function of time in Fig. 1, which is considered as the sum of two components: imbalance fault torque T_{im} and mechanical torque T_{mech} under the condition of wave and turbulence [35]. The total torque T_{m} is described as:

$$T_{\mathrm{m}}(t) = T_{im}(t) + T_{mech}(t) \tag{1}$$

2.1. Effect of imbalance fault

For three blades MCT, blade-passing frequency can be introduced by yaw error, water shear or tower shadow [36,37]. Shaft rotating frequency, also known as 1P frequency, can be introduced by blade imbalance fault or hydrodynamic asymmetry. When an imbalance fault exist, the motion equation is modified as [38]:

$$J_m \frac{d\omega_m}{dt} = T_{mech} - T_e - c_v\omega_m + T_{im} \tag{2}$$

where J_m is the moment of inertia; c_v damping coefficient; T_e electromagnetic torque; $\omega_m = 2\pi(f_m + f_t)$; f_m is MCT shaft rotating frequency, which changes with marine current velocity in a large range; f_t is noise frequency caused by turbulence. The imbalance fault torque T_{im} is induced in the shaft.

Fig. 2 illustrates biofouling phenomena that lead to imbalance as species distribution and growth levels of fouling organism are fully random. Indeed, this figure shows the Clean Current Company shrouded tidal turbine fouling just 6 months of immersion where many areas, such as the blades, were completely covered with diatoms or hydroids encrustations [3,5]. This kind of growth on blades can cause the blade imbalance fault. The mass distribution of one blade is different from others. A rotor mass imbalance will occur and induce vibrations in shaft rotating speed of the MCT. As shown in Fig. 2(c), from top to the bottom of the rotating plane, the shaft speed is accelerating. On the other hand, the power of gravity decelerates the shaft. Imbalance fault torque for direct-drive MCT is written as:

$$T_{im}(t) = \left(mg - \rho g V\right)\mathrm{r}_u \cdot \sin\left(\omega_m t\right) \tag{3}$$

where r_u is the distance between attachments to the center of the shaft; m equivalent imbalance mass; g the gravitational acceleration; ρ water density; V volume of imbalanced mass.

From (2), if the MCT operates under steady state $d\omega_m/dt = 0$, we have $T_e = T_{mech}$ [31,39]. Ignoring the effect of damping, then by injecting Eq. (3) into Eq. (2), the rotation speed variations can be obtained as:

$$\Delta\omega_{\mathrm{m}} = \frac{\rho g V - mg}{J_m\omega_{\mathrm{m}}}\mathrm{r}_u \cdot \cos(\omega_{\mathrm{m}} t) \tag{4}$$

With blade imbalance fault, the stator current can be expressed as:

$$i_s(\mathrm{t}) = \mathrm{A}_t \cdot \cos\left[p\omega_m t + p\Delta\omega_m t + \vartheta\right] \tag{5}$$

where A_t is the amplitude of the stator current; ϑ the initial angle; p the number of pole pairs. Therefore, the phase of the stator current can be considered as the sum of two components: $p\omega_m t + \vartheta$ and $p\Delta\omega_m t$. The fault characteristic frequency can be extracted from $p\Delta\omega_m t$.

Combining (4) with (5), it can be deduced that: 1) the fault characteristic frequency changes with shaft rotating frequency; 2) Frequency difference between healthy case and imbalance fault current signal is p times as high as that of 1 P frequency.

2.2. Effect of tidal current

The energy harnessed by the turbine varies with tidal current

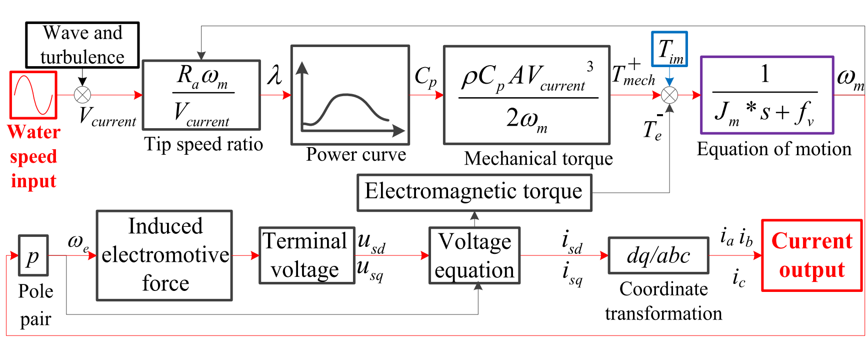

Fig. 1. Relationship between variables of MCT system.

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