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To cite this article: Jagath Sri Lal Senanayaka *et al* 2016 *J. Phys.: Conf. Ser.* **753** 052031

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Direct Torque Control of a Small Wind Turbine with a Sliding-Mode Speed Controller

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Abstract. In this paper, the method of direct torque control in the presence of a sliding-mode speed controller is proposed for a small wind turbine being used in water heating applications. This concept and control system design can be expanded to grid connected or off-grid applications. Direct torque control of electrical machines has shown several advantages including very fast dynamics torque control over field-oriented control. Moreover, the torque and flux controllers in the direct torque control algorithms are based on hysteretic controllers which are nonlinear. In the presence of a sliding-mode speed control, a nonlinear control system can be constructed which is matched for AC/DC conversion of the converter that gives fast responses with low overshoots. The main control objectives of the proposed small wind turbine can be maximum power point tracking and soft-stall power control. This small wind turbine consists of permanent magnet synchronous generator and external wind speed, and rotor speed measurements are not required for the system. However, a sensor is needed to detect the rated wind speed overpass events to activate proper speed references for the wind turbine. Based on the low-cost design requirement of small wind turbines, an available wind speed sensor can be modified, or a new sensor can be designed to get the required measurement. The simulation results will be provided to illustrate the excellent performance of the closed-loop control system in entire wind speed range (4-25 m/s).

1. Introduction

Small-scale wind turbines are becoming more popular in modern household applications. This green electrical energy generation method is suitable for both off-grid and grid connected applications. However, further improvements are necessary to increase the reliability and performances and reduce the cost of small wind turbines. In this paper, a new control solution is presented to improve the performances and reliability of small wind turbines.

Small wind turbines have limited active control options than large-scale wind turbines. For the majority of small wind turbine applications, the pitch angle of the blades are fixed, and yaw control is achieved using the passive tail-vane method. Yaw control is an inexpensive solution but gives decent performances for small wind turbines. Furthermore, in most of the small wind turbines, power limiting at higher wind speeds is realised using passive mechanisms such as furling or passive stalling. However, in numerous cases, the above techniques do not provide the required performances. For example, furling methods have several limitations, such as introducing unbalance force on wind turbine rotor and structure, which can reduce the lifetime of the components. The soft-stall power control method is proposed in this paper which eliminates some limitations of furling and other methods. Soft-stalling or electrical stalling for small wind turbines can be accomplished via generator speed control where the



generator speed is forced to below its stalling speed at higher rated wind speeds. After this speed reduction, the wind turbine can capture its rated power and operates in low efficient mode and eliminate the additional power extraction available at higher wind speed conditions. The sliding-mode speed controller is used as speed controller, to satisfy the requirement of soft-stall power control method which requires a fast speed controller with less overshoot. Furthermore, an accurate torque estimation and control techniques are mandatory for the proposed soft-stall power control method. Therefore the direct torque control (DTC) method is implemented.

DTC is an important method for torque and flux control in electrical motors, and this technique has been considered in many studies, see for instance [1]-[3]. The main advantage of this method is that, instead of controlling the torque and flux via an indirect current control in field-oriented control (FOC) methods, the torque and flux are controlled directly. The stator flux and torque values are estimated and controlled directly using two hysteric controllers. The flux and torque estimations play the key role in this algorithm. The stator flux position information is also derived using the estimator. The main advantage of this method is that since the torque and flux are controlled directly, it gives a faster response than an indirect FOC method. Furthermore, rotor position information is internally derived in the estimator, and an external position sensor is not required. Different than previous results in the literature on FOC and scalar current control strategies for small wind turbines [4]-[5], in this paper, the novel soft-stall power control method is introduced for a small wind turbine. Soft-stall power control method has been previously studied in the literature [6]-[9] where various control methods were adopted. However, in this study, a combined DTC and sliding mode control are used to improve performance from the proposed soft-stall power control method. The developed DTC sliding-mode controller provides a fast response with less overshoot, which is appropriate for the proposed small wind turbine application. Usually, DTC controllers consume a considerable level of computing power. However, availability of low-cost microcontrollers facilitates to implement this method for small wind turbines.

The rest of this paper is organised as follows. The system layout details are discussed in Section 2. The implementation details of proposed control algorithm are presented in Section 3. The simulation results are discussed in Section 4. Finally, the conclusion is given in Section 5.

