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Sliding Mode Control with MPPT for DFIG to Improve the Dynamic Performance

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Abstract—**Linearization approach is the common practice used to address the control problem of wind based turbines; generally, it is tedious and not good because of unavoidable uncertainties and vague operating conditions present in the system which leads to indigent system performance with low reliability. Therefore the need of dynamic resilient Sliding Mode Controller (SMC) strategy is required to take into account these control problems. In this paper, control of the power generation in wind generator is investigated. The wind energy systems have two operating regions depending on the wind turbine tip-speed ratio, which are distinguished by minimum phase behavior in one of these regions and a non-minimum phase in the other one. In spite of the model uncertainties, to fortify stability in two operating regions and to apply the best possible feedback control solution, a SMC strategy with Maximum Power Point Tracking is proposed in this paper which is applied to Doubly Fed Induction Generator (DFIG). The dynamic performance and power capture is improved in the case of the SMC strategy based DFIG compared to standard control of the DFIG. The proposed SMC strategy and standard control of DFIG are validated by using Fatigue, Aerodynamics, Structures, and Turbulence code (FAST).**

Index Terms—**power generation control, sliding mode control, doubly fed induction generator, wind energy conversion system**

I. INTRODUCTION

Nowadays, wind energy conversion is playing a vital role in the world's power energy generation, it is expected by 2030 and by 2050 it will reach to supply 29.1% and 34.2% of the world's electricity respectively as indicated in the 2006 report of the Global Wind Energy Council (GWEC). This tendency of increase of wind energy among the renewable energy power generation sources has been fast growing these years, and this trend will remain for quite some time. Some of the European countries had chosen wind power as the main stream power. In the world, the total capacity of wind power has crossed 4.32GW by end of 2015 and this value increases with commissioning of new installations. In India, the total capacity of wind power has reached to 26,932MW, as on May 2016, which makes to 68.14% of the total renewable energy and the target by the Ministry of New and Renewable Energy is to achieve 1,00,000 MW by 2020.

Nowadays prominence is more on exploiting the available wind energy which is turning out to be the latest area of research with the economical utilization of the energy available focusing more on reliability and quality of the power supply [1]. There is a drastic development in the wind turbine sizes from last two decades, the sizes varied from 20kW to 3.3MW for onshore wind energy technology, and 80kW to 8MW for offshore wind energy technology. In India, sizes of the wind turbine varied from 55kW to 2.6MW, while the Ministry of New and Renewable Energy (MNRE) are planning for a large-size wind turbine for both onshore and offshore wind energy.

The state of art of wind generators were developed with various concepts and were tested [2]. The optimal tracking is possible in currently used Variable-Speed Wind Energy Conversion Systems (VS-WECS) by continuous tracking changes in wind speed. Therefore, they are gaining their market share and are investigated at large as their behavior depends on the control strategy used. In the VS-WECS, the composition of aerodynamic controls along with power electronics to modulate torque, speed, and power are used, in particularly when the turbine is large in size. The variable-pitch blades present in aerodynamic control systems usually are not economical and are complicated which makes to choose alternative approaches of control.

The primary control objective of VS-WECS is to have the power efficiency maximization and improved dynamic characteristics, which results in the reduction of the drive train mechanical stresses and fluctuations in output power [3]. In [4], Sliding Mode Control (SMC) approach is developed for Doubly Fed Induction Generator (DFIG) and the results are compared with the standard mode of control applied for two operating regions of the wind turbine. The proposed controller is simulated for a 2.6MW three-blade wind turbine to evaluate its constancy and performance. The proposed control strategy presents pretty good features such as

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potent to uncertainties in the parameters of the wind turbine and the generator as well as the disruptions in electrical grid. The results are also carried out for the pitch fault condition for the SMC approach applied to DFIG. The simulation results show the effectiveness of the proposed controller. Moreover, the SMC approach is arranged so as to produce no variations in the electromagnetic torque generated that could lead to increased mechanical stress because of strong torque variations.

