Control Strategy to Maximize Power Extraction in Wind Turbine

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ABSTRACT

This article deals with nonlinear control of variable speed wind turbine (VSWT), where the dynamics of the wind turbine (WT) is obtained from a single mass model. The main objective of this work is to maximize the energy capture form the wind with reduced oscillation on the drive train. The generator torque is considered as the control input to the WT. In general the conventional control techniques such as Aerodynamic Torque Feed-Forward (ATF) and Indirect Speed Control (ISC) are unable to track the dynamic aspect of the WT. To overcome the above drawbacks the nonlinear controllers such Sliding Mode Controller (SMC) and SMC with integral action (ISMC) with the estimation of effective wind speed are proposed. The Modified Newton Raphson (MNR) is used to estimate the effective wind speed from aero dynamic torque and rotor speed. The proposed controller is tested with different wind profiles with the presence of disturbances and model uncertainty. From the results the proposed controller was found to be suitable in maintaining a trade-off between the maximum energy capture and reduced transient on the drive train. Finally both the controllers are validated by using FAST (Fatigue, Aerodynamics, Structures, and Turbulence) WT simulator.

Keywords: Variable speed Wind turbine, Integral sliding mode controller, Modified Newton Raphson, ATF and ISC.

INTRODUCTION

Because of the power crises and environmental issues, renewable energy sources play a vital role in the world energy market. Among all renewable energy sources wind energy is one of the rapidly growing energy technologies having own benefits such as less pollution or cleaner than fossil energy and thus more environmental friendly. In recent years due to the advanced in drive technology and grid interconnection control the production of wind power is increased. Generally wind turbine (WT) has two different types i.e. fixed speed WT (FSWT) and variable speed WT (VSWT). By comparing these two technologies VSWT is more versatile then FSWT. The main advantages of VSWT over FSWT are the reduction in mechanical stress and power fluctuations [1-2]. In VSWT the operating regions are classified in to two major categories i.e. below and above rated wind speed. At below rated wind speed the main objective of the controller (i.e. torque control) is to optimize the wind energy capture by tracking the wind speed. At above rated wind speed the major objective of the controller (i.e. pitch control) is to maintain the rated power of the WT. For extracting the maximum power at below rated wind speed the WT rotor speed should operate at reference rotor speed which is derived from effective wind speed. In practical point of view, an accurate measurement of wind speed is very difficult. Wind speed is measured by the anemometer, which provides 5-10 % accuracy in wind velocity measurement. One of the best ways to achieve the effective wind speed is to use different estimation algorithms. In literature some of the authors have discussed the control of WT with the assumption of measurement of effective wind speed. In [3] a fuzzy controller used to maximize the power capture, improve the efficiency, and the controller was found to be more robust to the wind gust and oscillatory torque. In [4] control algorithm i.e. fuzzy logic control (FLC) tracks the maximum power by controlling the WT rotor speed without estimation the effective wind speed. Several literatures have reported WT control with estimation of effective wind speed. In [5] the rotor speed and aerodynamic torque are estimated by the input and state based estimation with the known pitch angle, the effective wind speed is calculated by the inversion of the static aerodynamic model. In [6-8] Kalman filter (KF) is used to estimate rotor speed and aerodynamic torque and finally the effective wind speed is calculated using Newton Raphson. For the single mass model give in [6-7] and two mass model given in [8], nonlinear controllers such as nonlinear static state feedback linearization with estimator (NSSFE) and Nonlinear dynamic state feedback linearization with estimator (NDSFE) are used to control the WT at below rated wind speed. For both the

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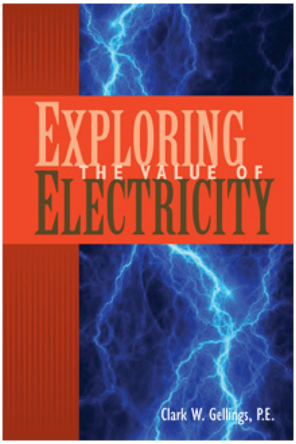

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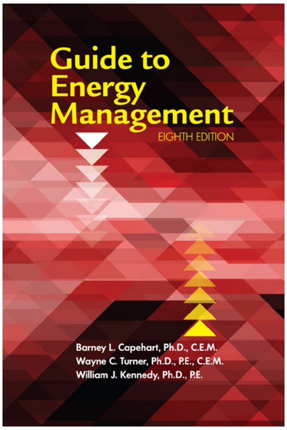

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controllers the wind speed is estimated using Newton Raphson. In [9] calculation of effective wind speed is achieved by the particle filter and FLC is used to control the WT at below rated wind speed. In [10-12] the SMC based controllers are applied to the WT without estimating the effective wind speed. Authors in [10-11] discussed higher order sliding mode control (HSMC) of WT at below and above rated speed and it was found that HSMC is more robust with respect to parameter uncertainty of the WT. In [12] conventional sliding mode controller (SMC) based control with adaptive sliding gain is used to control the WT where the sliding gain is varied by an adaptation algorithm.

