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Robust Nonlinear Terminal Integral Sliding Mode Torque Control for Wind Turbines Considering Uncertainties

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Abstract: Power maximization and fatigue alleviation are essential for variable speed wind turbines operating in partial load zone. It is within this framework that the present paper gives a global state of art of the application of sliding mode control (SMC) for wind turbines and proposes a new application of Terminal Integral Sliding Mode Control (TISMC) for variable speed wind turbines, described as a mechatronic system, represented by uncertain lumped mass dynamics. In order to represent a relatively exhaustive study, a stability proof is also synthesized and verified using the Lyapunov criterion. In order to evaluate the proposed solution, a numerical validation has been done on Controls Advanced Research Turbine (CART 2) using the National Renewable Energy Laboratory (NREL) simulator Fatigue, Aerodynamics, Structures and Turbulence (FAST). For more accuracy 9 DOFs (Degrees of Freedom) were enabled with a realistic turbulent wind field. The obtained results shown the effectiveness of TISMC compared to some existing linear and nonlinear controllers in term of output power maximization and loads mitigation.

Keywords: *Wind turbine Control, SMC, ISMC, TISMC, FAST.*

1. INTRODUCTION

With a growth rate of the cumulative installed capacity of wind turbine conversion systems of 19% GWEC (2020), wind energy is considered as the most commercially attractive renewable energy vector. However, the cost of wind power is relatively expensive compared to fossil fuels energy. In order to be more competitive, the optimization of initial costs and energy efficiency by introducing advanced control laws is a key concern. Thus, the productivity of the machine can be increased within its physical limits, while maximizing the availability of wind turbines Burton et al. (2011).

Nowadays, two types of horizontal axis turbines are in use, fixed speed and variable speed wind turbines. The latter is predominant on the market due to its ability to operate under all wind conditions. In fact, there are two active operating areas of this type of machines, under low wind speeds, in which the objective is to maximize output power by controlling the rotor speed around its optimal curve by acting on the electromagnetic torque. Under high wind speeds the objective is to regulate the speed and equivalently the power around the nominal value by acting on the pitch system. Hence, the control of wind turbines is absolutely essential Chehaidia et al. (2020).

A specefic research was carried out using keywords search tool of Scopus database[1]. It shown an extensive bibliography investigating wind turbine control in the last decade with over 55,000 documents. A quantitative analysis of the evolution of research activities on wind turbines control is shown in Figure 1. It illustrates that the research tendencies are towards nonlinear control technics, du to the highly nonlinear dynamics of wind turbine and its environment. In addition, one can observe that Sliding Mode Control (SMC) has attracted a particular attention from scientists, or, it dominating over 18% of published works focussing on nonlinear controllers and 9% of all works, with a peak production recorded in late 2016. That evolution is mainly due to its simplicity, robustness, efficiency and technological boom in PCs developpement and their ability to analyze increasingly complex models and control laws. Linear control has been widely used, including PI and PID controllers Merabet et al. (2011). In order to cope with the nonlinearities of wind turbine, the optimal control, also called Linear Quadratic Control (LQR) has been proposed by Jin et al. (2013), in which, a good reference speed tracking with a reduction of the mechanical loads on the drivetrain was noticed. Despite its robustness and self-adjustment, this technique does not provide the expected performance since it is synthesized from the linearized model of the turbine. Nonlinear control of wind turbines has been the subject of several studies in order to ensure optimal maximization of electrical power, in spite of system nonlinearities. The Ref Beltran et al. (2008) investigate a robust sliding mode control,