The principal objective of this paper is the output power regulation produced by the generator which in general the primary objective of the wind power generation system. In practice, due to limitations of mechanical and electrical quantities, all the available energy in the wind cannot be captured and the maximum power efficiency can be obtained by selecting the optimal point of wind turbine tip-speed ratio. The simulation results show that the proposed control strategy is effectual in terms of regulation of power.

II. MODELING OF WIND TURBINE

Fig. 1 shows the general block diagram for the VS-WECS [4], [5]. In this paper, fixed pitch variable-speed wind turbine is considered. The schematic diagram is shown in Fig. 2.

Equation (1) represents the aerodynamic power P_a apprehended by the wind turbine:

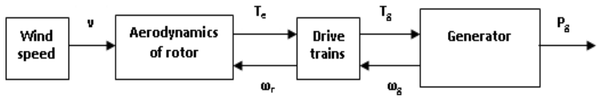


Figure 1. General scheme for VS-WECS.

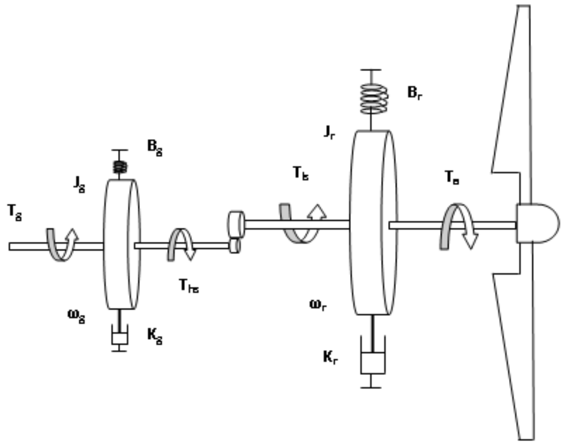


Figure 2. Schematic of WECS.

$$P_a = \frac{1}{2}\pi\rho r'^2 C_p(\lambda,\theta)v^3 \tag{1}$$

where C_p represents the power coefficient which represents wind turbine power conversion efficiency. Considering the pitch control based wind turbine, the power coefficient is the function of tip-speed ratio λ and the blade pitch angle θ. The tip-speed ratio λ is defined as the ratio of tip speed to the wind speed and is given as

$$\lambda = \frac{r'\omega_r}{v} \tag{2}$$

Generally, at one specific λ, the efficiency of wind turbine is maximum, which can be illustrated in Fig. 3. Fig. 3 shows the typical characteristics power coefficient, C_p- λ with respect to different values of the pitch angle θ (β in Fig. 3). To keep the system at λ_{opt}, normally $C_{p\,max}$ is followed to record the maximum power up to the rated speed by varying the rotor speed, after that the wind turbine operates at maximum allowable power with power regulation during high-wind instances by controlling actively the pitch angle of the blade or passive regulation depending on the aerodynamic stall [6].

The product of angular rotor speed and the aerodynamic torque gives the aerodynamic power or the rotor power, given by