AIM AND SCOPE

The objective of this work is to maximize the energy capture form the wind with reduced oscillation in drive train by using the proposed ISMC control. Modified Newton Rapshon (MNR) is used to estimate the effective wind speed. A comparison of WT efficiency, with respect to maximum power capture, reduced transient load on drive train is done between the conventional controller and the proposed ISMC. The results are validated for different wind speed profile. Finally the controller performances were validated by FAST wind turbine simulator developed by National Renewable Energy Laboratory (NREL).

WT MODEL

A WT is a device which converts the kinetic energy of the wind in to electric energy. Simulation complexity of the WT purely depends on the type of control objectives. In case of WT modelling complex simulators are required to verify the dynamic response of multiple components and aerodynamic loading. Generally dynamic loads and interaction of large components are verified by the aero elastic simulator. For designing a WT controller, instead of going with complex simulator the design objective can be achieved by using simplified mathematical model. In this work WT model is described by the set of nonlinear ordinary differential equation with limited degree of freedom. This article describes the control law for a simplified mathematical model with the objective of optimal power capture at below rated wind speed and reduced oscillation of the drive train. The proposed controller is tested with different wind profiles in the presence of model uncertainty and disturbances.

Generally VSWT system consists of the following components i.e. Aerodynamics, Drive trains, and Generator are shown in figure 1.

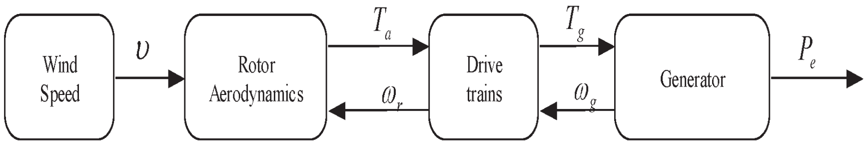

Figure 1. Schematic of WT.

Equation 1 gives the nonlinear expression for aerodynamic power capture by the rotor

$$P_a = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)\upsilon^3 \tag{1}$$

Where R is the radius, ρ is the air density, ω is the rotor speed (rad/sec), C_P is the power coefficient of the WT and ν is the wind speed (m/sec). From equation 1 aerodynamic power (P_a) is directly proportional to the cube of the wind speed. The power coefficient C_P is the function of blade pitch angle (β) and tip speed ratio (λ) and is defined as ratio between linear tip speed and wind speed.

$$\lambda = \frac{\omega_r R}{\upsilon} \tag{2}$$

Generally wind speed is stochastic nature with respect to time. Because of this tip speed ratio gets affected which leads to the variation in power coefficient. The relationship between aerodynamic torque (T_a) and rotor speed with respect to aerodynamic power P_a is given next by equation 3.

$$P_a = T_a\omega_r \tag{3}$$

$$T_a = \frac{1}{2}\rho\pi R^3 C_q(\lambda,\beta)\upsilon^2 \tag{4}$$

where C_q is the torque coefficient given as

$$C_q(\lambda,\beta)=\frac{C_P(\lambda,\beta)}{\lambda} \quad (5)$$

Substituting equation (5) in equation (4) we get

$$T_a=\frac{1}{2}\rho\pi R^3\frac{C_P(\lambda,\beta)}{\lambda}\upsilon^2 \quad (6)$$

In the above equation the nonlinear term C_p can be approximated by the 5[th] order polynomial.

$$C_P(\lambda)=\sum_{n=0}^{5}a_n\lambda^n=a_0+\lambda a_1+\lambda^2 a_2+\lambda^3 a_3+\lambda^4 a_4+\lambda^5 a_5 \quad (7)$$

Where a_0 to a_5 are the WT power coefficient.

The values of approximated coefficients are given in Table 1. Figure 2 shows the C_p versus λ curve.

Table 1. Coefficients values

a_0=0.1667	a_3=-0.01617
a_1=-0.2558	a_4=0.00095
a_2=0.115	a_5=-2.05×10^{-5}

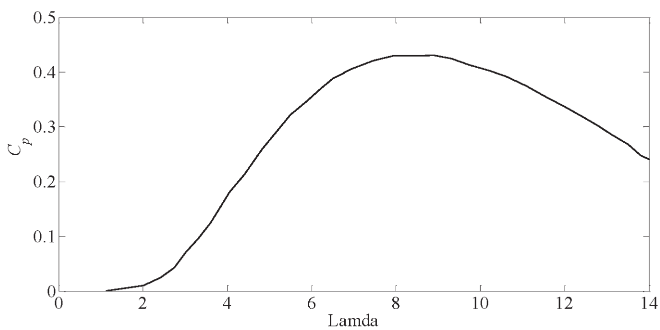

Figure 2. C_p vs λ curve

Figure 3 shows the two mass model of the WT. Equation 8 represents dynamics of the rotor speed ω, with rotor inertia J_r driven by the aerodynamic torque (T_a).