[1] https://www.scopus.com/search/form.uri#basic

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the weakness of the proposed control law is the use of a monotonic approximation of the sign function in order to reduce the chattering, which increase drivetrain's mechanical loads. In Ref Yang et al. (2013), authors propose a Terminal Sliding Mode Control. On can see integral sliding mode in the partial load region. The Lyapunov criterion was used to test the stability, validation results using FAST simulator show that the addition of the integral action reduces the static error and mitigates chattering phenomenon. Unfortunately, the neglect of uncertainties and the reduced number of DOFs taken into consideration do not allow the prediction of the real behaviour of the wind turbine. In Ref Feng et al. (2013), a High Order Terminal Sliding-Mode Control strategy is prosed for a grid connected wind turbine system. In the Refs Rajendran et al. (2014), Saravanakumar et al. (2015), Integral Sliding Mode Control is proposed based on lumped mass mechanical model. In Ref Saravanakumar et al. (2016), Integral Sliding Mode Control is presented, the control law was synthetized from elastic two mass model. An Adaptive Fuzzy Integral Sliding Mode was investigated by Mani et al. (2021). Terminal Proportional Integral Sliding Mode Control Jain et al. (2021). Various Second Order Sliding Mode Controllers were presented in the manuscript herein Golnary et al. (2019). In Ref Chojaa et al. (2021), authors proposes a Neural Network controller at turbine level's and an Integral Sliding Mode controller at the DFIG level for energy maximization under realistic wind speed profile. In Ref Chojaa et al. (2021), a comparative study between serval controllers have been conducted for wind turbine control under low speed conditions, results shown that the Artificial Neural Networks performs well than PI, Adaptive Backstepping and Sliding Mode controllers In Ref Movahhed Neya et al. (2022), a new Disturbance Observer-based Controller was proposed for maximum power extraction without prior knowledge of system's parameters. The obtained results shown the effectiveness of the proposed controller compared To Second Order Sliding Mode, Second Order Fast Terminal Sliding Mode Control and Adaptive Robust Control. However, in term of control effort, the proposed control law provoques a harder action which increases the fatigue loads. Although each type of control is distinct from the others, the following observations can be made:

- the dynamics of the control system depends directly on the sliding surface;
- the inclusion of the nonlinear terms contributes significantly in reducing the impact of the chattering, which is mainly due to the unmodeled dynamics and switching frequency;
- the integral action has the most notable influence compared to the other terms added to the sliding surface;

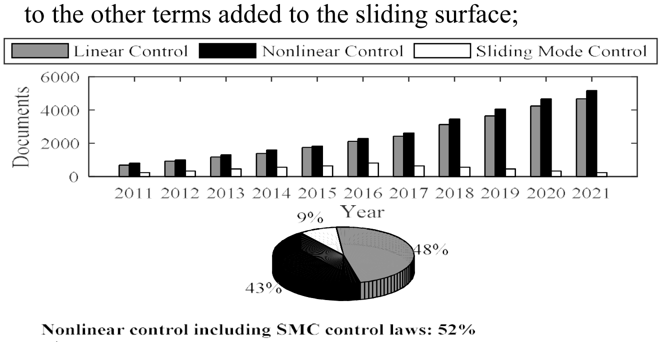

Figure 1. Number of papers by year with keyword

- the nonlinearity of the sliding surface improves the tracking performance, however, it results in an increase of the number of variables, which requires more optimization efforts.

The present manuscript proposes a nonlinear robust terminal integral sliding mode controller for wind turbine operating in partial load region considering parametric uncertainties. The proposed law ensures output power maximization and fatigue alleviation, with an effective improvement compared to some existing control laws. Moreover, in order to verify the stability of the proposed control laws, the Lyapunov candidate function is used. As far to our knowledge, the proposed control law has not been subject of further study in the available bibliography. The rest of the manuscript is organized are follows: the wind turbine modeling is presented in Section 2, then, torque control strategies are synthetized in Section 3, the discussion of main results and conclusion are presented respectively in Section 4 and Section 5.

2. SYSTEM MODELING

Wind turbines transforms the kinetic energy of wind into electrical energy. Its captured aerodynamic power P_a *[W]* is given by (1), such as Chehaidia et al. (2020):

$$P_a = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\beta)v^3 \quad (1)$$

where $\rho\ [kg.m^{-3}]$ is the air density, $R\ [m]$ is rotor radius and $v[m.s^{-1}]$denotes the wind speed. The power coefficient $Cp(\lambda,\beta)$ depending on blade pitch angle β [°] and tip-speed ratio λ , expressed as follows :

$$\lambda = \frac{\omega_r}{v}R \quad (2)$$

where $\omega_r\ [rad.s^{-1}]$ is the rotor speed. The aerodynamic torque $T_a\ [N.m]$ developed by a wind turbine is the following:

$$T_a = \frac{P_a}{\omega_r} = \frac{1}{2\lambda}\rho\pi R^2 C_p\left(\lambda,\beta\right)v^2 \quad (3)$$