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

and also

$$C_q(\lambda,\theta) = \frac{C_p(\lambda,\theta)}{\lambda} \tag{4}$$

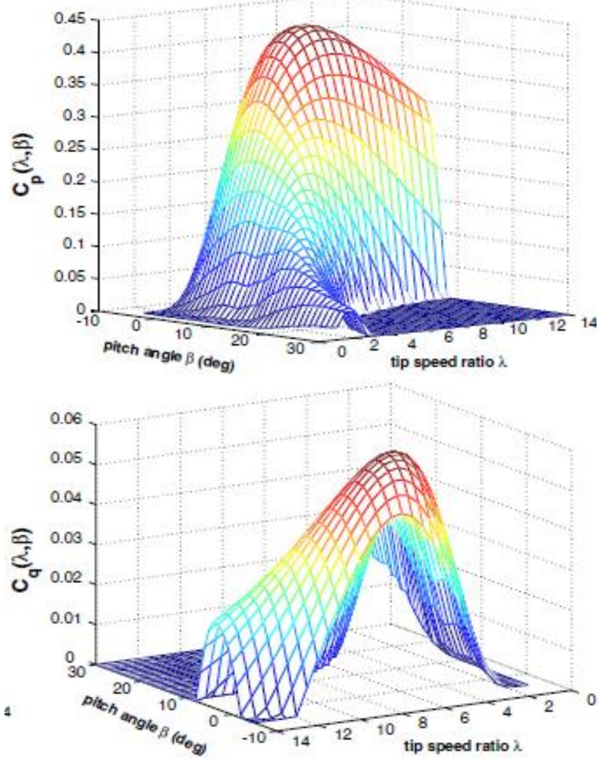


Figure 3. Characteristics of power coefficient ($C_p - \lambda$ vs θ) and torque coefficient ($C_q - \lambda$ vs θ) [4], [5].

The torque coefficient, C_q- λ with respect to different values of the pitch angle θ (β in Fig. 3) is shown in Fig. 3. From equations (1), (2), (3), and (4) the aerodynamic torque can be written as:

$$T_a = \frac{1}{2}\pi\rho r'^3 C_q(\lambda,\theta)v^2 \tag{5}$$

Fig. 2 shows the actual dynamics of a drive train. The wind turbine is rotated at a speed of ωr because of aerodynamic torque T_a, but there is always a braking torque for the rotor which is low-speed torque T_{ls}. The electromagnetic torque T_{em} acts opposite to the high speed torque T_{hs}, which acts as the driving torque for the generator. The speed of the rotor can be increased to get the generator speed ωg, by using gearbox in terms of gearbox ratio n_g and low-speed torque is added to it.

The dynamics of the rotor along with the inertia of the generator are given below:

$$\begin{aligned} J_r\dot{\omega}_r &= T_a - K_r\omega_r - B_r\theta_r - T_{ls} \\ J_g\dot{\omega}_g &= T_{hs} - K_g\omega_g - B_g\theta_g - T_{em} \end{aligned} \tag{6}$$

The ratio of ωg to ωr or the ratio of T_{ls} to T_{hs} gives the gearbox ratio which is given below:

$$n_g = \frac{\omega_g}{\omega_r} = \frac{T_{ls}}{T_{hs}} \tag{7}$$

From (6) and (7),

$$J_t\dot{\omega}_r = T_a - K_t\omega_r - B_t\theta_r - T_g \tag{8}$$

where

$$\begin{aligned} J_t &= J_r + n_g^2 J_g \\ K_t &= K_r + n_g^2 K_g \\ B_t &= B_r + n_g^2 B_g \\ T_g &= n_g T_{em} \end{aligned} \tag{9}$$

Neglecting external stiffness B_t which is low in value and it leads to Fig. 4, which is a simplified control form of drive train dynamics [7], [8].

$$J_t\dot{\omega}_r = T_a - K_t\omega_r - T_g \tag{10}$$

From the above equation, finally the generated power is mentioned as

$$P_g \cong \omega_r T_g \tag{11}$$

III. Basis for Proposed Control Scheme

A. Identification of Problem

Wind turbines cannot be operated in all types of wind conditions hence it is limited by control of power generated. Generally, the wind turbine is made to be operated at maximum value of the power coefficient C_p curve as a part of standard control law.

$$T_g = k'\omega_r^2 with k' = \frac{\frac{1}{2}\pi\rho r'^5 C_{p\max}}{\lambda_{opt}{}^3}$$

where λ_{opt} is the optimum tip-speed ratio.

This standard control law has two main problems; the first one is no perfect method to calculate k' and second one is if k' can be perfectly determined by actual tracing of the peak value of power coefficient C_p. This may lead to more stress mechanically and transmit fluctuations in aerodynamics into the actual system, which indeed leads to a low capture of energy. This situation can be avoided by the proposed control strategy.

