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A Novel Sensorless Control for Small Wind Turbines via a Speed Estimator Based on Model Reference Adaptive Controller

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Abstract

This paper focuses on a sensorless control method for small wind turbines based on permanent magnet synchronous generators. An adaptive intelligent algorithm is proposed to estimate the rotor speed for designing sensorless controllers of small wind turbines. In the proposed algorithm, a model reference adaptive system has been formed by using the instantaneous and steady-state powers to estimate the rotor speed. Then a power speed feedback (PSF) control carries out maximum power point tracking by using the optimum relationship between speed and power, which is kept in a lookup table. The efficiency of the system is improved by vanishing the observation errors and tracking errors. The validity of the proposed algorithm is verified by the simulation results.

Keywords*: Small wind turbines, Model reference adaptive controller, Maximum power point tracking, Sensorless control*

1. Introduction

Small wind turbines (SWTs) have great potential to distributed generation because of: limited size, lower environmental impact and capability to work in island-mode for isolated communities[1, 2]. Among currently available SWTs, permanent magnet synchronous generator (PMSG)–based SWTs are continuously increasing their market share, since they have many advantages such as the elimination of dc excitation, less repair requirement, and high power to weight ratio [3, 4]. However, the problems with the controller design for the PMSG–based SWT are as follows: the maximum power point tracking (MPPT) without using an anemometer, that may give wrong values due to shadow effects, and the rotor speed estimation since the use of a sensor is not always practical because the converter is placed outside the nacelle[2, 5].

Without measuring the wind speed, it is well–known that the power speed feedback (PSF) control methods are usually used to achieve the MPPT[6, 7, 8]. The problem with this method is that a shaft speed sensor is required. Without mechanical sensors, the variables such as the shaft speed and wind speed are need to be estimated. Therefore, many sensorless control strategies are proposed to implement MPPT control for PMSG–based SWTs [9, 10, 11].

For SWTs with a diode bridge, the sensorless control methods based on the Vdc–P curve are used [5, 12, 13]. In these methods, the rotor speed can be estimated by using the well–known six pulse dc voltage waveform, but the extracted power decreases as the wind speed increases [2, 14]. For those SWTs followed by a back-to-back converter, many sensorless control methods, such as back-EMF-based methods[15], perturbation and observation (P&O) methods[16, 17, 18, 19] and phase-locked loop (PLL) based methods[20],[21], are largely used in practice. However there are some deficiencies in these methods. For instance, back-EMF-based methods perform poorly at low-speed regimes and are sensitive to parameter

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uncertainty [22]; The problem with P&O method is that larger power variations are often caused by wind changes [5]; the problem with PLL method is that an error in the rotor position occurs when the converter starts to switch it produces a voltage at the point of connection with the PMSG [2].

To overcome these problems, model reference adaptive controller (MRAC) based methods are used to estimate rotor speed of PMSG [23]. Theoretically MRAC computes a desired state using two different models, such as reference and adjustable models. The error between the two models is used to estimate an unknown parameter. Moreover, the adjustable model should only depend on the unknown parameter. Here, the reference model is independent of rotor speed, whereas the adjustable model is dependent on the same. To generate the error signal, many MRACs are developed. In [24], an MRAC is developed with d- and q-components of flux. However, the method is heavily dependent on stator resistance variation and suffers from the integrator related problems like drift and saturation. To overcome the first problem, an MRAC with on-line stator resistance estimation is reported in [25]. Reactive power based MRAC are presented in [26, 27]. Among all of these methods, reactive power based MRAC is more popular for speed estimation as it is independent of stator resistance.

In this paper, a MRAC based algorithm is proposed to estimate the rotor speed for designing a sensorless controller. Here, the reference model utilizes instantaneous power and is independent of rotor speed, whereas the adjustable model uses steady-state power and is dependent on the rotor speed. The error signal is fed to the adaptation mechanism for the tuning in adjustable model. Then a power speed feed-back (PSF) control carries out maximum power point tracking by using the optimum relationship between speed and power, which is kept in a lookup table. The efficiency of the system is improved by vanishing the observation errors and tracking errors. The scheme is simulated in MATLAB/SIMULINK. The validity of the proposed algorithm is verified by the simulation results.

2. SWT Modeling

A typical PMSG–based SWT is shown in Figure 1. It consists of a wind turbine, a PMSG and a back-to-back converter. The PMSG is driven directly by the wind turbine. PWM converters between the grid-side and the rotor-side also allow for power flow bi-directionally.