Wind turbine blades are driven by the aerodynamic torque produced after the interaction with wind, which provokes the rotation of the rotor and consequently the low speed shaft with a specific rotor speed. The last is braked by the low speed torque. The gearbox is used to increase the rotor speed in order to drive the generator with its appropriate high speed. Similar to the dynamics on the rotor side, the high speed shaft is driven by the high speed torque and braked by the electromagnetic torque on the generator side Yang et al. (2020). The two-mass drivetrain model can be described as follows:

$$J_r\dot{\omega}_r = T_a - T_{ls} - D_r\omega_r \quad (4)$$

$$J_g\dot{\omega}_g = T_{hs} - T_e - D_g\omega_g \quad (5)$$

where $T_{hs}\ [N.m]$ and $T_{ls}\ [N.m]$ are respectively, high speed shaft torque and low speed shaft torque expressed as follows:

$$T_{ls} = k_{ls}\left(\theta_r - \theta_{ls}\right) + D_{ls}\left(\omega_r - \omega_{ls}\right) \quad (6)$$

where $K_{ls}\ [N.m.rad.s^{-1}]$ and $D_{ls}\ [N.m.rad^{-1}.s^{-1}]$ are the low shaft speed stiffness and damping respectively $\theta_r[rad]$. and $\theta_{ls}[rad]$ represent the rotor side angular deviation and the gearbox side angular deviation respectively.

The so called n_g, namely the gear box ratio defining the relationship between the rotor and generator sides as follows:

$$n_g = \frac{\omega_g}{\omega_{ls}} = \frac{T_{ls}}{T_{hs}} = \frac{\theta_g}{\theta_{ls}} \quad (7)$$

By neglecting the external stiffness of both rotor and generator; assuming that the low-speed shaft If perfectly rigid and using (4), (5) and (7), one deduced the lumped model expressed by a first order differential equation as follows:

$$J_t\dot{\omega}_r = T_a - D_t\omega_r - T_g \quad (8)$$

where J_t $[kg.m^2]$,D_t $[N.m.rad^{-1}.s^{-1}]$ and T_g $[N.m]$ denote respectively, the turbine total inertia, turbine total external damping, and generator torque in the rotor side such as:

$$\left\{J_t = J_r + n_g{}^2J_g;\ D_t = D_r + n_g{}^2D_g; T_g = T_e n_g\right\} \quad (9)$$

Finally, the electric power produced by generator is:

$$P_e = \omega_r T_g \quad (10)$$

In an attempt to better modeled the uncertainties of wind turbine, the parametric uncertainty quantification approach introduced by Colombo et al. (2020) is used. In addition, uncertainties bounding approach used by Nayeh et al. (2020), which consists in setting the uncertainties around 10% of the nominal values of the model parameters. Finally, an additive disturbance d is added on T_g. By considering the model uncertainties and additive disturbance, (8) becomes:

$$\dot{\omega}_r = \frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{1}{J}T_g + d \quad (11)$$

$$\begin{cases} J = J_t + \Delta J; \left|\Delta J\right| \le \rho J \\ D = D_t + \Delta D; \left|\Delta D\right| \le \rho D \end{cases} \quad (12)$$

where ΔJ and ΔD are parametric uncertainties of total inertia and total external damping respectively. While, ρJ and ρD are two known positive constants.

3. TORQUE CONTROL STRATEGY

SMC is a robust nonlinear control technique, widely used for uncertain nonlinear dynamic systems. It is known for its fast response, good transient performance, insensitivity to uncertainties and its ability to deal with rapid dynamic responses while achieving global stability. The principle of the SMC control consists in bringing the system back to its equilibrium state. In this section, advanced sliding mode controllers for variable speed wind turbine operating in partial load region is presented. As a crucial for any control system, the stability robustness of each controller is approved based on Lyapunov criterion.