2. Proposed wind turbine

Off-grid water heating application of a small wind turbine is considered in this study. An overview of the proposed wind turbine and its control system is discussed in this section. Figure 1 shows a block diagram of the system under consideration.

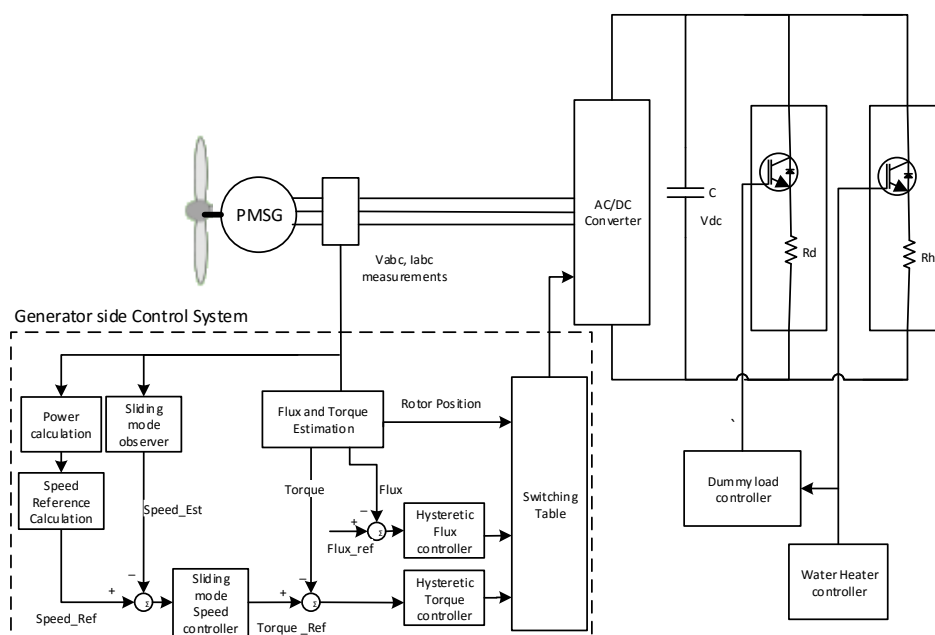


Figure 1. The block diagram of the DTC based small wind turbine

Permanent magnet synchronous generators (PMSGs) are widely used in small wind turbine applications. PMSGs are high efficient generators when compared with other types of generators used in wind turbines. In the small wind turbine, a mechanical sensor-less approach is adopted where a sliding mode observer is used to estimate the rotor speed [4]. Power signal feedback method is implemented to compute the optimum rotor speed [5], which eliminates the requirement of external wind speed sensors. There are two different speed reference inputs. At below-rated wind speed, the power signal feedback technique is used for the speed reference. Furthermore, at higher wind speeds soft-stall method gives the speed reference. At the below-rated wind speeds, maximum power point tracking (MPPT) operation is achieved using generator speed control, where the rotor is rotated at its optimum speed by measuring the output power of the wind turbine. The sliding-mode speed controller generates the torque reference of the DTC algorithm, and hysteretic controllers are implemented to control the torque and flux of the generator. In this application, the 'sigmoidal' function is selected as the switching function of the given sliding-mode speed controller. Based on the torque and flux controller outputs, the switching table generates the required control signals for the AC/DC converter. In the DC side, a protection dump load and the water heater are considered as the loads. The system can be easily extended for any other grid connected or off-grid applications. A MATLAB/Simulink simulation model is developed to validate the proposed control algorithms. Table 1 shows some important model parameters used in the model. The details of the control algorithm are presented in Section 3.

Table 1: Parameters of the wind turbine simulation model

Sub Unit	Parameter	Value
Wind Turbine	Wind turbine rotor diameter	4 m
	Max C_p value	0.36
	Optimum Tip speeds ratio	5
	Total Rotating Inertia	1 kg. m ²
Generator	Generator rated speed	286 rpm
	No of pole pairs	12
Sliding mode controller	Switching function [a c]	[0.25 0]
	Gain [K]	[400]
DC bus and Water heating unit	DC intermediate Voltage	0- 250V
	Resistance (3 parallel units)	40 ohm
	Temp. Limit of the hysteretic controller	60 – 70 °C
Dummy load	Resistance (3 parallel units)	40 ohm
	Voltage limit of hysteretic controller	245 – 255 V