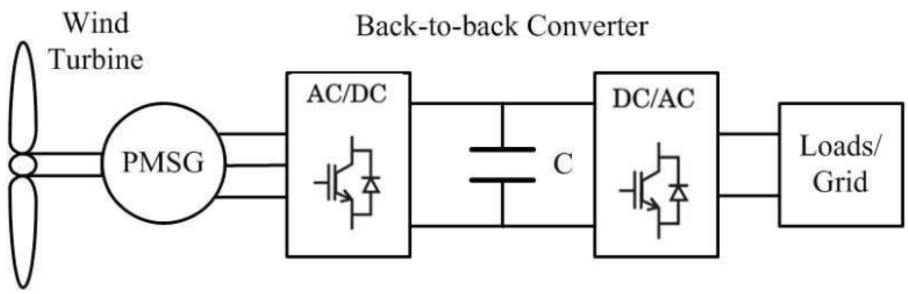

Figure 1. The Structure of SWT

2.1. Wind Turbine Model

It is well known that the mechanical power, which is extracted by the WT, is expressed as [28].

$$P_m = \frac{1}{2}\rho A C_p\left(\lambda\right) v_w^3 \tag{1}$$

where, ρ is the air density at the turbine site, R is the blade length, A is swept area of the blades (πR^2), v_w is the wind velocity at the turbine height, $Cp(\lambda)$ is the turbine power coefficient, λ is the Tip Speed Ratio (TSR).

We define ω as the shaft speed of the wind turbine, the λ is represented by

$$\lambda = \frac{\omega R}{v_w} \tag{2}$$

Cp(λ) is the function of the turbine pitch angle β and λ. Pitch control is not used for SWT because of its cost [29]. So, the SWT pitch angle β is assumed to be a constant β_0. The function Cp(λ) can be written as [28]

$$C_p(\lambda) = \left(0.44 - \frac{\beta_0}{60}\right)\sin\left[\frac{\pi(\lambda-3)}{15-0.3\beta_0}\right] - 0.00184(\lambda-3)\beta_0 \tag{3}$$

2.2. PMSG Model

PMSG is modeled by the following voltage equations in the *dq* reference frame [4]

$$\begin{cases} u_d = R_s i_d - p\omega_m L_q i_q + L_d \dfrac{di_d}{dt} \\ u_q = R_s i_q + p\omega_m L_d i_d + L_q \dfrac{di_q}{dt} + p\omega_m \Phi_m \\ T_e = \dfrac{3}{2} p\left[\Phi_m i_q + (L_d - L_q) i_d i_q\right] \end{cases} \tag{4}$$

where, L_d and L_q are the armature inductances in dq axes, u_d and u_q are the stator voltages in dq axes, i_d and i_q are the stator currents in dq axes, ω_m is the rotor speed, R_s is the armature resistance, p is the number of the pole pairs, Φ_m is the permanent magnetic flux, T_e is the electrical torque.

For SWT, the generators usually are non–salient pole, such that $L_d = L_q$. So, the T_e in (4) is rewritten as

$$T_e = \frac{3}{2} p \Phi_m i_q \tag{5}$$

Neglecting the deformation of the shaft, it can be assume that the PMSG's rotor speed ω_m is equal to the WT's shaft speed ω because of the PMSG is directed driven by the WT. To make it clear, in the remainder of this article, the notion ω denotes the mechanical speed of the WT and PMSG.

The mechanical equations of SWT is represented by

$$T_m - T_e = J\frac{d\omega}{dt} + B\omega \tag{6}$$

where, T_m is the mechanical torque of the SWT, J is the equivalent inertia and B is the friction constant.

3. MRAC-Based Speed Estimation

In the following, the MRAC scheme for rotor speed estimation is given in Figure 2. The control objective is either to regulate the error values to zero or to track the states of a reference model. The adaptive control is used to adjust the controller parameters online, which is based on a measured system response.