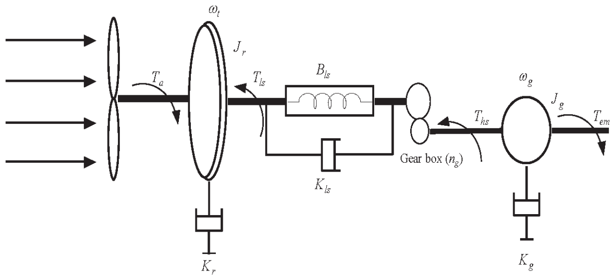

Figure 3. Two mass model of the WT.

$$J_r\dot{\omega}_r = T_a - T_{ls} - K_r\omega_r \tag{8}$$

Breaking torque acting on the rotor is low speed shaft torque (T_{ls}) which can be derived by using stiffness and damping factor of the low speed shaft given in equation (9).

$$T_{ls} = B_{ls}(\theta_r - \theta_{ls}) + K_{ls}(\omega_r - \omega_{ls}) \tag{9}$$

Equation (10) represents dynamics of the generator speed ω_g with generator inertia J_g driven by the high speed shaft torque (T_{hs}) and braking electromagnetic torque (T_{em}).

$$J_g\dot{\omega}_g = T_{hs} - K_g\omega_g - T_{em} \tag{10}$$

Gearbox ratio is defined as

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} \tag{11}$$

Transforming the generator side dynamics into the low speed shaft side we will get

$$n_g^2 J_g\dot{\omega}_g = T_{ls} - n_g K_g\omega_g - n_g T_{em} \tag{12}$$

If a perfectly rigid low-speed shaft is assumed, the dynamics of the rotor characteristics of a single mass WT model can be expressed by a first order differential equation given as

$$J_t\dot{\omega}_r = T_a - T_g - K_t\omega_r \tag{13}$$

where

$$J_t = J_r + n_g^2 J_g \tag{14}$$

$$K_t = K_r + n_g^2 K_g \tag{15}$$

$$T_g = n_g T_{em} \tag{16}$$

CONTROL OBJECTIVES

Generally WT is classified into two types i.e. fixed and variable speed WT. Variable speed WT has more advanced and flexible operation than to fixed speed WT. Operating regions in variable speed WT are divided in to three types. Figure 4 shows the various operating region in variable speed WT.

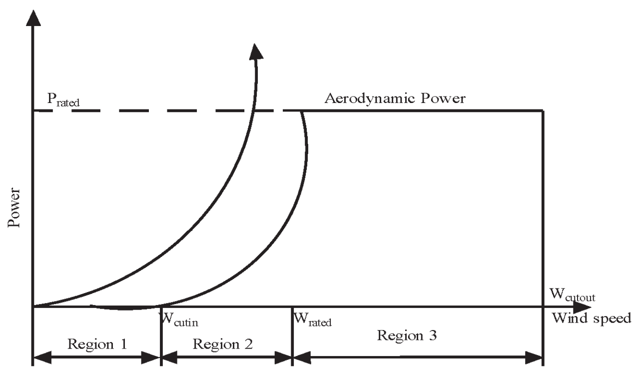

Figure 4. Power operating region of WT.

Region 1 represents the wind speed below the cut in wind speed. Region 2 represents the wind speed between cut in and cut out. In this region the main objective is to maximize the energy capture from the wind with reduced oscillation on the drive train. Region 3 describes the wind speed above the cut out speed. In this region pitch controller is used to maintain the WT at its rated power.

To achieve the above objective (Region 2) the blade pitch angle (β_{opt}) and tip speed ratio (λ_{opt}) are set to be its optimal value. In order to achieve the optimal tip speed ratio the rotor speed must be adjusted to the reference/optimal rotor speed (ω_{ropt}) by adjusting the control input i.e. generator torque (T_g). Equation 17 defines the reference/optimal rotor speed (ω_{ropt}).

$$\omega_{ropt} = \frac{\lambda_{opt}\upsilon}{R} \tag{17}$$

Figure 5 shows the WT control scheme. From this figure it is clear that WT has two control loops i.e. inner and outer loop. The inner control loop consists of electrical generator with power converters. The outer loop having the aero turbine control which gives the reference to the inner loop is shown in Figure 5. In this article we made an assumption that, the inner loop is well controlled.

Conventional controllers

The results of conventional controllers such as aerodynamic torque [ATF] control and indirect speed control [ISC] are compared in this work. The ATF control is adapted for single mass model. The aerodynamic torque and rotor speed are estimated by the Kalman filter [13]. In ISC WT is considered as locally stable in aerodynamic efficiency curve around its equilibrium point [14].

The above conventional control techniques have three major drawbacks. First the ATF control has a steady state error and a more accurate value of ω_{ref} is needed. Second the ISC control made the assumption to operate the WT its optimal efficiency curve but unfortunately is not suitable for high wind speed turbulence and it introduces power losses. Third both the controllers are not robust with respect to disturbances. In order to overcome these drawbacks the FSMC control with MNR estimator in the presence of disturbance and model uncertainty are proposed.