3. DTC based speed control algorithm

The design of a DTC-based speed control algorithm is discussed in this section. The algorithm consists of three main parts, reference speed calculation, speed controller and torque & flux control sections. Aerodynamically designed rotor blades capture the available power in the wind and transfer it to the wind turbine rotor as follows;

$$P_m = 0.5\rho\pi R^2 v_w^3 C_p(\lambda, \beta) \quad (1)$$

where ρ represents the air density, R denotes the turbine radius, v_w provides the wind speed and $C_p(\lambda, \beta)$ presents the wind turbine power coefficient which is a function of tip speed ratio (λ) and the pitch angle (β). In small wind turbines, fixed pitch blades are used. Therefore, the C_p is a function of λ only. At the below rated wind speeds, $C_p(\lambda, \beta)$ should be maximized. This can be achieved by keeping rotor speed at optimum value (or λ optimum value) for respective wind speeds. When the turbine rotor is directly coupled to the electrical generator, the dynamic model of wind turbine can be defined as;

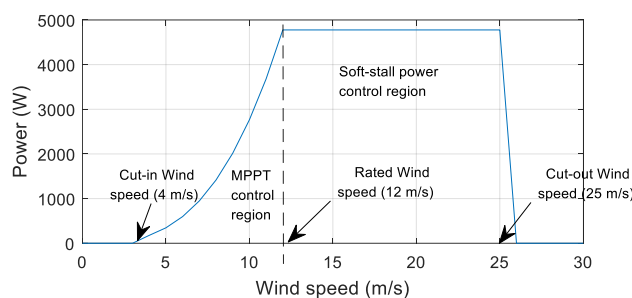
$$\frac{d\omega_r}{dt} = \frac{1}{J} (T_m - T_e - B\omega_r) \quad (2)$$

where ω_r denotes the rotor speed, J represents the wind turbine total rotational inertia, T_m gives the torque produced by wind turbine blades, T_e is the torque produced by the generator and B is the

viscous friction coefficient of the generator bearings. Therefore to achieve wind turbine speed control, electromagnetic torque and flux of the generator have to be controlled according to the given speed reference.

3.1. Generator Speed control strategies

The main objective of the generator side control system is controlling the wind turbine generator torque/speed according to the dynamic conditions of the system or user commands. The generator speed is controlled in such way that, at the below-rated wind speeds, the turbine speed reference is generated from the MPPT algorithm. At the above-rated wind speed, the speed reference is computed to force the wind turbine to its stalling speed, and this is called soft-stall power control method. The ideal power curve with different control strategies is shown in Figure 2. A sliding-mode speed controller can be used as the speed controller of the generator, which gives a fast response of speed controller without high overshoots. The speed control strategy is defined by equation (3);



$$\begin{aligned} \omega_{ref} &= \omega_{mppt} & V &\leq V_{rated} \\ \omega_{ref} &= \frac{P_{rated}}{T_{Meas}} & V &> V_{rated} \end{aligned} \quad (3)$$

Figure 2: Ideal Power Curve of the wind turbine

where V_{rated} is the rated wind speed, ω_{mppt} is the speed reference for the MPPT operation which is calculated using the power signal feedback (PSF) method. P_{rated} denotes the rated power of wind turbine. T_{Meas} represents the electromagnetic torque of the generator which can be calculated by the torque estimation method used in the DTC algorithm. The wind turbine power-speed relation for optimum operation can be generated using the simulation of the wind turbine and this information is stored in control algorithm as a lookup table. Based on the output voltage and current measurements, the output power is calculated, and a lookup table is used to get the optimum speed for the given power level. It is noting that the PSF method does not require any wind speed information. More implementation details of the PSF method can be found in [5].

3.2. The sliding mode speed controller

The block diagram of sliding mode controller is shown in Figure 3. The speed reference is generated according to the speed control strategy discussed in the previous section. Sliding-mode control (SMC) is a robust nonlinear control method which has many advantages over widely used control techniques such as proportional integral control. The SMC gives quick control actions and low overshoots with less computational requirement than other advanced control methods [10]-[11].

