A pitch control system deterioration model considering wind speed turbulence intensity

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Abstract As a consequence of high failure rate occurring to wind turbines (WTs), more and more asset owners begin to pay attention to WT's maintenance planning. To implement an efficient condition-based maintenance policy, the deterioration modeling is of primary importance.

The inherence character of wind makes WT's operation full of uncertainties, hence, the pitch actuator movement is random and it can be modeled by a stochastic process. Meanwhile, the deterioration of the pitch control system related to the usage of the actuator is random. When the wind speed is higher than the rated wind speed (a design WT parameter, when wind speed is higher than the rated wind speed, the pitch system begin to operate) and the wind speed turbulence intensity (TI) is very important, the deterioration rate of the pitch control system increases significantly. For instance the pitch system has more failures in a windy season. Therefore, in order to propose an appropriate maintenance policy for pitch control system, it is more sensible to take into account the influence of wind speed in deterioration modelling.

In this paper, we focus on the deterioration of hydraulic pitch control system. After studying the factors influencing the deterioration, a stochastic process considering wind speed as covariates is used to model the deterioration. A maintenance policy based on an alarm threshold is considered.

1. Introduction

A WT is expected to operate at least 20 years. In reality, divers subsystem failures cause undesirable downtime of WT (Pérez et al. (2013)). Moreover, pitch system has a higher failure rate compared with other subsystems. For a material, a component or a system, evolves from the healthy state to the failure. For example, the oil deterioration in a hydraulic system is a long-term process which associates with gradually accumulated metal particles, increased air/oil ratio and entrained water. In a hydraulic control system, physical deterioration brings unsatisfactory control response leading to loss efficiency. With the bigger scale of WT, off-shore location of wind farms and uncertainty operation environment, Prognostics and Health Management (PHM) of WT attract many research interests. To optimize the operation cost, to predict reliable deterioration level and to provide low-cost maintenance policy, studying the deterioration of WT components is necessary and can meet the wind power market requirements. Besides, the Supervisory Control And Data Acquisition (SCADA) system installed on each WT and used for Condition Based Maintenance (CBM), collects a massive source of WT operation data which provide the practicability of component's deterioration estimation and its Remain Useful Life (RUL) prognosis.

The aim of this paper is to study the pitch system deterioration by using the operation data. The wind influence on the deterioration is another interest of this paper. A brief introduction about the pitch controller and the hydraulic pitch actuator is arranged in section 2; Section 3 discusses the wind influence on the deterioration of pitch system followed by the deterioration model in section 4. Section 5 briefly introduces the RUL prediction and the maintenance policy. The conclusion is organized in the end.

2. Pitch controller and hydraulic pitch actuator

2.1. *Pitch controller*

The PI controller shown in Figure 1 is realized in SIMULINK environment. The error between the rated generator speed and the filtered generator speed allows the PI pitch controller to work out a satisfactory pitch angle implemented by hydraulic actuators. The gain factor is dependent on the blade pitch angle. The pitch rate is limited to 8 $^o/s$ in absolute value, the minimum and maximum pitch settings are 0^o and 90^o, respectively. These values' setting is based on General Electric (GE) Wind's long-blade test program. Table 1 lists the pitch control properties. This pitch controller is used as collective pitch control.