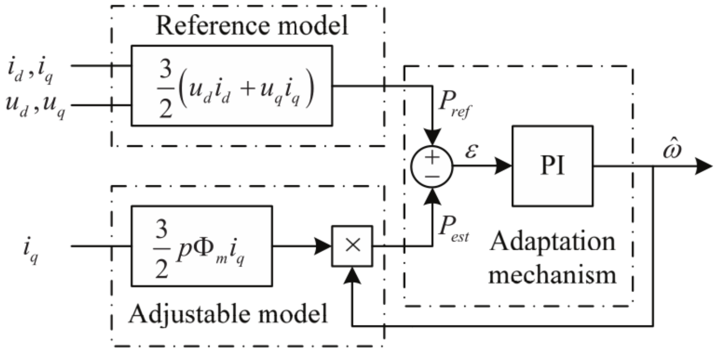

Figure 2. The Scheme of MRAC

As seen in Figure 2, reference model computes the instantaneous power (P_{ref}) of PMSG and is independent of rotor speed ω. It is expressed as

$$P_{ref} = \frac{3}{2}\left(u_d i_d + u_q i_q\right) \tag{7}$$

Whereas the adjustable model computes steady-state power (P_{est}) and it is represented by

$$\begin{aligned} P_{est} &= T_e \omega \\ &= \frac{3}{2} p\Phi_m i_q \omega \end{aligned} \tag{8}$$

According to MRAC scheme shown in Figure 2, the error between the power P_{est} and P_{ref} is used as a input of the adaptation mechanism to adjust estimated speed $\hat{\omega}$. For the adaptation mechanism of MRAC, it is important to ensure that the system will be stable and the estimated quantity will converge to the actual value. Here, we use a practical synthesis technique for MRAC structures, which is based on the concept of hyper-stability [30]. This concerns the stability properties of a class of feedback systems as shown in Figure 3.

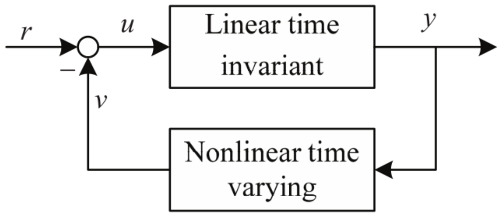

Figure 3. Nonlinear Time Varying Feedback System

As defined in [30], Hyper-stability requires that the forward path transfer matrix be strictly positive real, and that the nonlinear feedback including the adaptation mechanism satisfies Popov's integral inequality defined as

$$\int_0^t v^T y d\tau \le -\delta^2 \tag{9}$$

Subtracting (8) from (7), we can obtain

$$\varepsilon = \frac{3}{2}\left(u_d i_d + u_q i_q\right) - \frac{3}{2} p\Phi_m i_q \hat{\omega}(\varepsilon, t) \tag{10}$$

The right side of (10) can be configured as the input of feed-forward block. Therefore,

$$u = \rho_1 - \rho_2 \hat{\omega}(\varepsilon, t) \tag{11}$$

where, $\rho_1 = \frac{3}{2}\left(u_d i_d + u_q i_q\right)$, $\rho_2 = \frac{3}{2} p\Phi_m i_q$.

Without having any external signal (r = 0), the input signal u of the linear time invariant block is associated with the output v of the nonlinear time varying block. Therefore

$$v = -u \qquad (12)$$

substituting (12) in (9), the inequality can be rewritten as

$$\int_0^t y\left(\rho_2\omega(\varepsilon,t)-\rho_1\right)d\tau \le -\delta^2 \qquad (13)$$

where y is the output of a linear block, which will process the error ε according to (14).

$$y = D(s)\varepsilon \qquad (14)$$

Letting

$$\hat{\omega} = \left(K_P + \frac{K_I}{p}\right)y \qquad (15)$$

and substituting it in (13), this inequality become

$$\int_0^t y\left[\rho_2\left(K_P + \frac{K_I}{p}\right)y - \rho_1\right]d\tau \le -\delta^2 \qquad (16)$$

where, $p = \frac{d}{dt}$.

Using the following well-known inequality:

$$\int_0^t h\left[\frac{df(t)}{dt}\right]f(t)dt \le -\frac{1}{2}hf^2(0) \qquad (17)$$

where h is infinity positive constant. it can be shown that inequality (15) is satisfied. Therefore the adaptation law is a PI controller in adaptation mechanism.

4. Control Strategy

SWTs are designed to track maximum power point over a wide range of wind speeds. With a variable speed operation it has become possible to adjust continuously the rotor speed of the wind turbine to the wind speed [31]. The directly torque control is a very effective control strategy to achieve the speed control for PMSG–base SWT [32, 33]. When the rotor speed of a SWT is obtained, PSF control strategy can be used to track maximum power point for SWTs. In the following section, the PSF control strategy based on MRAC speed estimation is studied. The scheme of the control strategy is shown in Figure 4.