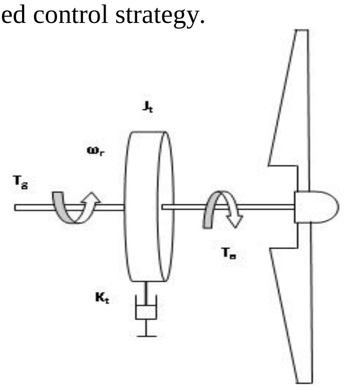


Figure 4. The simplified control form of drive train.

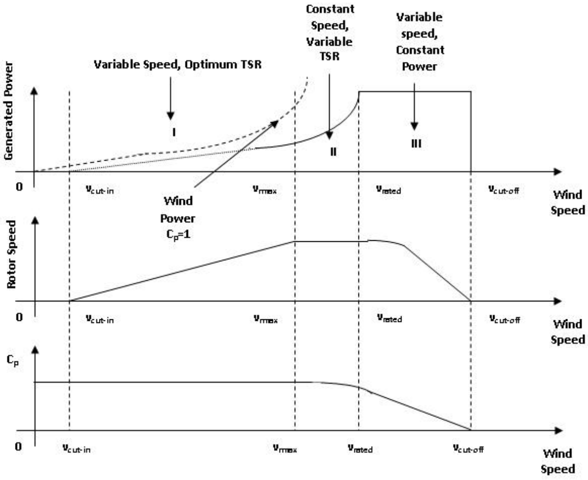


Figure 5. Three zones of operations of wind turbine for efficiency optimization.

The three different zones of operation are shown in Fig. 5, which makes the wind turbine to be operated safely with maximum extraction of wind power [7], [9].

Linearization approach is the general method which is used for the adverse behavior of the wind turbine in the two basic operating regions, i.e., the high speed III region, which is restricted by the speed limit of the turbine and low speed II region, which has a non-linear non-minimum phase dynamics with power regulation is not constrained with wind speed.

But because of the problematic conditions of operation and unavoidable uncertainties embedded within the wind system [7], the linearization approach method comes with a poor performance of the system with less reliability.

Therefore, these problems need to be addressed and for this non linear and a robust control method, [8] i.e., the SMC strategy with MPPT for the generator is the best solution.

B. The Proposed Control Strategy

Fig. 6 shows the proposed control scheme. As shown in Fig. 6, the Maximum Power Point Tracking (MPPT) algorithm contains the power-speed curve from which the actual maximum power is found out and it is fed as the reference power [10] for the SMC block. A flexible gain which increases such that the power tracking error is not equal to zero is chosen for the dynamic sliding mode controller. The aim of SMC employed is to make the tracking error and derivative of the tracking error to converge it to zero asymptotically.

From the Fig. 6, the tracking error, which is chosen as the sliding surface, is given by

$$\varepsilon_p = P_{sref} - P_s \tag{12}$$

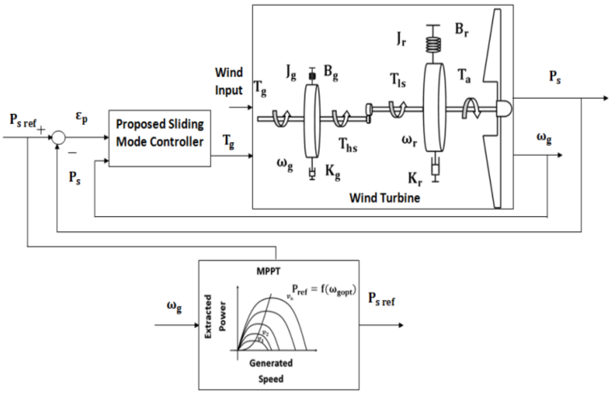


Figure 6. Proposed control scheme.