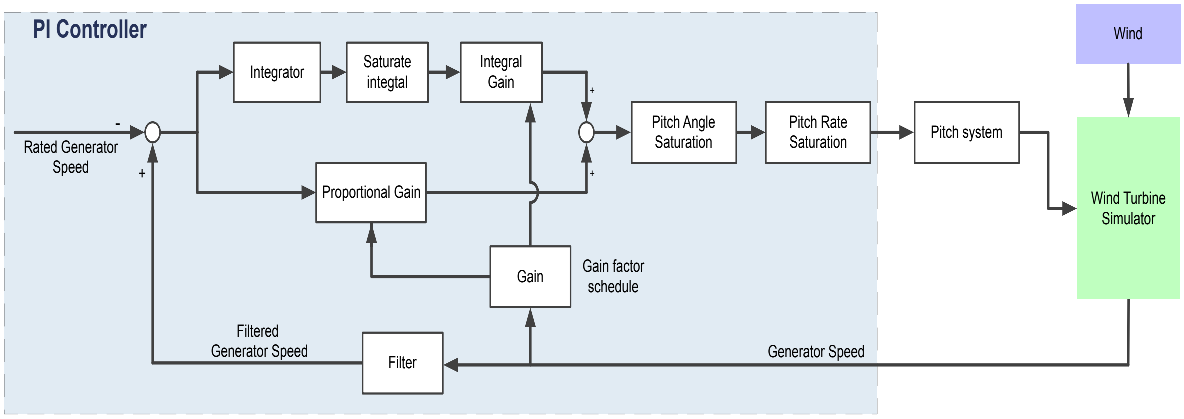


Figure1. Wind turbine simulator

Blade-Pitch Minimum Setting	0^o
Blade-Pitch Maximum Setting	$90\ ^o$
Maximum Absolute Blade Pitch Rate	$8\ ^o/s$
Proportional Gain at Blade-Pitch Minimum Setting	0.01882681 s
Integral Gain at Blade-Pitch Minimum Setting	0.008068634
Rated Rotor Rotational Speed	12.1 rpm
Rated Generator Rotational Speed	1173.7 rpm

Table 1. Parameters of the pitch control system (Source: Jonkman et al. (2009))

2.2. *Hydraulic pitch system*

Hydraulic pitch system has the advantages letting it widely used in the commercial market, such as simple condition monitoring, emergency stop without electrical power, good electrical insulative and stable performance.

The considered collective pitch control scheme has a single reference pitch angle input acting on the pitch hydraulic system to implement the desired pitch angle. In principle, the fault-free hydraulic pitch system is a piston servo system which can be modeled by a second-order dynamic equation as follow

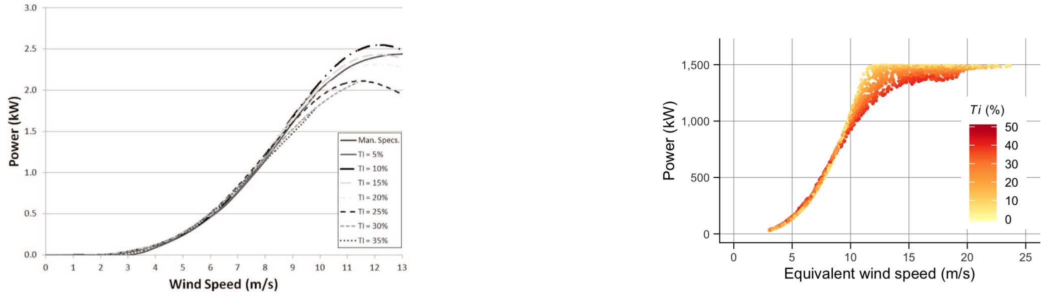
$$\ddot{\beta} + 2\zeta\omega_n\dot{\beta} + \omega_n^2\beta = \omega_n^2\beta_r \tag{1}$$

where β is the blade-pitch angle measurement, β_r is the reference blade-pitch angle from pitch control system, ω_n is the natural frequency, and ζ is the damping ratio. In the case of no deterioration occurring to the actuator, the following parameters are used: $\zeta = 0.6$, ω_n = 11.11 rad/s (Odgaard et al. (2013)).

3. Wind influence

SCADA system notes 10 minutes average wind speed value, and it neglects wind speed turbulence. However, the same average wind speed with different turbulence intensity affects differently the WT out-put power (Clifton and Wagner (2014); Ward and Stewart (2015)). The essential reason is that with the same average wind speed, pitch operations are different relating to the various turbulence intensity at full load region.

Tavner et al. (2006) concerned with the influence of wind speed on the reliability of WT. This research quantifies the wind speed data as Wind Energy Index (WEI) which is defined as



(a) Power curves adjusted to different TI based on experimentally observed data (Source :Ward and Stewart (2015))

(b) Power curve of the WindPACT 1500 kW WT (Source: Clifton and Wagner (2014))

Figure2. Variation of out-put power with different turbulence intensity

WEI =(Actual monthly energy production from a collection of wind turbines)/
(Long term expected monthly energy production from
those turbines in the presence of average weather)

Figure 3 shows the relationship between the failure rate and WEI. From this figure and the research result of Tavner et al. (2013), we can conclude that weather and wind speed have significant influence on WT components deterioration and failure. Moreover, Tavner et al. (2006) points out that some WT components are more affected by wind speed than others, such as hydraulic system, generator, yaw control and mechanical brake (shown in Figure 4). In the opinion of the author, the reason is that these components are not designed with the rapidly changing effects of the wind speed variation. A Chinese report about WT pitch failure affirms that most pitch system failure occur in windy season as a consequence of high wind speed variationLin (2013).