3.1. Sliding Mode Control

Considering the objective of the rotor speed regulation by acting on generator torque signal in order to maximize the produced power and mitigate the structural loads of the wind turbine. The present subsection is dedicated to the conventional SMC torque control for variable speed wind turbine presented in the reference herein Rajendran et al. (2015).

First, assuming that the desired trajectory deduced from (2) is ω_{ref}, the tracking error is defined as follows:

$$\varepsilon = \omega_r - \omega_{ref} \quad (13)$$

The suitable sliding surface is defined, such as:

$$S_1 = \varepsilon_r = \omega_r - \omega_{ref} \quad (14)$$

The first time derivative of (14) is :

$$\dot{S}_1 = \dot{\omega}_r - \dot{\omega}_{ref} \quad (15)$$

Substituting (11) in (15), one gets:

$$\dot{S}_1 = \frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{T_g}{J} - \dot{\omega}_{ref} + d \quad (16)$$

By putting the sliding surface S_1 at its extremum, by forcing its time derivative given by (16) to zero; the SMC torque control law of variable speed wind turbine operating in partial load region is the following:

$$T_g = T_a - D\omega_r - J\dot{\omega}_{ref} + d + JK_s \tan\left(\frac{S_1}{\varphi}\right) \quad (17)$$

The Lyapunov candidate function is given as:

$$V_1 = \frac{1}{2}\left(S_1\right)^2 \quad (18)$$

Its first time derivative is the following:

$$\dot{V}_1 = S_1\dot{S}_1 = S_1\left(\frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{T_g}{J} - \dot{\omega}_{ref} + d\right) \quad (19)$$

$\dot{V}_1$ is negative meets:

$$\frac{1}{J}T_a - \frac{D_t}{J}\omega_r - \frac{1}{J}T_g - \dot{\omega}_{ref} + d\begin{Bmatrix} < 0\ for\ S_1 > 0 \\ > 0\ for\ S_1 < 0 \end{Bmatrix} \quad (20)$$

Since the condition (21) is verified the closed loop system is stable and its trajectory reach the sliding surface.

$$T_g\begin{Bmatrix} < T_a - D\,\omega_r - J\,\dot{\omega}_{r_{ref}}\ for\, S_1 > 0 \\ > T_a - D\,\omega_r - J\,\dot{\omega}_{r_{ref}}\ for\, S_1 < 0 \end{Bmatrix} \quad (21)$$

3.2. Integral Sliding Mode Control

The sliding mode control ensures the infinite time convergence the asymptotic stability of the system and it's also able to cope with the system nonlinearities Feng et al. (2002). However, the conventional SMC is tiring to the system because of high-frequency turbulence mainly, due to the reaching phase and chattering phenomenon, therefore, using ISMC can solve this problem by eliminating the reaching phase which considerably reduces the chattering and static error as well Irfan et al. (2018). The suitable integral sliding mode control ISMCE sliding surface is chosen such as Rajendran et al. (2015):

$$S_2 = \varepsilon + K_i\int_0^{\infty}\varepsilon\left(\tau\right)d\left(\tau\right) \quad (22)$$

where K_i denotes the integral gain. The first time derivative of S_2 is:

$$\dot{S}_2 = \left[\dot{\omega}_r - \dot{\omega}_{ref}\right] + K_i\varepsilon \quad (23)$$

Based on (23) , (11) and (12), one gets:

$$\dot{S}_2 = \frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{T_g}{J} + d - \dot{\omega}_{ref} + K_i\varepsilon \quad (24)$$

The ISMCE torque control law of variable speed wind turbine operates under low wind speed condition is expressed as follows:

$$T_g = T_a - D\omega_r - J\dot{\omega}_{ref} + JK_i\varepsilon + d + JK_s \tan\left(\frac{S_2}{\varphi}\right) \quad (25)$$