Wind speed estimator

The aero dynamic torque is approximated with the 5th order polynomial given in equation 7 and the corresponding rotor speed is measurable. Estimation of effective wind speed depends on aerodynamic torque and rotor speed with the pitch angle at optimal value, as follows

$$F(\upsilon) = T_a - \frac{1}{2}\rho\pi R^3 \frac{C_P(\lambda)}{\lambda}\upsilon^2 \tag{18}$$

The MNR algorithm is used to solve equation 18. This equation has unique solution at below rated region. Then, with known wind

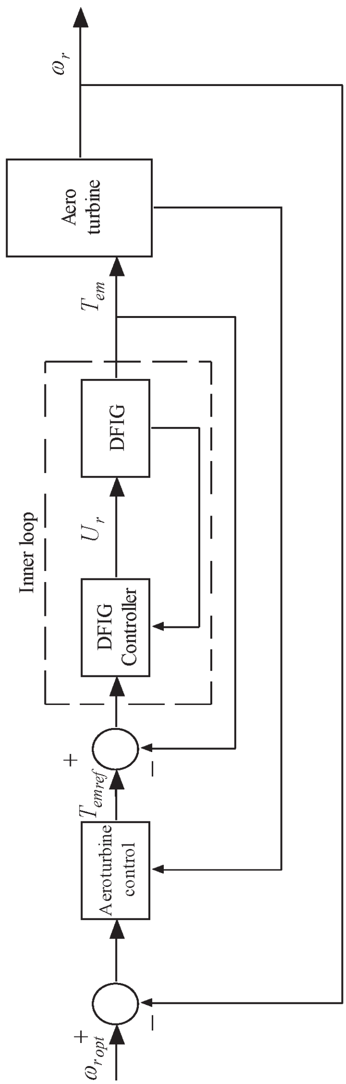

Figure 5. WT control scheme.

speed υ the optimal rotor speed ω_{ropt} is calculated by using equation 17.

Sliding mode control (SMC)

To achieve the maximum power at below rated wind speed, sliding mode based torque control is proposed in [12]. The main objective of this controller is to track the reference rotor speed ω_{ref} for maximum power extraction. The WT single mass model can be rearranged and is given by

$$\dot{\omega}_r = \frac{1}{J_t}T_a - \frac{K_t}{J_t}\omega_r - \frac{1}{J_t}T_g \tag{19}$$

For speed control a sliding surface is defined as

$$S(t) = \omega_r(t) - \omega_{ref}(t) \tag{20}$$

The reference rotor speed ω_{ref} was established in equation 17. Next taking the time derivative of the equation 20 we get

$$\dot{S}(t) = \dot{\omega}_r(t) - \dot{\omega}_{ref}(t) \tag{21}$$

By substituting $\dot{\omega}_r$ in the above equation (21) we get

$$\dot{S} = \frac{1}{J_t}T_a - \frac{K_t}{J_t}\omega_r - \frac{1}{J_t}T_g - \dot{\omega}_{ref} \tag{22}$$

In order to evaluate the stability of the SMC by using Lyapunov candidate function we define

$$V = \frac{1}{2}S^2 \tag{23}$$

Taking the time derivative of the above equation (23) we have

$$\dot{V} = S\dot{S} = S\left[\frac{1}{J_t}T_a - \frac{K_t}{J_t}\omega_r - \frac{1}{J_t}T_g - \dot{\omega}_{ref}\right] \tag{24}$$

if $\dot{V}$ is negative definite

$$\frac{1}{J_t}T_a - \frac{K_t}{J_t}\omega_r - \frac{1}{J_t}T_g - \dot{\omega}_{ref}\begin{Bmatrix} < 0 \ \ for\ S > 0 \\ > 0 \ \ for\ S < 0 \end{Bmatrix} \tag{25}$$

Stability of the controller is achieved provided the torque control satisfies equation (25). So

$$T_g \begin{Bmatrix} < T_a - K_t\omega_r - J_t\dot{\omega}_{ref} \;\; for\; S > 0 \\ > T_a - K_t\omega_r - J_t\dot{\omega}_{ref} \;\; for\; S < 0 \end{Bmatrix} \tag{26}$$

Finally the torque control structure is given in equation 27 and 28

$$T_g = T_a - K_t\omega_r - J_t\dot{\omega}_{ref} + J_t k\,\mathrm{sign}(S) \tag{27}$$

$$T_g = T_a - K_t\omega_r - J_t\dot{\omega}_{ref} + J_t k\,\tanh(S/\varphi) \tag{28}$$

where k is the sliding gain, *sign* is signum function and φ thickness of the boundary layer.