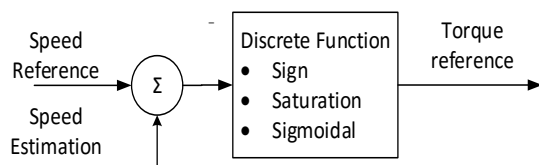


Figure 3: Block diagram of sliding mode speed controller

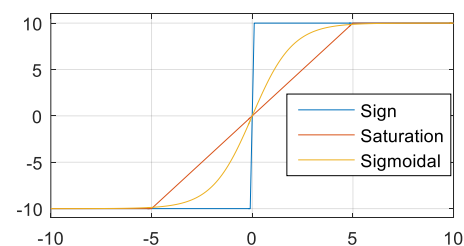


Figure 4: Different switching functions used in sliding-mode controller

A sliding-mode observer is designed to estimate the back-emf of the generator. Based on the back-emf information, the rotor speed can be accurately calculated. The implementation details of the sliding-mode observer are not discussed in this paper. The implementation details of the sliding-mode observer can be found in [4]. The heart of the sliding-mode controller is the selection of proper discrete switching function. There are several options for selection of the switching function. Three possible switching functions are considered in this study and compared the results of each switching function. The definitions of each switching function are given in the following;

Sgn function is defined as;

$$\text{sgn}(x) = \begin{cases} -1 & x < 0 \\ 0 & x = 0 \\ 1 & x > 0 \end{cases} \quad (4)$$

Saturation function is defined as;

$$\text{saturation}(x) = \begin{cases} x_L & x < x_L \\ x & x_L \leq x \leq x_H \\ x_H & x > x_H \end{cases} \quad (5)$$

where x_L and x_H are the lower and upper limits of the saturation function, respectively. Sigmoidal function can be defined as;

$$\text{sigmf}(x, a, c) = \frac{1}{1 + e^{-a(x-c)}} \quad (6)$$

where the shape of the sigmoidal function is defined by the constants 'c' and 'a'; In each case, a suitable positive gain value can be used to increase the error convergence speed. Figure 4 gives the typical shapes of each switching function. If necessary, an additional gain factor can be used to control the switching function.

3.3. Stator Torque and Flux Controllers

DTC was initially introduced to induction motors [12] and later extended to PMSMs also. A block diagram of the DTC control system is shown in Figure 5. There are three major sections of the control algorithm. First, the stator flux vector and stator torque are estimated. The second section includes two hysteresic controllers to control the magnitude of each component. In the third section, proper space voltage vectors are generated to control the torque and flux of the generator.

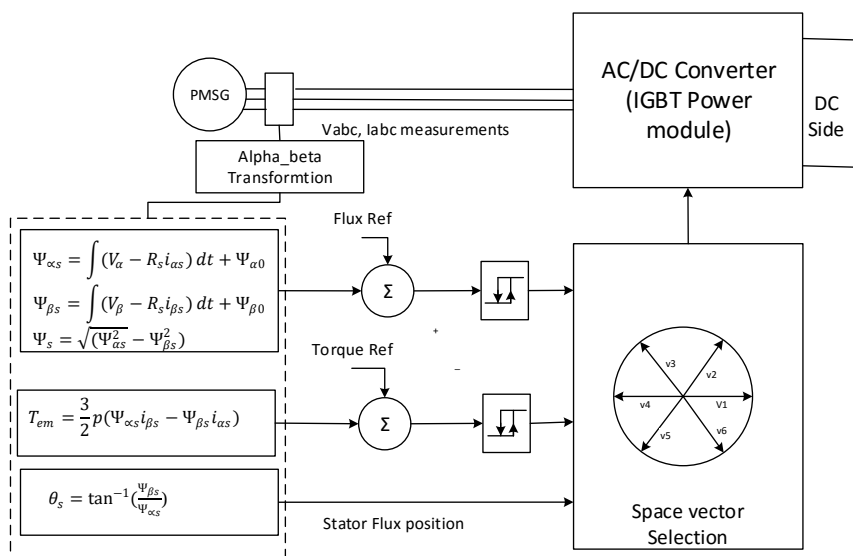


Figure 5: Direct torque control system

The voltage relationship of a permanent magnet synchronous motor in stationary coordinate system can be represented as;

$$\left. \begin{aligned} v_{\alpha s} &= R_s i_{\alpha s} + \frac{d\Psi_{\alpha s}}{dt} \\ v_{\beta s} &= R_s i_{\beta s} + \frac{d\Psi_{\beta s}}{dt} \end{aligned} \right\} \quad (7)$$