The Lyapunov candidate function is given as:

$$V_2 = \frac{1}{2}\left(S_2\right)^2 \quad (26)$$

The first derivative of (26) is the followings:

$$\dot{V}_2 = S_2\dot{S}_2 = S_2\left(\frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{T_g}{J} + d - \dot{\omega}_{ref} + K_i\varepsilon\right) \quad (27)$$

$\dot{V}_2$ is negative if:

$$\frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{T_g}{J} - \dot{\omega}_{ref} + C_1\varepsilon + d\begin{Bmatrix} < 0 \; for \; S_2 > 0 \\ > 0 \; for \; S_2 < 0 \end{Bmatrix} \quad (28)$$

So the closed loop stability is verified if T_g verifies the condition (29).

$$T_g\begin{Bmatrix} < T_a - D\omega_r - J\dot{\omega}_{ref} + JK_i\varepsilon + d \quad for \; S_2 > 0 \\ > T_a - D\omega_r - J\dot{\omega}_{ref} + JK_i\varepsilon + d \quad for \; S_2 < 0 \end{Bmatrix} \quad (29)$$

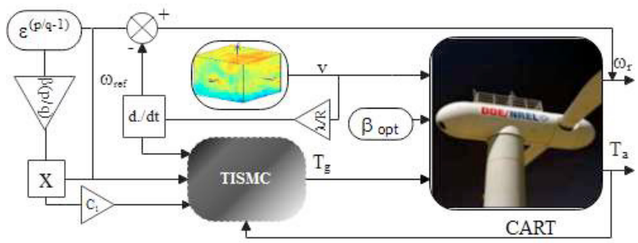

Figure 2. Bloc diagram of the proposed TISMC

3.3. Terminal Integral Sliding Mode Control

Contrary to ISMC, the TISMC ensures finite time convergence and guarantees fast and accurate response, which contributes to improving the efficiency of the control law Zafran et al. (2020). Defining the TISMCE sliding surface S_3, such as :

$$S_3 = \varepsilon + K_i\int_0^t \varepsilon(\tau)d\tau + \beta_1\varepsilon^{p/q} \quad (30)$$

where $\beta_1 > 0, p, q; (p > q)$ are positive constants.¨

As already noticed in Ref. Zhang et al. (2020), the main disadvantage of the terminal sliding mode is the singularity problem. Indeed, the singularity can be avoided by changing the upper bound of the uncertainties, defined by (12).The presence of the adaptive nonlinear term $\beta_1 e^{p/q}$ accelerates convergence by reducing the sliding surface reaching phase time which increases the accuracy of control system. Deriving (30), one obtains:

$$\dot{S}_3 = \frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{1}{J}T_g - \dot{\omega}_{r_{ref}} + d + K_i\varepsilon + \beta_1\frac{p}{q}\left[\varepsilon^{\left(\frac{p}{q}-1\right)}\dot{\varepsilon}\right] \quad (31)$$

By setting (31) to zero, the TISMC torque control law of variable speed wind turbine operating under low wind speed, which bloc diagram is being shown in Figure 2, is expressed as follows:

$$T_g = \left(T_a - D\omega_r - J\dot{\omega}_{ref} + d + JC_1\varepsilon + J\beta_1\frac{p}{q}\left[\varepsilon^{\left(\frac{p}{q}-1\right)}\dot{\varepsilon}\right] + JK_s\tanh\left(\frac{S_3}{\varphi}\right)\right) \quad (32)$$

The Lyapunov candidate function is given as:

$$V_3 = \frac{1}{2}(S_3)^2 \quad (33)$$

The first time derivative of the above equation is:

$$\dot{V}_3 = S_3\left(\frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{1}{J_t}T_g - \dot{\omega}_{r_{ref}} + d + C_1\varepsilon + \beta_1\frac{p}{q}\left[\varepsilon^{\left(\frac{p}{q}-1\right)}\dot{\varepsilon}\right]\right) \quad (34)$$

In order to keep (34) negative, the condition (35) should be verified, such as :

$$\left\{\frac{1}{J}T_a - \frac{D}{J}\omega_r - \frac{T_g}{J} - \dot{\omega}_{ref} + d + C_1\varepsilon + \beta_1\frac{p}{q}\left[\varepsilon^{\left(\frac{p}{q}-1\right)}\dot{\varepsilon}\right]\right\}\begin{Bmatrix} < 0 \, for \, S_3 > 0 \\ > 0 \, for \, S_3 < 0 \end{Bmatrix} \quad (35)$$