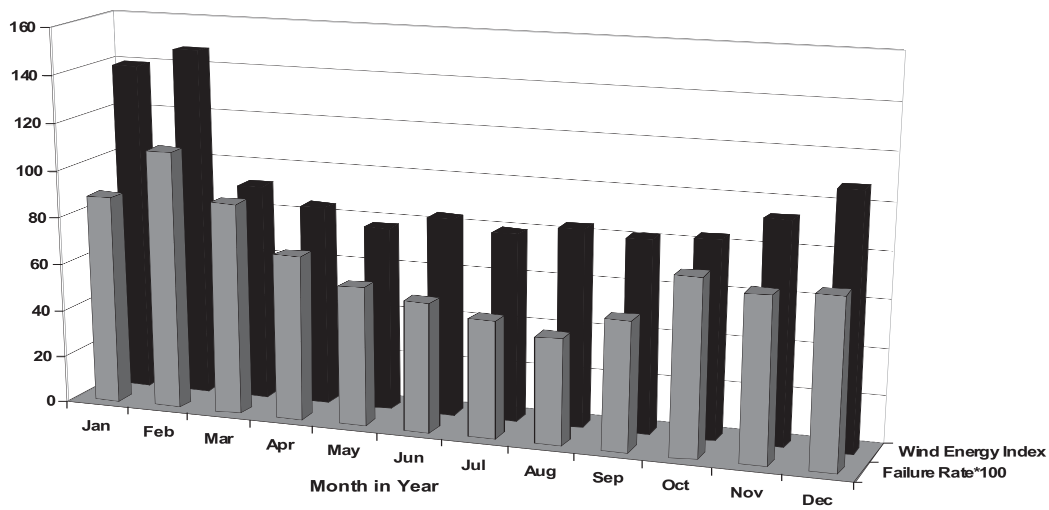


Figure3. Average monthly Failure Rate and WEI for each of the 12 months over the Survey period 1994-2004(source: Tavner et al. (2006))

In this research, we mainly consider the influence of wind speed turbulence. When wind speed is higher than the rated wind speed, small velocity changes from wind lead to the sensible action of pitch system. Combining the fact of high pitch system's failure rate in windy season, one can deduce, the variable wind accelerates the deterioration of pitch system. In other words, wind speed turbulence is the main factor causing actuator deterioration. Frequent usage of the actuator in a windy season is the reason for its failure. Therefore, we assume that for a pitch system frequent pitch actions caused by high wind speed turbulence accelerate the former's deterioration and that the pitch system only deteriorates when it implements the pitch requirements. This opinion has double meanings, firstly, WT's operation in partial load region doesn't cause the pitch actuator's deterioration