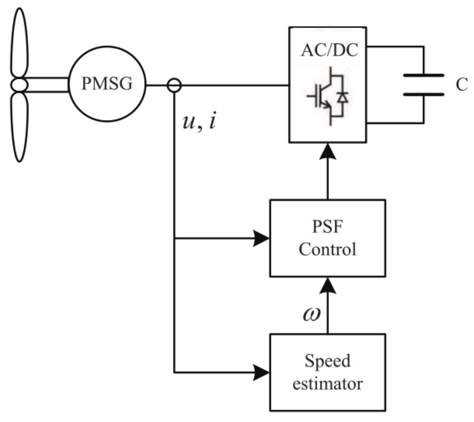

Figure 4. The Scheme of the PSF Control Strategy

4.1. PMSG Speed Control

Controlling PMSG–based SWTs can be achieved by adjusting the rotor speed of PMSG. The directly torque control is a very effective control strategy to achieve the speed control [32, 33]. The torque control is achieved through the control of the generator currents.

The generator currents including i_d and i_q can be controlled through the following equations [2]

$$\begin{cases} u_d^* = u_d - p\omega L_d i_q \\ u_q^* = u_q + p\omega L_d i_d + p\omega \Phi_m \end{cases} \tag{18}$$

The right choice of the control variables including u_d^* and u_q^* leads to a decoupled control of the two current components [2]

$$\begin{cases} i_d = \dfrac{-u_d^*}{L_d s + R_s} \\ i_q = \dfrac{-u_q^*}{L_d s + R_s} \end{cases} \tag{19}$$

Then a PWM rectifier control is carried out where the stator p axis current component is used to control the generator torque, but a freedom degree remains to set direct current that can be used for flux weakening [2, 34].

In practical, the current loop in q-axis just is a inner loop for the torque control. An outer loop, which used to generate the reference current i_q^*, is needed and it is referred to as the speed loop. The speed loop is designed to achieve maximum power extraction for SWTs. In the following, the scheme of the speed loop is explained.

4.2. Maximum power extraction

For SWTs, the optimal operating condition can be achieved by employing PSF control strategy based on the ω–P curve [8]. The principle of Maximum power extraction based on the ω–P curve is developed as follows.

When the optimum power coefficient ($C_{p,opt}$) can be obtained, the maximum power ($P_{m,opt}$) is expressed as

$$P_{m,opt} = \frac{1}{2}\rho A C_{p,opt} v_w^3 \tag{20}$$

From (2), the optimum TSR (λ_{opt}) can be obtained by adjusting the speed ω to adapt the wind velocity v_w changes. So, $P_{m,opt}$ can be represented by

$$P_{m,opt} = \frac{1}{2}\rho A C_{p,opt} \frac{R}{\lambda_{opt}}^{3} \omega_{opt}^3 \tag{21}$$

Where, ω_{opt} is denotes the optimum rotor speed.

Therefore, $P_{m,opt}$ can be extracted by adjusting ω to its optimum value ω_{opt} at various wind velocity. For instance, a family of curves P_m against ω at different wind speeds are plotted in Figure 5.

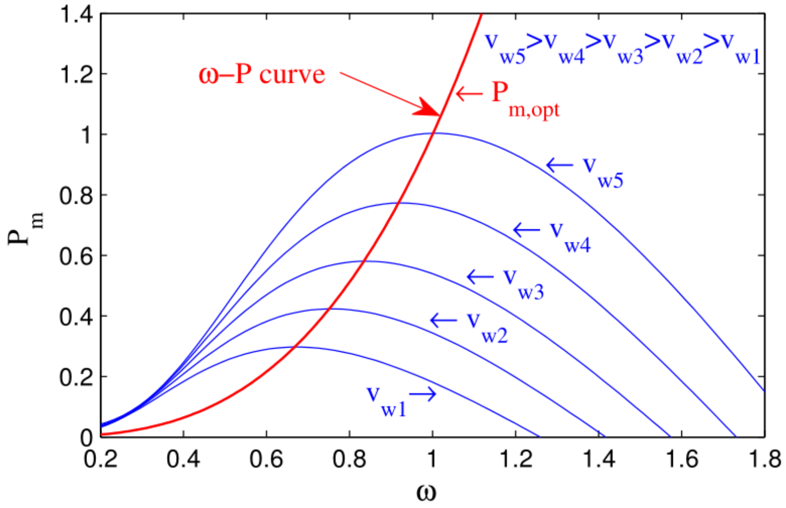

Figure 5. The Curves P_m against ω

Where, the SWT parameters are compiled in Tab.1.