Finally, if T_g meets condition (36), the control system stability is verified.

$$T_g\left\{\begin{matrix} \left\{< T_a - D\omega_r - J\dot{\omega}_{ref} + JC_1\varepsilon + d + J\beta_1\frac{p}{q}\left[\varepsilon^{\left(\frac{p}{q}-1\right)}\dot{\varepsilon}\right]\right\} for \, S_3 > 0 \\ \left\{> T_a - D\omega_r - J\dot{\omega}_{ref} + JC_1\varepsilon + d + J\beta_1\frac{p}{q}\left[\varepsilon^{\left(\frac{p}{q}-1\right)}\dot{\varepsilon}\right]\right\} for \, S_3 < 0 \end{matrix}\right\} \quad (36)$$

4. RESULTS AND DISCUSSION

The validation of advanced sliding mode torque control laws presented in Section is performed using the aeroelastic simulator FAST, based on CART 2 wind turbine located in NREL, National Wind center, Golden, Colorado Stol (2004). Using drivetrain parameters derived from Boukhezzar et al. (2010), and considering 9 DOFS, namely:

- first flapwise blade mode (2 × 1 DOF);
- second flapwise blade mode (2 × 1 DOF),
- first edgewise blade mode (2 × 1 DOF);
- rotor-teeter (1 DOF);
- drivetrain rotational-flexibility (1 DOF);
- generator mode (1 DOF).

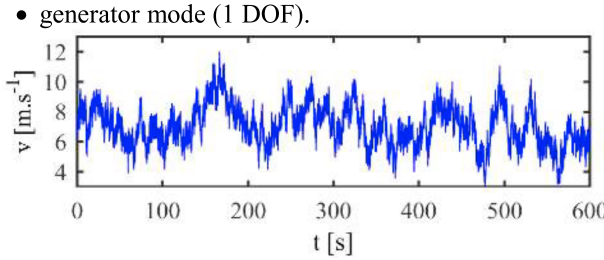

Figure 3. Wind Speed Profile Chehaidia et al. (2020)

All numerical simulations were performed using 600 [s] wind speed profile, with a mean value of 7[ms^{-1}] and a turbulence intensity of 20% (Figure 3). As FAST is chosen for validation, the used wind profile have been generated using TurbSim Jonkman et al. (2006). In addition, all presented controllers were tested and validated by filleting ω_{ref}, ω_r and T_g in order to smooth control action; adding an additive noise measurement on ω_r ; with SNR=7[dB]; in presence of additive disturbance d=5000[N.m] on T_g . Considering the following initial conditions $\{v_0 = 7[m.s^{-1}], \omega_{r_0} = 22[tr.\min^{-1}], T_{g_0} = 35[kN.m]\}$ Chehaidia et al. (2020). Finally, based on trial and error, the selected gains for control laws (17), (25) and (32) are: K_s=0.15, C_1=0.01, a=50, β =0.005 p=3, q=5 . Figure 4 shows the rotor speed in which one can see that the nonlinear control gives the best performance in terms of tracking the reference speed. This is primarily due to the nature of the wind turbine system's. We notice that the SMC and ISMC controllers contribute spectacularly to the improvement of the performance of the control system in terms of speed and precision, which corroborates the results of Rajendran et al. (2015). The TISMC controller leads to the best transient regime and can be described as fast and damped, in spite of uncertainties, additive disturbances and fast variation of the wind speed profile, a such improvement can be explained by the effet of the added nonlinear term $\beta_1 e^{p/q}$ which can be qualified as an artificial nonlineariry dealing with natural machine nonlinearities. Figure 5 shows the generator torque; regarding to PI controller objectives and it's tunning requirements and method does not consider the structural load reduction and fatique. However a significant reduction in loads is observed. This resulted in a decrease in standard deviation of T_g time serie signal from 13.08 [kN.m] for PI to 9.44 [kN.m] for TISMC, and smoothy evolutions despite high turbulent wind speed profil, model incertainties and additive disturbance. We calculate and draw the Power Spectral Density of the generator torque time serie signal PSD (T_g) as illstrated in Figure 6.