The major drawback in the signum function is it has discontinued values between +1 and -1. Because of this it introduces a chattering phenomenon. So the signum function is changed by a smooth function, i.e. saturation (sat) and hyperbolic tangent (tanh) with a boundary layer (φ). Thus, the chattering phenomenon is eliminated by the boundary layer. For robust control the boundary layer thickness is small, but if it is too small it increases the chattering. In order to select the boundary layer thickness it is necessary to know about the system behaviour inside the boundary layer

Proposed sliding mode control with integral action

The conventional sliding mode control sliding surface generally depends on error and derivative of the error signal is given in equation 29.

$$S(t) = \left(\lambda + \frac{d}{dt}\right)^{n-1} e(t) \tag{29}$$

Where λ is the positive constant and n is the order of the uncontrolled system.

To improve the sliding surface and overcome the steady state error the integral action is included in the sliding surface. A sliding surface is defined as

$$S(t) = \left(\lambda + \frac{d}{dt}\right)^{n-1} e(t) + K_i \int_0^{\infty} e(t)\,dt \tag{30}$$

where K_i is the integral gain.

The order of the system n=1 then the sliding surface modified as

$$S(t) = e(t) + \int_0^{\infty} e(t)dt \tag{31}$$

The major objective of the controller is the tracking error *e(t)* should converge to zero. The stability of the controller is determined by using the Lyapunov candidate function is already defined in equation 41 with *V(0)=0* and *V(t)>0* for $S \neq 0$.

By taking the time derivative of the equation 32

$$\dot{S}(t) = \dot{e}(t) + K_i e(t) \tag{32}$$

$$\dot{V} = S\dot{S} = S\left[\frac{1}{J_t}T_a - \frac{K_t}{J_t}\omega_r - \frac{1}{J_t}T_g - \dot{\omega}_{ref} + K_i e(t)\right] \tag{33}$$

Generally the SMC have two parts i.e. equivalent control U_{eq} and switching control U_{sw}. By combining this two control to minimize the tracking error and satisfies the stability of the controller.

$$U(t) = U_{eq} + U_{sw} \tag{34}$$

The Switching control is defined in two ways

$$U_{sw} = k\,\mathrm{sign}(S/\phi) \tag{35}$$

or

$$U_{sw} = k\tanh(S/\phi) \tag{36}$$

Finally the torque control structure is given in equation 37.

$$T_g = T_a - K_t\omega_r - J_t\dot{\omega}_{ref} + J_t k_i e(t) + J_t k \tanh\left(S/\phi\right) \tag{37}$$

RESULT AND DISCUSSION

Figure 6 shows the test wind profile of the WT. Generally wind speed consists of two parts i.e. mean and turbulent component. From this figure it is clear that wind speed having the data 10min and it is applied to a WT. Figure 7 shows the rotor speed comparisons different control strategy. From this figure it is clear that ISMC is almost tracking the reference rotor speed without any turbulence. Figure 8 shows the generator torque comparison for different control strategy.

For better clarity of the control action all the controllers are evaluated with different objectives such as,

- Electrical and aero dynamic efficiency.
- Control input is evaluated by its maximum value and standard deviation (STD).
- Control algorithm tested with added disturbance and model uncertainty.

As shown in Table 2 SMC is having the highest value of electrical and aero dynamic efficiency i.e. 91.10% and 93.23 %. This ensures the maximum power capture among all other controllers. In comparison to ISMC, SMC is better in capturing the more power. At the same time it is having more transient load on drive train because the STD of T_g is also having the highest value i.e. 1.928 kNm. According to