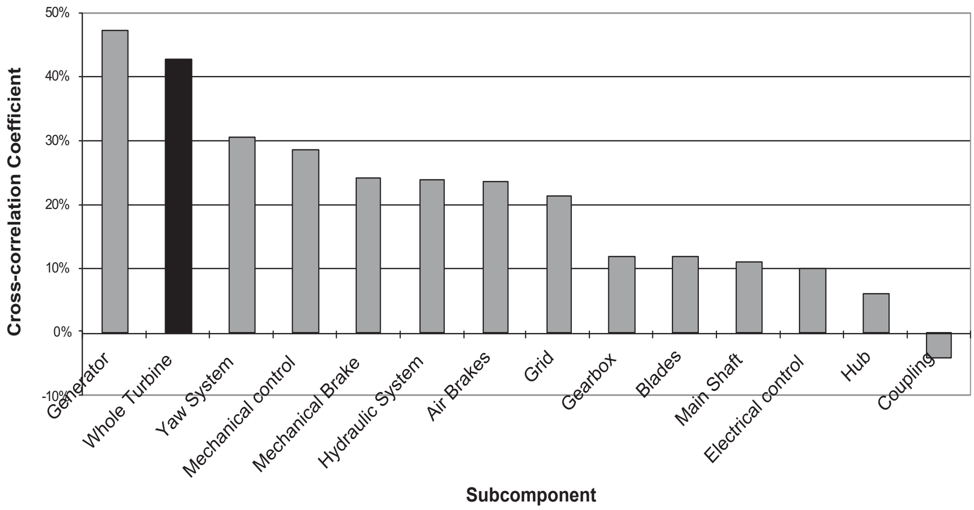


Figure4. Summary of cross-correlograms of subcomponent failure rates to WEI, 1994-2004 (source: Tavner et al. (2006))

as the pitch system is not in service. Secondly, in full load region different wind speed turbulence causing different deterioration. However, wind speed is random, how to measure the deterioration in a specific period?

4. Pitch system deterioration model considering the wind influence

4.1. *Deterioration model*

The available operation data relating to pitch system are pitch angle and pitch rate. To quickly adjust the generator rotational speed and the one of the rotor over the change of wind speed, current pitch rate can reflect the current wind speed turbulence. Hence we introduce the Accumulate Pitch Rate (APR) during one minute as a parameter used to represent the wind influence.

$$\mathrm{APR}_i = \int_{t=i*60-60}^{i*60} B_t dt \, (i = 1, 2, \cdots, n) \tag{2}$$

APR_i is the i_{th} minute APR, B_t is the pitch rate at time t, the integral is carried out in the second time scale, please pay attention to the units (second, minute).

The usage of pitch actuator, which is quantified as APR_i, is considered slowly increasing the air/oil ratio of hydraulic pitch system. And the latter is assumed as monotonously increasing before maintenance. The increment of air content at time t_{i+1} only depends on the one at time t_i. As the intrinsic randomness of wind, the operation of pitch system is stochastic. Hence, for a given time period — one minute, APR_i is a random value and $\mathrm{APR}_i \in \mathbb{R}^*$ $(i = 1, 2, \cdots, n)$ (an example is shown in Figure 5). The deterioration increment distribution at time t could be defined as follows:

$$f(x|g(\mathrm{APR})t, b) = \frac{1}{b^{g(\mathrm{APR})t}\Gamma(g(\mathrm{APR})t)} x^{g(\mathrm{APR})t-1} e^{-\frac{1}{b}x} \tag{3}$$

where, $g(\mathrm{APR})$ is a function related to APR, the value is $\mathrm{APR}_{\lfloor t/60 \rfloor}$, b is constant.

4.2. *Health indicator*

Since the reference pitch angle (β_{ref}) and measured pitch angle (β_{mes}) can be easily achieved from SCADA, they are used to estimate the parameters of the transfer function, the estimated value of natural frequency ($\hat{\omega}$) is the indicator for the hydraulic pitch system deterioration.

Taking into account of the SCADA data acquisition frequency and the actual long-term deterioration process, $\hat{\omega}$ is estimated for every ten minutes. Hence, the estimated natural frequencies constitute a time series $\hat{\omega}\{i\}$ $(i = 1, 2, \cdots, n)$. If the latest $\hat{\omega}$ is smaller than 3.42 rad/s, the hydraulic pitch system is considered as failed.

