Energy Conversion and Management 157 (2018) 587–599

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Maximum power extraction for wind turbines through a novel yaw control solution using predicted wind directions

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A R T I C L E I N F O

Keywords:
Maximum power extraction
Yaw control
Wind direction prediction
ARIMA-KF
Model predictive control

A B S T R A C T

For modern horizontal axis wind turbines (WTs), a yaw drive mechanism is utilized to adjust the nacelle position to face the wind direction. Depending on historical signals from wind direction sensors, conventional yaw control methods could not provide sufficient performance in tracking winds, and thus result in a reduction of wind power extraction. This issue needs to be tackled using advanced control solutions. Taking advantage of predicted wind directions, a novel control solution is proposed in this study. Specifically, the proposed solution refers to a novel control structure that consists of a wind direction predictive model and a novel yaw control method. Under the proposed control structure, a hybrid autoregressive integrated moving average method-based Kalman filter (ARIMA-KF) model is used to predict the wind direction, and two novel yaw control methods are proposed: one created by using the predicted wind direction as the tracking reference, and the other based on a model predictive control (MPC) using a finite control set. To demonstrate the feasibility and the superiority of the proposed solution, two novel yaw controllers are developed and tested through some simulation tests using industrial data. Their performance is compared to the one of two industrial yaw controllers. Comparison results show that the two novel yaw controllers are capable of reducing yaw error, and thus increase wind power extraction for the WTs. Meanwhile, it is noticeable that the MPC-based controller has an advantage in the aspect of reducing yaw actuator usage.

1. Introduction

As the increasing demands of wind energy, the focus of research today in wind turbines (WTs) lies in maximizing the power production per unit investment. To make wind energy more competitive with other sources of renewable energy, optimal solutions have been developed constantly for WTs [1], where the control technology plays an indispensable role that directly affects performance of the WTs in the both aspects of power production [2] and component loads [3]. Modern WTs with horizontal axis have three control actuators: pitch actuator, torque actuator, and yaw actuator. The former two actuators are considered as the two dominating ones, since they can provide a fast response that answers to the rapid variation of wind force. Accordingly, there are large quantities of literature that focus on control methods for the pitch and torque actuators. By comparison, the literature about the yaw system control is limited. Nevertheless, the function of the yaw system should not be neglected.

The operation of the yaw system may affect performance of the WT. On the one hand, a yaw misalignment leads to a decreased wind power capture. Theoretically, the wind power captured by a horizontal axis WT is decreased by the cube of the yaw error [4]. Although empirical data have shown that the relationship could be cosine-squared instead of cosine-cubed [5], it is obvious that the yaw error results in the power reduction of the WT. On the other hand, a yaw misalignment may bring about an increment of component loads. The impact of yaw misalignment on loads of the WTs has been investigated and validated by researchers using calculation and measurement methods. For instance, Schepers conducted a comparison investigation between calculations and measurements on a small WT with 10 m rotor diameter in yaw, which revealed that the yaw misalignment had effects on blade root and shaft loads on a sectional level [6]. Boorsma presented a report of power and loads for a 2.5 MW WT in yawed flow conditions, in which the edgewise fatigue equivalent loads were found to be increased along with the increasing yaw error [7]. Kragh et al. [8] showed the potential

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https://doi.org/10.1016/j.enconman.2017.12.019
Received 18 September 2017; Received in revised form 15 November 2017; Accepted 6 December 2017
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Nomenclature

Abbreviations

WT wind turbine
MPP maximum power point
HCM hill climbing method
ARIMA autoregressive integrated moving average
KF Kalman filter
MPC model predictive control
MY Ming Yang
NREL National Renewable Energy Laboratory
MAE mean absolute error
RMSE root mean squared error
MAPE mean absolute percentage error
QF quality function
SCADA Supervisory Control and Data Acquisition System