where $v_{\alpha s}, v_{\beta s}$ and $i_{\alpha s}, i_{\beta s}$ are the voltage and current components in a stationary coordinate system respectively, R_s is the stator resistance, $\Psi_{\alpha s}$ and $\Psi_{\beta s}$ denote the stator flux linkage which are defined as;

$$\left. \begin{aligned} \Psi_{\alpha s} &= L_s i_{\alpha s} + \Psi_{PM} \cos(\theta_r) \\ \Psi_{\beta s} &= L_s i_{\beta s} + \Psi_{PM} \sin(\theta_r) \end{aligned} \right\} \quad (8)$$

where L_s is the stator inductance, Ψ_{PM} is the permanent magnet flux and θ_r denotes the rotor position. Combining equation (7) with (8), one obtains;

$$\left. \begin{aligned} v_{\alpha s} &= R_s i_{\alpha s} + e_{\alpha s} + L_s \frac{di_{\alpha s}}{dt} \\ v_{\beta s} &= R_s i_{\beta s} + e_{\beta s} + L_s \frac{di_{\beta s}}{dt} \end{aligned} \right\} \quad (9)$$

where $e_{\alpha s}$ and $e_{\beta s}$ as back electromagnetic force components are defined in the following where ω_r denotes the rotor speed.

$$\left. \begin{aligned} e_{\alpha s} &= -\Psi_{PM} \omega_r \sin(\theta_r) \\ e_{\beta s} &= \Psi_{PM} \omega_r \cos(\theta_r) \end{aligned} \right\} \quad (10)$$

From equation (7), the flux vector components in stationary coordinate system can be estimated as;

$$\left. \begin{aligned} \Psi_{\alpha s} &= \int (V_{\alpha s} - R_s i_{\alpha s}) dt + \Psi_{\alpha 0} \\ \Psi_{\beta s} &= \int (V_{\beta s} - R_s i_{\beta s}) dt + \Psi_{\beta 0} \\ \Psi_s &= \sqrt{(\Psi_{\alpha s}^2 - \Psi_{\beta s}^2)} \\ \theta_s &= \tan^{-1}\left(\frac{\Psi_{\beta s}}{\Psi_{\alpha s}}\right) \end{aligned} \right\} \quad (11)$$

The initial conditions for integral terms in equation (11) can be selected at $\theta_r = 0, \Psi_{\alpha 0} = \Psi_{PM}$ and $\Psi_{\beta 0} = 0$. The electromagnetic torque (T_{em}) can be estimated as;

$$T_{em} = \frac{3}{2} p (\Psi_{\alpha s} i_{\beta s} - \Psi_{\beta s} i_{\alpha s}) \quad (12)$$

where p denotes the number of poles in the generator. Flux, torque hysteretic controller and space vector selection are the critical in the DTC algorithm. The space vector definition and the corresponding sector angles are given in Figure 6. and Table 1. All together there are 8 space vectors and only 6 useful space vectors are defined with 60 degrees apart each other. Each vector represents a switching combination in three arms of the AC to DC converter. As shown in Table 2, ± 30 degrees are considered as the effective region for each space vector.

Table 2: Space vector selection for DTC

Stator Flux vector angle	Sector selection
$-30 < \theta_s \leq 30$	θ_1
$30 < \theta_s \leq 90$	θ_2
$90 < \theta_s \leq 150$	θ_3
$150 < \theta_s \leq -150$	θ_4
$-150 < \theta_s \leq -90$	θ_5
$-90 < \theta_s \leq -30$	θ_6

Considering that flux vector is in $-30 < \theta_s \leq 30$ position (effective area of V_1 vector). The stator flux and electromagnetic torque variation for each voltage space vector selection can be shown as in Table 3. There are 6 options, but only 4 vectors are adjacent and proper vector has to be selected as the control requirement of the generator. This can be graphically represented as shown in Figure 7;

Table 3: Voltage vector and its impact on flux and torque

Voltage Vector	V_1	V_2	V_3	V_4	V_5	V_6	V_0/V_7
Ψ_s	↑	↑	↓	↓	↓	↑	-
T_{em}	↓	↑	↑	↑	↓	↓	-