Table 1. SWT Parameters

parameters	values
Blade length	1.8 m
Blade number	3
Nominal power	2000 W
Cut-in wind speed	3 m/s
Cut-out wind speed	20 m/s
Wind speed for nominal power	11 m/s
Nominal speed	390 rpm
Number of pole pairs	16
Stator equivalent resistance	0.8 Ω
Stator equivalent inductance	4.9 mH

As seen in Figure 5. The optimum relation between $P_{m,opt}$ and ω_{opt} can be summarized as look up table. Then the reference current i_q^* can be obtained by employing the ω–P curve.

5. Simulation Results

In this section, the simulation software Matlab is used. The behaviors of the proposed control method is compared with the ones of an existing approach. The whole model of a 2 kW SWT is developed according to the basic parameters are given in Tables 1.

In case of the turbulence intensity of the wind is 10%, a wind profile is applied to the SWT model to study the controller performance. The test results are shown in Figure 6.

The profile of wind speed is shown in Figure 6(a). The optimum and actual shaft speeds are shown in Figure 6(b), and the optimum and actual turbine powers are shown in Figure 6(c). Seen from Figure 6(b), there is an expected delay caused by the inertia, but the optimum speed can be followed by the speeds, which are obtained by the method based on the speed estimator and the method using a speed sensor. There are few difference between the results, which are obtained by using the proposed senseless control method and the method with a speed sensor respectively. Seen from Figure 6 (c), as a result of the MPPT control, maximum power is extracted by using both of the methods. More precisely, 36.55 kJ of the 36.71 kJ available are extracted by using the proposed method during the 25 s, similarly, 36.46 kJ available are extracted by the method with a speed sensor.

As a conclusion, the proposed approach is good enough to being considered in case of a damaged sensor or without shaft speed measurement, and it is an efficient and cost effective solution for SWT control.

5. Conclusion

In this paper, a sensorless control method based on the speed estimator for SWT is proposed to improve the efficiency. In the proposed method, a model reference adaptive system is used to estimate the rotor speed. The error between the instantaneous and steady-state powers is fed to the adaptation mechanism tuning the output of the adjustable model. Then a MPPT is carried out by using the optimum relationship between speed and power. The efficiency is improved by vanishing the observation errors and tracking errors. The simulation results show that there are few difference between the proposed method and the method with a speed sensor.

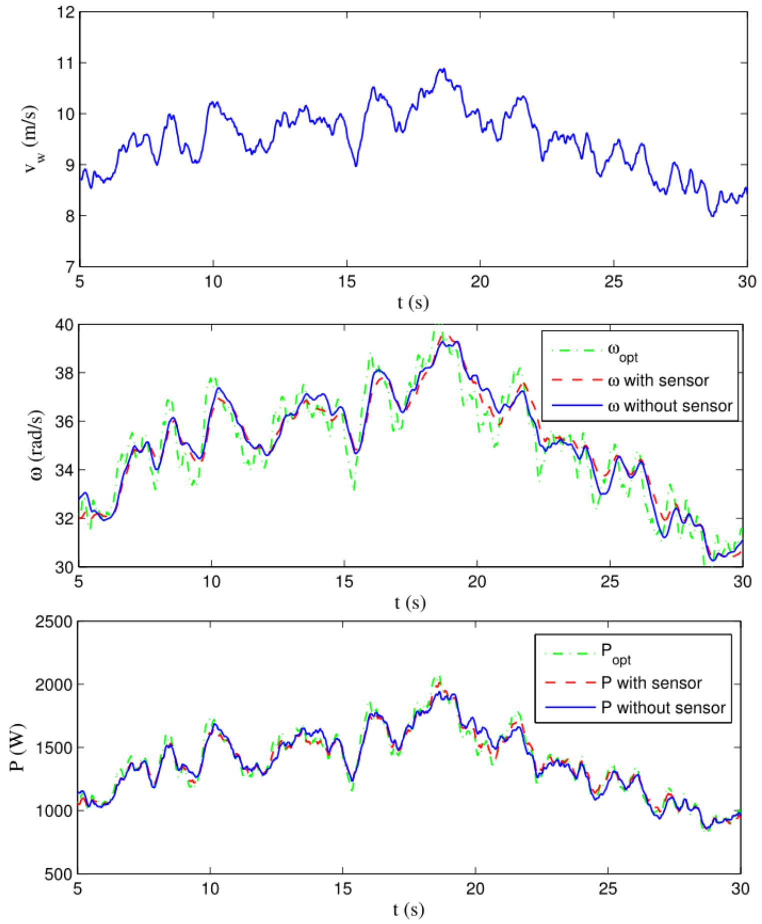

Figure 6. The Simulation Results

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