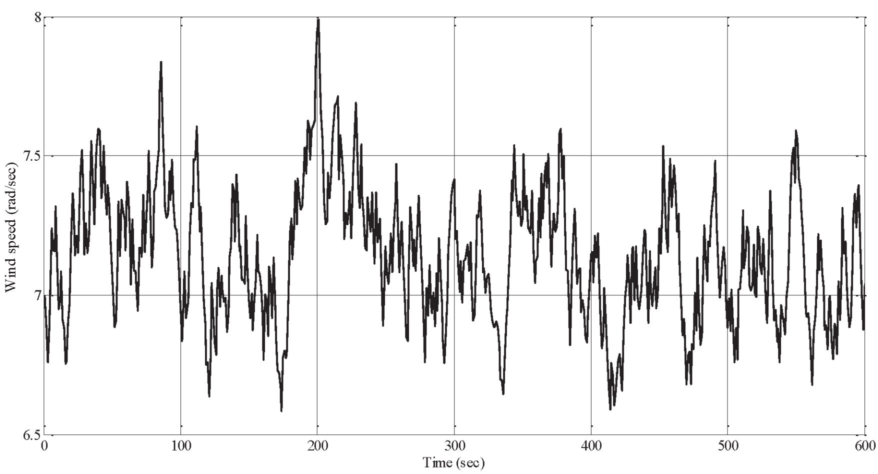

Figure 6. Wind profile of mean 7 m/sec

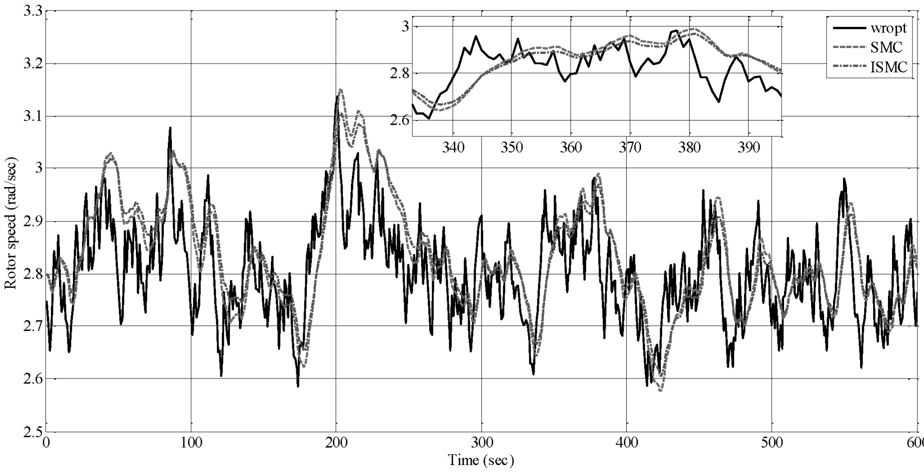

Figure 7. Rotor speed comparison of different control strategy.

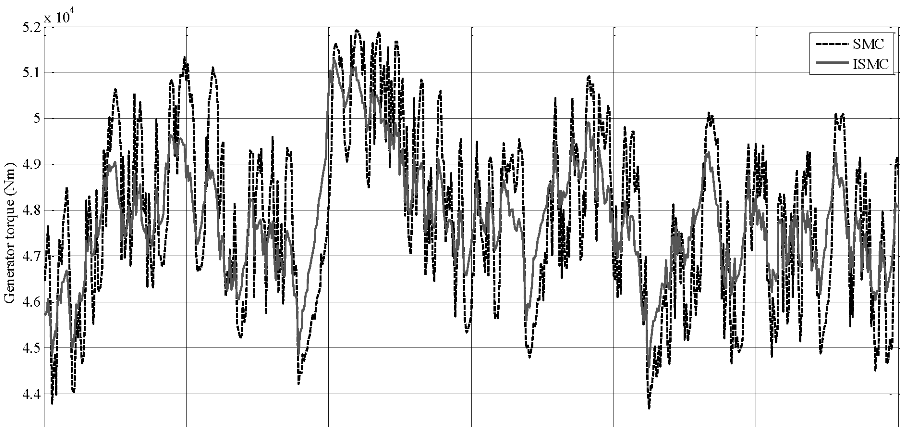

Figure 8. Generator torque comparison of different control strategy

the STD of T_g, ISMC is lowest compared to the all the controllers i.e. 1.26 kNm which indicate less transient load on drive train. As both the objectives cannot be achieved simultaneously a compromise has to be made between them. So for good control a trade-off is to be maintained between the maximum power capture and oscillation in drive train. Analysis of Table 2 gives a complete comparison on the results obtained for different controllers which clears that ISMC having almost same electrical and aerodynamic efficiency (91.06% and 93.21 %) with the SMC (i.e. 91.10% and 93.23 %). But at the same time ISMC having lowest standard deviation of control input which ensures reduced transient load on drive train. Analysis of Table 2 also gives that, ISMC is having better performance in terms of relative variation in generator torque, compared with its counterpart i.e. SMC. The conventional controllers ATF and ISC are found to be unsuitable in capturing the maximum power and less oscillation on the drive train.

Table 2. Comparison of different control strategy

Control Strategy	ATF	ISC	SMC	ISMC
STD(T_g)kNm	2.42	2.12	1.928	**1.260**
η_{ele}(%)	89.43	89.37	**91.10**	91.06
η_{aero}(%)	91.6	91.56	**93.23**	93.21
Relative variation T_g (%)	30.41	25.30	17.25	**14.04**

In order to analyse the robustness of the controllers a parameter uncertainty is introduced in the WT system parameters i.e. turbine inertia J_t and turbine damping K_t. The WT parameter is varied between +30% of its nominal values. Table 3 gives the controller performance with the presence of +30% parameter uncertainty. From this table it is found that for the proposed ISMC the STD of T_g is lowest i.e. 2.219 kNm with acceptable tracking error. For SMC the change in STD of T_g varies with a higher margin i.e. in the interval [0 1.543] (3.471-1.928=1.543 kNm) whereas for ISMC this margin comes in the interval [0 1.193] (2.219-1.260=0.959 kNm). The electrical and aerodynamic efficiency for both the SMC and ISMC are found to be almost same but the percentage of the relative variation in the generated torque is minimum for ISMC i.e. at 22.34%. This indicates that in the presence of parameter uncertainty, for achieving the desired objective of maximum power capture and less oscillation on the drive train, ISMC is more robust than SMC.