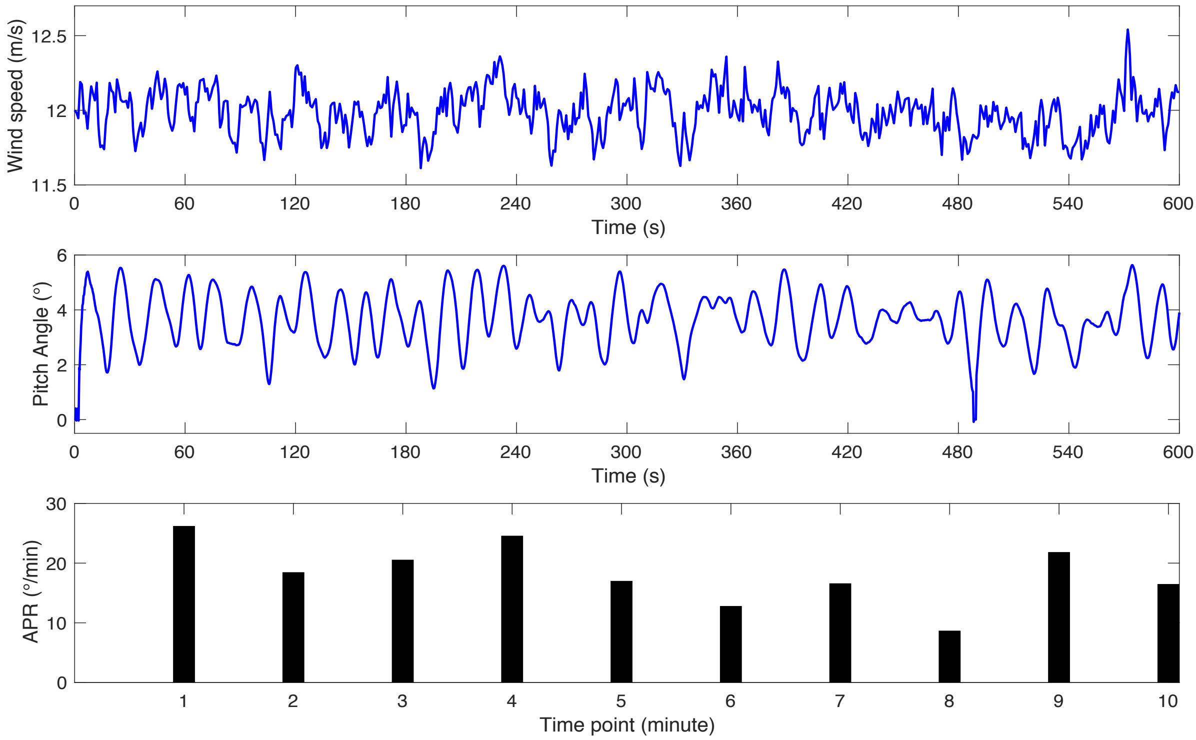


Figure5. A sample for APR value

5. RUL prediction and maintenance

The failure time T_F is the time when deterioration process reahces at the failure threshold L. $RUL(T_i)$ is the remaining useful life of the hydraulic pitch system at inspection time T_i. However, the $RUL(T_i)$ is a random value, more precisely, at time T_i, it follows a probability distribution defined as below:

$$\begin{aligned} F_{RUL(T_i)}(\tau) &= \mathbb{P}(RUL(T_i) < \tau) = \mathbb{P}(\hat{\omega}(T_i+\tau) < L | \hat{\omega}(T_i) = \omega_i) \\ &= \mathbb{P}(\hat{\omega}(T_i+\tau) - \hat{\omega}(T_i) < L - \hat{\omega}(T_i)) \\ &= \frac{\Gamma(a(T_i+\tau) - a(T_i), (L-\omega_i)\beta)}{\Gamma(a(T_i+\tau) - a(T_i))} \end{aligned} \tag{4}$$

where $a(x) = \alpha x$ and $\Gamma(m,n) = \int_{z=n}^{\infty} z^{m-1} \exp^{-z} dz$ is the incomplete gamma function.

The RUL estimation method can refer to (Moore (1982)).

The maintenance decision is based on the RUL estimation. For the role played by the pitch system in a WT, predictive maintenance is a good choice (Langeron et al. (2016),Le Son et al. (2016)). Le Son et al. (2016) propose an estimated-RUL-based maintenance policy which takes the estimation RUL into account. This policy defines a RUL_{min} as a fixed threshold, comparing the RUL_{min} with the estimated RUL $E(RUL(i))$ at each inspection time T_i, ω_i is the estimated natural frequency at time T_i

- if $\omega_i < L$ and $E(RUL(i)) \leq RUL_{min}$, the pitch system is preventively repaired.
- if $\omega_i < L$ and $E(RUL(i)) > RUL_{min}$, the maintenance decision is postponed until next inspection T_{i+1}.
- if $\omega_i \geqq L$, the pitch system has failed, a corrective repair should be carry out.

6. Conclusion

A deterioration model of a hydraulic pitch system considering the wind influence is discussed in this paper. Future research will focus on the relationship between the pitch system deterioration and different wind profiles. The online RUL prediction and the maintenance policy will be deeply study.

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