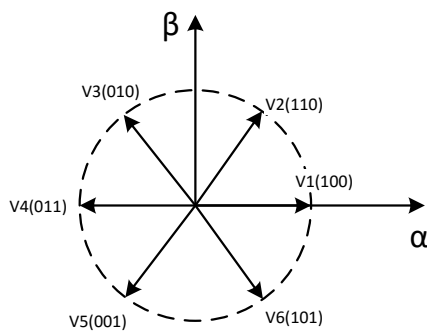
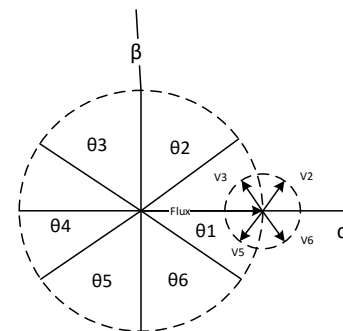


Figure 6: Space vectors definition

Figure 7: Adjacent vector for V_1 vector

It is clear that selection of V_2 and V_3 vectors are required to increase the torque while the other two to decrease the torque. V_2 and V_6 can be used to increase the flux and the other two to decrease the flux. This information can be extended for other sectors using the hysteresis control laws. The hysteresis control law can be defined as Table 4, where '1' and '0' represent increase and decrease commands for torque and flux variables respectively.

Table 4: Hysteresis controller output relation

Controller output	Condition
$d_\psi = 1$	$\Psi_s < \Psi_s^{ref} - H_\psi$
$d_\psi = 0$	$\Psi_s < \Psi_s^{ref} + H_\psi$
$d_{T_{em}} = 1$	$T_{em} < T_{em}^{ref} + H_{T_{em}}$
$d_{T_{em}} = 0$	$T_{em} < T_{em}^{ref} - H_{T_{em}}$

In Table 4, Ψ_s^{ref} denotes the stator flux reference and $\pm H_\psi$ denotes the limits of the hysteresis flux loop. T_{em}^{ref} is the torque reference of the generator and $\pm H_{T_{em}}$ denotes the limits of the hysteresis torque loop. For each control commands, the voltage vector selection can be selected as in Table 5. The switching table can be implemented as 2D lookup table.

Table 5: Switching table for DTC

Flux	Torque	Sector selection (stator flux linkage position)					
		θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
$d_\psi = 1$	$d_{T_{em}} = 1$	V_2	V_3	V_4	V_5	V_6	V_1
	$d_{T_{em}} = 0$	V_6	V_1	V_2	V_3	V_4	V_5
$d_\psi = 0$	$d_{T_{em}} = 1$	V_3	V_4	V_5	V_6	V_1	V_2
	$d_{T_{em}} = 0$	V_5	V_6	V_1	V_2	V_3	V_4

4. Simulation Results

The simulation results and performance of the proposed sliding-mode speed controller based DTC control algorithm are discussed in this section.

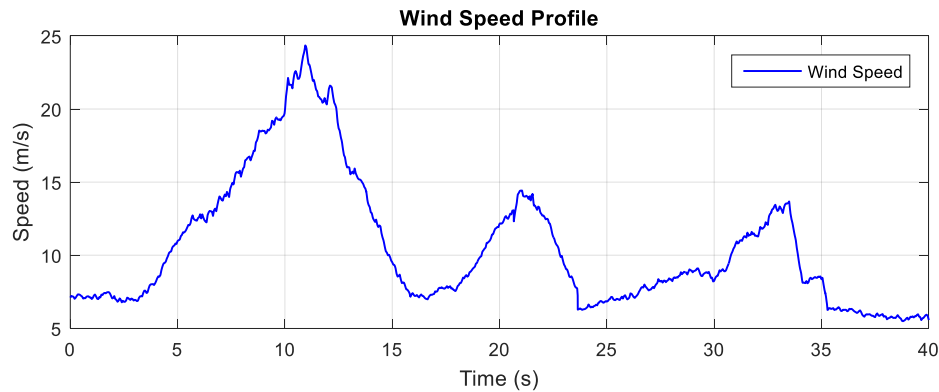


Figure. 8: Simulated wind speed profile

The simulated wind speed profile is shown in Figure 8. The wind profile has been generated section by section using 'TurbSim' software [13], which includes both below-rated and above-rated wind speeds.