Also from the Fig. 6,

$$\dot{\varepsilon}_p = \dot{P}_{sref} - T_g\dot{\omega}_r - \dot{T}_g\omega_r \tag{13}$$

The equations related to the chosen dynamic sliding mode scheme are as follows:

$$\dot{T}_g = \frac{(B+\lambda)\operatorname{sgn}(\varepsilon_p)}{\omega_r} \tag{14}$$

with $B \dot{=} |\varepsilon_p|$ and $\lambda > 0$, then we get

$$\dot{\varepsilon}_p = \dot{P}_{sref} - T_g\dot{\omega}_r - \left(B(t)+\lambda\right)\operatorname{sgn}(\varepsilon_p) \tag{15}$$

suppose if,

$$d = \dot{P}_{sref} - T_g\dot{\omega}_r \tag{16}$$

as a disruption that fulfils

$$|d| < B_1$$

where B_1 is an unknown positive constant. The equation (15) can be rewritten as

$$\dot{\varepsilon}_p = -\left(B(t)+\lambda\right)\operatorname{sgn}(\varepsilon_p) + d \tag{17}$$

The Lyapunov function is considered to prove the stability of the proposed controller, which is given by

$$V = \frac{1}{2}\varepsilon^2 + \frac{1}{2}\left(B - B_1\right)^2 \tag{18}$$

From (18), we can say that the time derivative satisfies

$$\dot{V} \le -\lambda|\varepsilon| \tag{19}$$

From the LaSalle theorem and from (19), we can say that error of tracking merges asymptotically to zero.

Chattering phenomena has its effect due to signum function sgn(.) in (17) to avoid we use a following approximation:

$$\operatorname{sgn}(\varepsilon_p) = \frac{\varepsilon_p}{|\varepsilon_p| + a_0}$$

where a_0 is equal to small constant, which is positive. Due to the above approximation, there will be no chattering in generated torque, which leads to lessening the effect of increased mechanical stress due to sturdy torque deviations.

Preferably the wind turbine has to be operated less than the maximum efficiency, which helps in maintaining the buffer level of energy for control of grid frequency, to counter the challenge of sudden load changes [10]. This consideration is adopted in the present case which leads to

$$P_{sref} = 0.9T_{opt}\omega_{opt} \tag{20}$$

for region II velocities of wind, (21) gives the generator optimum calculations for torque and speed

$$\begin{gathered} T_{opt} = \frac{1}{2}\pi\rho r'^3 \frac{C_{p\max}}{\lambda_{opt}} v^2 \\ \omega_{opt} = \frac{\lambda_{opt} v}{r'} \end{gathered} \tag{21}$$

IV. RESULTS AND DISCUSSION

Simulations are illustrated for the 2.6MW wind turbine. The Table I shows the ratings of the wind turbine. The proposed scheme and the standard control have been implemented using the available block sets from the MATLab/Simulink.

The wind inputs for regions II and III consists of 64 randomly chosen set of data, which are designed by using the signal builder in MATLab/Simulink with wind direction. The wind profiles for both the regions are illustrated in Fig. 7 and 12 respectively. The mean wind speed is 9.81 m/s and 15.87 m/s (since rated wind speed is considered as 15m/s) respectively, which are well within the limits of both the operating regions.

TABLE I. RATINGS OF WIND TURBINE

Number of blades	3
Rotor diameter	70 m
Hub height	84.3 m
Rated Power	2.6MW
Turbine total inertia	$4.4532\text{x}10^5$Kg m^2

A. Simulation Results for Region II

The performances of variable speed wind energy systems with the proposed control strategy and the standard control of DFIG are compared in region II with the wind profile chosen is as shown in Fig. 7. The stator active (P_s) and reactive (Q_s) powers along with electromagnetic torque (T_{em}) generated by DFIG for standard control and similarly for the proposed scheme are shown in Fig. 8, Fig. 9, and Fig. 10 respectively. The simulation results show that the SMC approach with MPPT increases the capture of power and dynamic characteristics in terms of electromagnetic torque. In particularly, the proposed controller with DFIG has improved performance and a good power capture in comparison with standard control and also exhibits good dynamic performance as it can be noticed from Fig. 9(a) and 10(b) that the stator active power generated and torque clearly tracks the reference values, whereas it is not good in case of standard control, as shown in Fig. 8(a) and 10(a), which indeed leads to slightly lower mechanical stresses.