Table 3. Different control strategy with +30% uncertainty

Control Strategy	SMC	ISMC
STD(T_g)kNm	3.471	2.219
η_{ele}(%)	90.46	90.40
η_{aero}(%)	93.23	93.19
Relative variation T_g (%)	29.26	22.34

The adaptability of the controller is analysed with different mean wind speed profiles at below rated wind speed. Table 4 and Table 5 shows the performance of all the controllers with a mean wind speed of 8 m/sec and 8.5 m/sec respectively. The results shown in Table 4 and 5 ensure the suitability of proposed ISMC among other conventional linear and nonlinear controllers that achieves the similar performance even though the mean wind speed changes. As predicted, the maximum generator torque increases with increase in mean wind speed which indicates the increase in power capture.

Power spectral density (PSD) is used to make the frequency analysis of the drive train torque. Figure 9 shows the PSD for different controllers. From this figure it is clear that ISMC curve is completely below the SMC cure so it gives the minimum excitation to the drive train. A trade off should be made between the power capture and smooth control action. From the analysis of results it is clear that SMC and ISMC are having almost same power capture but stress on the drive train is minimum in ISMC.

Table 4. Comparison of different control strategy with mean wind speed of 8 m/sec

Control Strategy	ATF	ISC	SMC	ISMC
STD(T_g)kNm	2.719	2.623	2.542	**1.384**
MAX(T_g)kNm	67.18	67.12	67.04	67.72
η_{ele}(%)	89.42	89.39	91.45	91.48
η_{aero}(%)	91.66	91.65	93.38	93.43
Relative variation T_g (%)	30.71	28.31	15.65	13.54

Table 5. Comparison of different control strategy with mean wind speed of 8.5 m/sec

Control Strategy	ATF	ISC	SMC	ISMC
STD(T_g)kNm	2.785	2.747	2.426	**1.424**
MAX(T_g)kNm	73.59	73.65	74.69	74.94
η_{ele}(%)	89.56	89.53	91.83	91.79
η_{aero}(%)	91.66	91.65	93.6	93.58
Relative variation T_g (%)	26.09	25.72	14.46	**12.56**

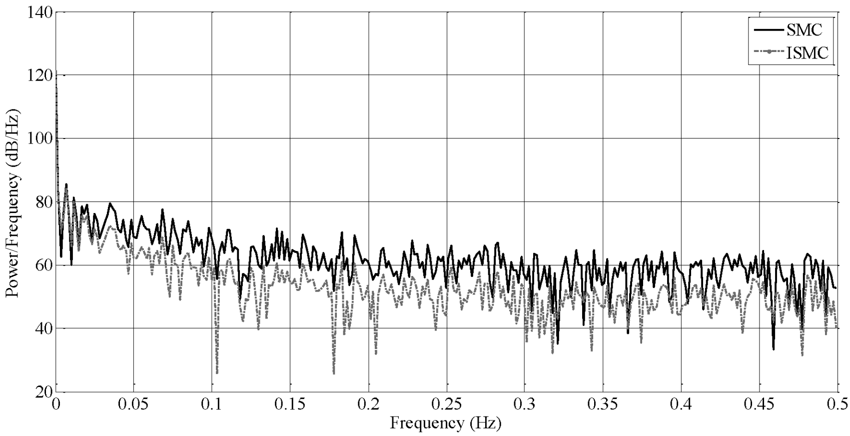

Figure 9. Power spectral density of generator torque.

VERIFICATION AND VALIDATION USING FAST

FAST is an aero elastic WT simulator which is developed by NREL. It can model both two and three blade horizontal axis wind turbine (HAWT). This FAST code can predict both extreme and fatigue loads. The tower and flexible blade are modeled by using the assumed mode method. Other components are modeled as rigid bodies. An advanced certified code is used in FAST to model the aerodynamic behavior of the WT. WT loads are calculated by using BEM (Blade Element Momentum) and multiple component of wind speed profile. FAST code is approved by the Germanischer Lioyd (GL) WindEnergie GmbH for calculating onshore WT loads for design and certification. Due to the above advantages and exact nonlinear modeling of the WT, the proposed controllers are validated by using FAST. In general three blade turbine have 24 DOF (Degree of Freedom) to represent the wind turbine dynamics. In this work 3 DOF is considered for WT i.e. variable generator, rotor speed and blade teeter. FAST codes are interface with S-function and implemented with Simulink model. FAST uses an AeroDyn file as an input for aerodynamic part. AeroDyn file contains aerodynamic analysis routine and it requires status of a WT from the dynamic analysis routine and returns the aerodynamic loads for each blade element to the dynamic routine. Wind profile acts as the input file for AeroDyn. The wind input file is generated by using TurbSim which is developed by the NREL.

Figure 10 shows the rotor speed comparison for SMC and ISMC using FAST simulator. Both SMC and ISMC are almost tracking the reference rotor speed. Figure 11 shows the PSD for generator torque which ensures, SMC having more variation compared to ISMC. Table 6 gives the performance of different control strategy for different mean wind speed using FAST simulator. From this table it is found that electrical and aerodynamic efficiency of both the controllers are almost same at the same time in STD of generated torque in ISMC is always less than SMC. So in ISMC the drive train oscillation is comparatively less than SMC.