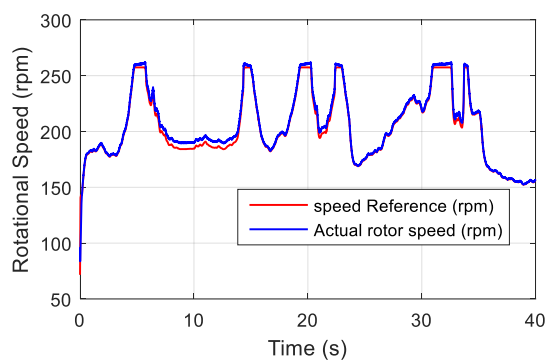


Figure 9: Performance of SMC speed controller

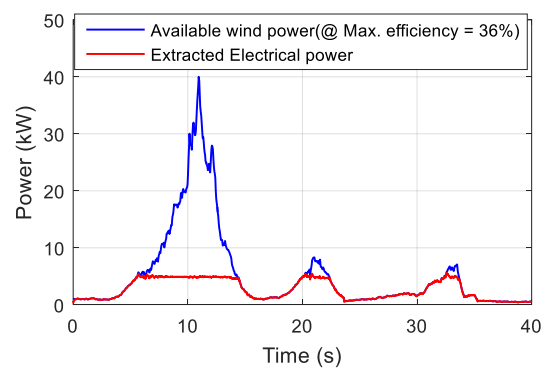


Figure 10: Power transfer stages of wind turbine with SMC speed controller

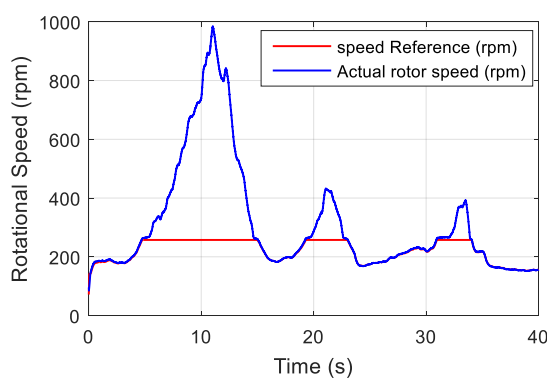


Figure 11: Performance of the PI speed controller

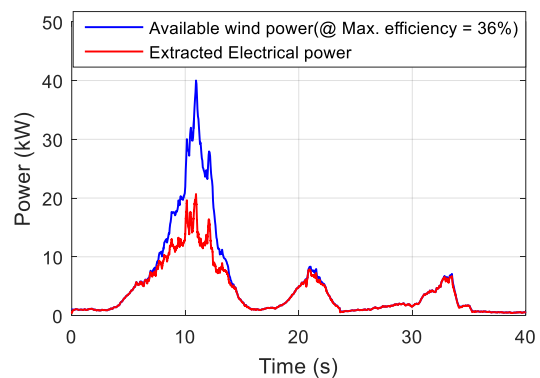


Figure 12: Power transfer stages of wind turbine with PI speed controller

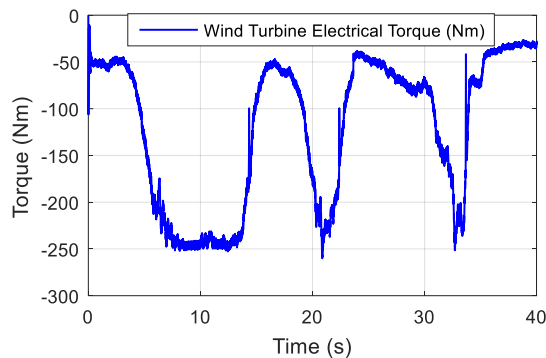


Figure 13: Wind Turbine torque variation with SMC speed controller

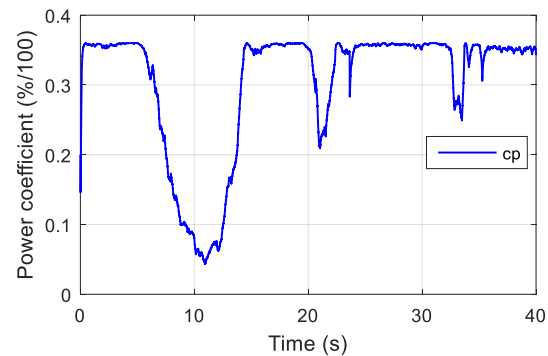


Figure 14: Wind turbine power coefficient with SMC speed controller

The performance of speed controller with SMC speed controller is given in Figure 9, where the generator speed follows the given speed reference in both MPPT region and soft-stall region. The output of speed controller is used as the reference for internal torque controller. The ultimate objective of control algorithms is to achieve MPPT operation and soft-stall behaviours at respective wind speed levels. The power transfer stages of the wind turbine are shown in Figure 10, where MPPT is accomplished below rated wind speeds, and successfully power limiting is attained in above-rated wind speeds.