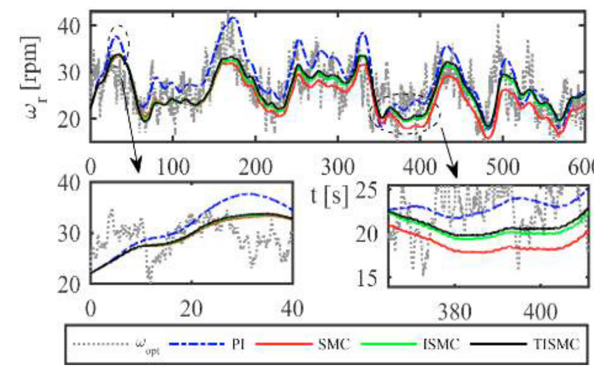

Figure 4. Rotor Speed

The PSD confirms time domain results; in which we see a significant reduction of the once per revolution (1P) at 0.7 [Hz] and twice per revolution rotor harmonics (2P), influencing directly the low speed shaft and consequently the hidh speed shaft through the drive train. On can obseve the reduction of the amplitude at 3.6 [Hz], which corresponds to the first drivetrain torsion mode in closed-loop. In global an overal signal power reduction of 15[dB] is obtained using the proposed TISMC.

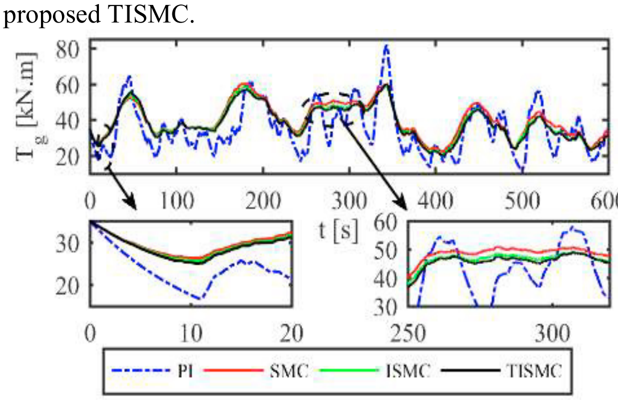

Figure 5. Generator Torque

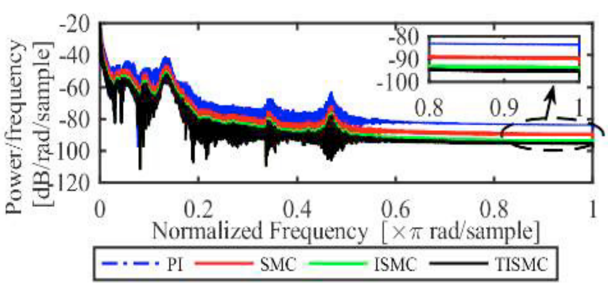

Figure 6. PSD (T_g)

Similar to the high speed shaft, the low speed shaft torque signal has been improved significantly under the nonlinear controllers action as can be seen in Figure 7, with a significant std (T_{ls}) reduction around 25%, from 12.27 [kN.m] for PI to 9.16 [kN.m] for the proposed TISMC. However high oscillations can be observed in the first 5 [s] for all presented nonlinear controllers. By invistigating the probables causes of such hard demarrage, we deduced that a filter delay of 10[ms] between signals increases the chatering effect of sliding mode controller. Based on the principle of sliding mode control, only infinite switching frequency leads to an ideal sliding regime and any delay due to the frequency of the real systems means that the control force will operate with a staggered step, which will cause high chattering, especially in the transient regime, due to the high inertia of the slow shaft. Figure 8 ilustrates PSD (T_{ls}), similarly to the generator, an attenuation of 1P and 2P harmonics is observed with a good reduction of signal power, around 15[dB].