Symbols

ρ air density
A_r rotor area
C_p aerodynamic power coefficient
V_0 free stream wind speed
θ_{ye} yaw misalignment error
θ_{wd} wind direction
θ_{np} nacelle position
t_{yaw} yaw action time
C_{yaw} yaw action count
ξ reduction factor of wind power extraction caused by yaw error
N number of distribution zones of yaw error
θ_{ye}^{j} averaged yaw error at the j th zone
$f_j \in [0,1]$ distribution probability of θ_{ye}^{j} in the j th zone
$(\cos(\theta_{ye}))_{eq}$ equivalent cosine of yaw error
P_a wind power extracted by a horizontal axis WT
P_{red},P_{ideal} reduced power extraction and ideal power extraction
k the kth sampling period
T_s sampling period
T_c control period
$Ah1$,$Ah2$,$Ah3$ amplitude thresholds predefined in yaw control algorithm
$Th1$,$Th2$,$Th3$ time thresholds predefined in yaw control algorithm
$\theta_{np}(k)$ nacelle position measured at kth sampling period
$\dot{\theta}_{np}(j)$ permissible yaw speed
$\dot{\theta}_{np}(k)$ yaw speed during the kth control period
w_1,w_2,w_3 weighting factors in the quality function
$\theta_{wd}(k)$ measured wind direction sampled at the kth sampling period
$\theta_{wd}(k+1|k)$ predicted wind direction at the kth sampling period
$\theta_{ye}(k+1|k)$
$\theta_{ye}(k+1|k)$ predicted yaw error at the kth sampling period
θ_{ye}^{10s},θ_{ye}^{30s},θ_{ye}^{60s} mean wind directions averaged at the sampling periods of 10 s,30 s,60 s
$\theta_{wd}(k+1|k)_{T_s=10s}$,$\theta_{wd}(k+1|k)_{T_s=30s}$,$\theta_{wd}(k+1|k)_{T_s=60s}$ predicted mean values of wind direction at the kth sampling period, $T_s = 10$ s,30 s,60 s
$\theta_{ye}(k+1|k)_{T_s=10s}$,$\theta_{ye}(k+1|k)_{T_s=30s}$,$\theta_{ye}(k+1|k)_{T_s=60s}$ predicted mean values of yaw error at the kth sampling period, $T_s = 10$ s,30 s,60 s

of alleviating blade load variations induced by the wind shear through yaw misalignment for wind speeds above rated wind speed. From their studies, it is observed that the operation of the yaw system significantly affects the performance of the WTs. A study of operating WTs revealed a fact that there was a static yaw error of 10 degree for wind speeds below 20 m/s and 5 degree for wind speeds above 20 m/s, which unavoidably reduced wind power extraction of the WTs [9]. Besides, an early survey of failures in wind power systems showed that the portion of downtime caused by yaw failure comprised 13.3% of the total downtime, and the yaw system failure rate comprised 6.7% [10]; and a recent analysis for wind turbine reliability concluded that the failure rate of wind turbines was increased up to 12.5% [11]. Thus, the controls for the yaw system deserve more attention than they received.

In the literature, the control methods for yaw systems are directly relevant to the measurement techniques which can be seen from Table 1. The employed techniques are broadly categorized into four types: free of measurement, normal measurement, advanced measurement and indirect measurement. Accordingly, relevant control methods can be also categorized into four types and they have the following features:

- Controls without wind direction measurement, which originates from early WTs limited by the wind measurement technology. Because the main objective of yaw control system is to maximize wind power extraction, the mechanism for controls without wind direction measurement is to directly search the maximum power point (MPP). Hill climbing method (HCM) was proposed to find the desired yaw angle corresponding to the MPP [12], and bisecting-plane algorithm was presented to enhance the efficiency and accurateness of conventional HCM [13]. Besides, a combined maximum

Table 1
Summary of the yaw control methods recorded in the literature.

Measurement	Control objective	Method	WT capacity	Refs.
Free	Searching optimal power	HCM	< 50 kW	[12]
	Searching optimal power	Modified HCM	1.5 MW	[13]
	Tracking optimal rotor speed	PI	1.1 kW/2.5 MW	[14]
Normal	Tracking wind direction	Fuzzy-PID	Unclear	[15]
	Tracking wind direction	Logic control	2 kW	[16]
	Tracking wind direction	Logic control	600 kW	[17]
	Tracking wind direction	Logic control	1.5 MW	[18]
Advanced	Tracking wind direction	Logic control	600 kW	[19–21]
	Tracking wind direction	Conventional MPC	5 MW	[22]
Indirect	Maximizing power production/minimizing structural loads	Conventional MPC	1 MW	[23]
	Searching optimal power	Logic control	1.1 kW	[24]

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