The wind turbine torque variation with SMC speed controller is given in Figure 13, where the chattering effect is observed in torque profile. The reasons for this fluctuations are the sliding-mode controller behaviour and the wind turbine dynamics. However, extreme torque variations are not present in the torque profile. Wind turbine rated torque is about 160 Nm at 286 rpm rotational speed that gives 4.8 kW power level. However, in the soft-stall region, the wind turbine speed is reduced, and constant power level is maintained. Therefore the wind turbine torque should be increased accordingly. The wind turbine rotor and the generator are designed that can handle higher torque than its rated torque. In this soft-stall method maxim torque is about 150% of its rated torque and it is a safe limit of typical wind turbine designed constraints. Therefore the proposed control algorithm can work within the general wind turbine design constraints. The wind turbine power coefficient is shown in Figure 14. Where C_p is kept closer to the maximum value in below-rated wind speeds and C_p is reduced at higher rated wind speed to achieve the soft-stalling and limit the power.

An additional simulation study was conducted to verify the performance of the sliding-mode speed controller. In this study, the sliding-mode controller was replaced with traditional proportional-integral (PI) controller. The same wind speed profile is used as the previous study. The PI controller was tuned using the Ziegler-Nichols' method, and system performances are given in Figure 11 and Figure 12. According to Figure 11, the PI speed controller works well in below rated wind speed and according to Figure 12, the maximum power point tracking operation is achieved in this region. However, at the above-rated wind speed levels, the PI controller is unable to tackle the given rotor speed level, where speed controller ask to retain maximum rotational speed, but actual speed has reached very unsafe 1000 rpm level. Also, the electrical power extraction is touched to 20 kW, which is 400% of its rated value. In these extreme conditions, any real wind turbine may destroy it instantaneously. Therefore, with a properly tuned PI controller, the soft-stall power control method is not possible. The reason is that PI controller does not have very fast dynamic speed control with fewer speed overshoots which are mandatory to success in proposed soft-stall power control method. However, the sliding-mode controller is capable of keeping the performance using its fast dynamic performances with fewer speed overshoots.

5. Conclusions

In this paper, a sliding-mode speed controller based direct torque control algorithm is presented for a small wind turbine. In addition to available hysteretic torque and flux controllers, a nonlinear sliding-mode controller has been developed as the speed controller. Therefore the combined control system consists of nonlinear controllers which give fast dynamic performances with minimum overshoot values.

The simulation model includes 4.75 kW wind turbine model, and the simulation results illustrate excellent performances at both MPPT operation and soft-stall power control modes. An extended study was conducted using a properly tuned PI speed controller by replacing the sliding-mode speed controller. Even though, PI speed controller performs well in MPPT operation at below rated wind speeds, it fails to perform soft-stall power control at higher wind speed levels. This speed control failure can end up with fatal damages to the wind turbine. Therefore the usage of the sliding-mode controller is necessary to achieve the proposed soft-stall power control method. Furthermore, for the proposed soft-stall power control method, the generator torque estimation is needed and which can easily get from the direct torque control algorithm. Modern low-cost microcontrollers are available to implement the DTC in small wind turbines. Furthermore, the system can operate without rotor speed measurements in both MPPT and soft-stall power control regions. However, still, a wind speed sensor is required to detect the rated wind speed overpass event which can be used to switch the MPPT operation or soft-stall power control algorithms. The accuracy of the proposed control system is validated using simulation results and shown the applicability of the proposed method in actual small wind turbine implementations.

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Acknowledgment

The research leading to these results has received funding from the Polish-Norwegian Research Program operated by the National Centre for Research and 24 Development under the Norwegian Financial Mechanism 2009-2014 in the frame of Project Contract No. Pol-Nor/200957/47/2013.