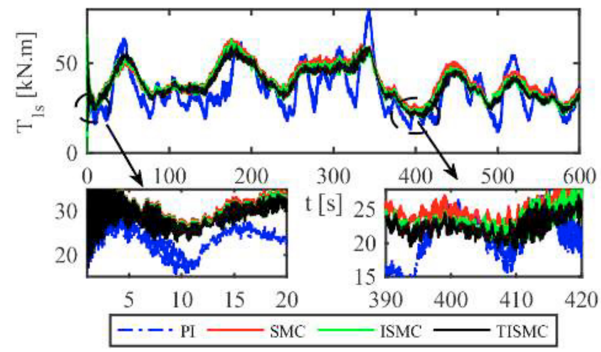

Figure 7. Low Speed Shaft Torque

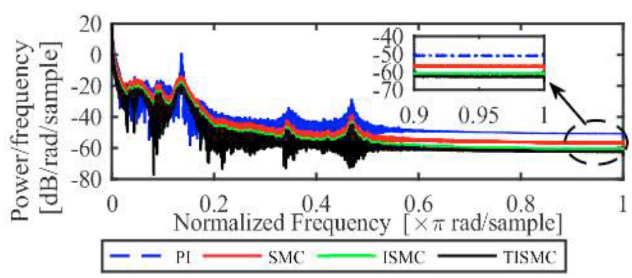

Figure 8. PSD (T_{ls})

As for the electrical power shown in Figure 9, it can be seen that PI can reaches much higher values compared to nonlinear sliding mode control laws control, but the strong oscillations have caused aerodynamic and therefore high electrical power losses which decrease considerably the efficiency of controller. Regarding the aerodynamic and elctrical efficiencies, the TISMC leads to the best performance 95.49% and 84.37% respectively, with an improuvement of 4.36% of produced electrical power compared to PI controller.

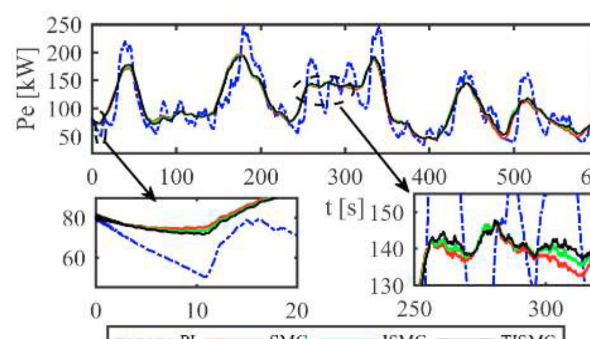

Figure 9. Electrical Power

Table 1. Performance comparison

Criterion	Performance			
	PI	SMC	ISMC	TISMC
η_{aero}[%]	89.22	93.98	95.48	**95.49**
η_{elc}[%]	80.01	83.13	84.35	**84.37**
$\bar{T}_{ls}[kN.m]$	34.82	39.99	38.65	38.67
$\max T_{ls}[kN.m]$	79.26	65.16	65.15	65.15
$\text{std}\, T_{ls}[kN.m]$	12.27	9.26	9.13	9.16
$\bar{T}_g[kN.m]$	34.80	39.99	38.64	38.66
$\max T_g[kN.m]$	81.51	60.51	58.86	59.08
$\text{std}\, T_g[kN.m]$	13.08	9.53	9.41	9.44

5. CONCLUSIONS

For the first time a robust integral terminal sliding mode control for wind turbine in partial load region is applied and validated by FAST simulator, using the parameters of CART 2 wind turbine. In order to make a closely analysis of controller's performances, the robustness of each have been verified and tested based Lyapunov stability criterion. Numerical simulation proved the improvement capacity of TISMC on system performance compared to some existing control laws, namely: PI, SMC and ISMC. This paper offers extensive research prospective in different areas. As a perspective, one can consider the same controller with aerodynamic torque state estimator, because even the presented controllers are efficient, the measurement of aerodynamic torque still difficult for field machines. It would also be interesting to consider Supertwisting TISMC and High Order TISMC, in order to solve in a better way, the problem of singularity and reduce the chattering phenomenon impact, which is highly undesirable for the lifespan of the wind turbine elements.

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