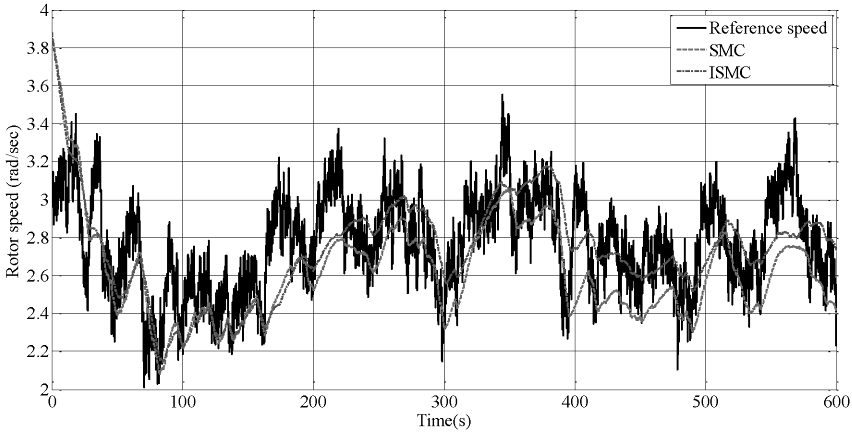

Figure 10. Rotor speed comparison for SMC and ISMC using FAST simulator

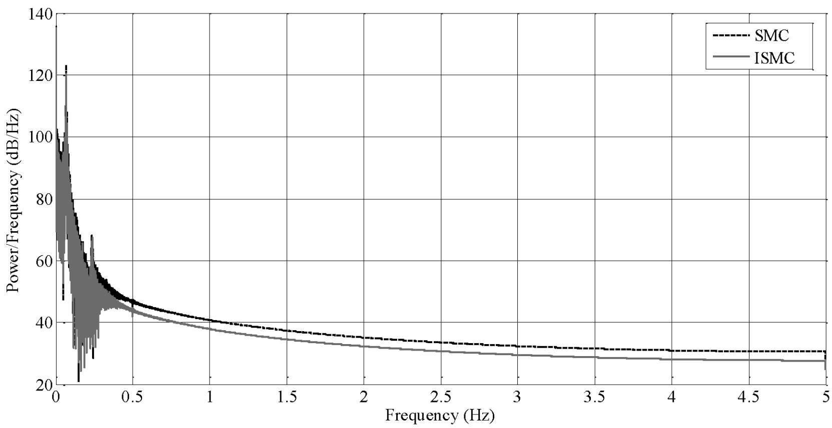

Figure 11. Power spectral density of generator torque for SMC and ISMC using FAST.

Table 6. Comparison of different control strategy with different mean wind speed.

Control Strategy	7 m/s		8m/s		8.5m/s	
	SMC	ISMC	SMC	ISMC	SMC	ISMC
STD(T_g) kNm	15.13	10.94	12.81	11.03	12.69	11.36
MAX(T_g) kNm	82.35	77.02	92.19	85.56	97.10	102.55
STD(T_{ls}) kNm	36.34	23.23	34.40	24.34	30.26	27.19
MAX(T_{ls}) kNm	194.59	129.24	226.67	141.24	204.04	175.64
η_{ele} (%)	77.64	76.02	75.76	74.91	75.84	74.69
η_{aero} (%)	91.11	92.17	90.13	92.76	91.17	92.76

CONCLUSION

This article deals with the objective of extracting maximum power generation with minimum mechanical stress on the drive train in VSWTs. Here SMC with integral action is proposed to ensure the above objective and to impose an ideal feedback control solution despite of model disturbance and uncertainty in the model parameters. The existing classical control techniques such as ATF, ISC, are also adapted in this article. Existing controllers are having the drawbacks of steady state tracking error, significance power loss and complex control law. In this work, a proposed ISMC is used to extract the maximum power capture at below rated wind speed where the wind speed is estimated using MNR. Different wind speed profiles are tested for proposed as well as existing controllers. From these results it is concluded that, the proposed ISMC controller gives better efficiency and reduced oscillation in the drive train compared with existing controllers. Indeed, the integral sliding-mode approach is used to minimize the tracking error between the rotor speed and optimal rotor speed.

APPENDIX A- Model Data

Rotor Radius	$R = 21.65\text{m}$
Air Density	$\rho = 1.29\text{Kg/m}^3$
Rotor Inertia	$J_r = 3.25.10^5\text{Kg.m}^2$
Generator Inertia	$J_g = 34.4\text{Kg.m}^2$
Shaft damping coefficient	$K_{ls} = 9500\text{Nm/rad}$
Shaft stiffness coefficient	$B_{ls} = 2.691.10^5\text{Nm/rad}$

Rotor friction coefficient	K_r = 27.36 Nm/rad/sec
Generator friction coefficient	K_g = 0.2 Nm/rad/sec
Gear ratio	n_g = 43.165

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