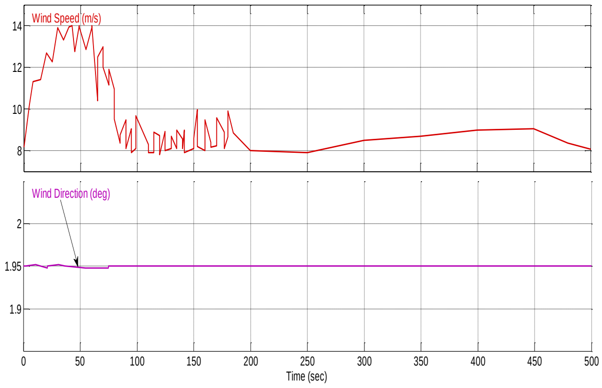
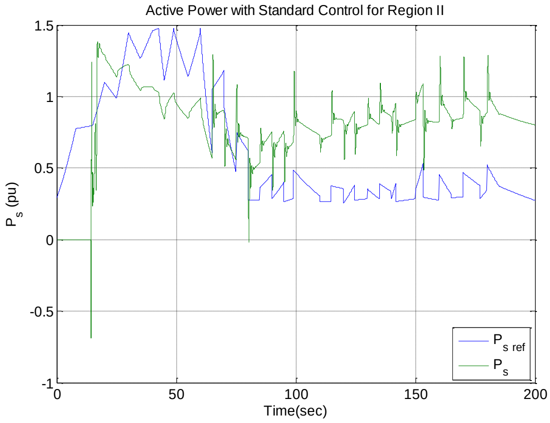
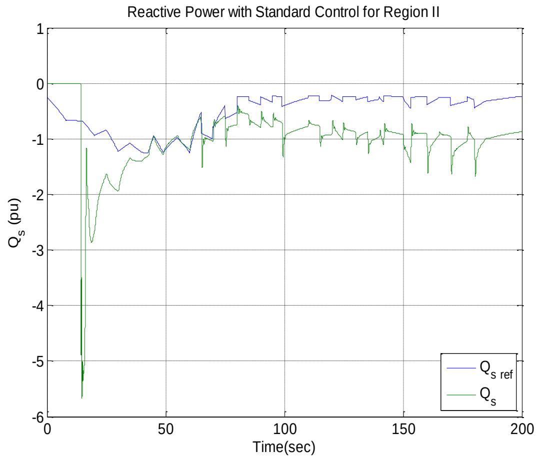


Figure 7. Wind speed profile for region II (Average wind speed is 9.81 m/s).



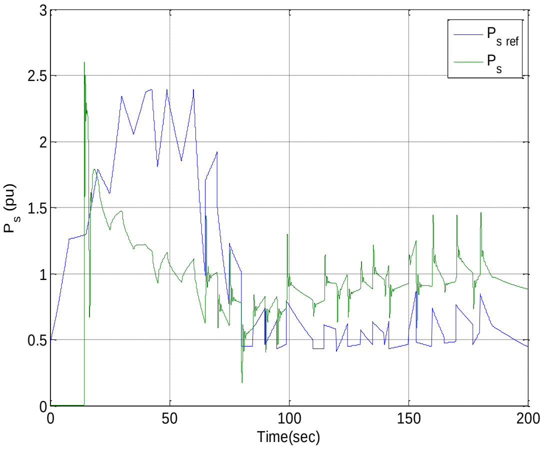
(a)



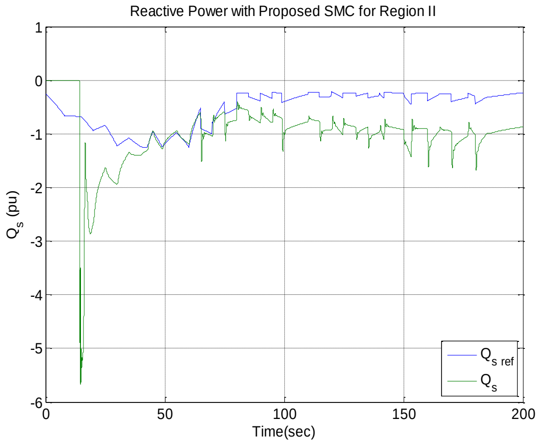
(b)

Figure 8. Standard control for Region II: (a) P_s (b) Q_s.

The stator reactive power generated are almost same for both the SMC strategy and standard control as the Q_s is not the direct control parameter, hence it is varying constantly and also tracks the reference value. This can be noticed in Fig. 8(b) and 9(b).

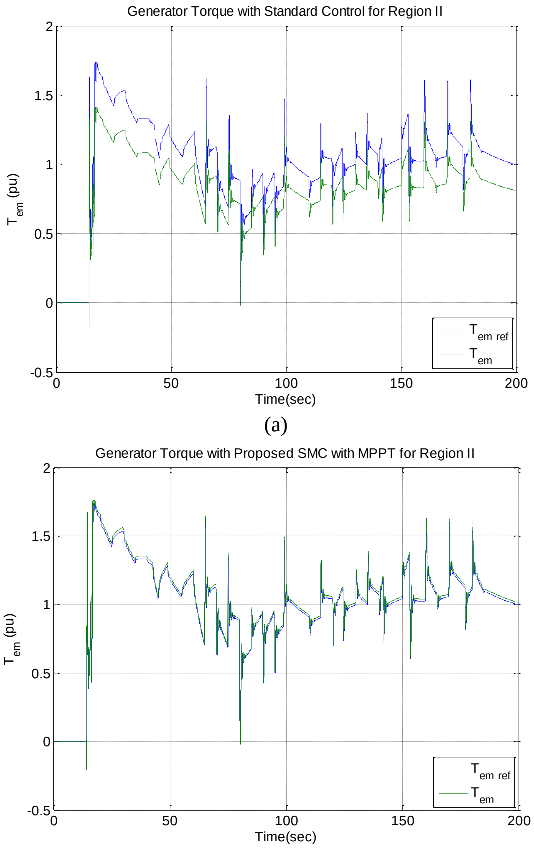


(a)



(b)

Figure 9. Proposed SMC strategy with MPPT for Region II: (a) P_s (b) Q_s.



(a)

(b)

Figure 10. Electromagnetic torque, T_{em}: (a) Standard control for Region II (b) proposed SMC strategy with MPPT for Region II.

B. Simulation Results for Region III

For region II, generally a generator torque control with fixed pitch is used and likewise for region III it is variable pitch control with fixed torque is used. The above-said control strategies are utilized in many wind turbines for switching operations, i.e., switching from one controller to other whenever required. But these changeovers will lead to mechanical and electrical constraints because of loading on the wind turbine. To avoid these constraints, the proposed controller should be active all the time for active pitch control etc. In case of high wind speed, the turbine has to be braked immediately mechanically or aerodynamically, in that case a part of excess kinetic energy is stored temporarily which can be used when wind speed decreases, this phenomenon is applied in particularly for the region III operation.

The wind profile chosen representing region III is as shown in Fig. 11. The active and reactive powers along with electromagnetic torque generated by DFIG versus its reference values for standard control and the proposed control scheme are shown in Fig. 12, Fig. 13, and Fig. 14 respectively. The results show that clearly that the proposed scheme with DFIG dominates in all respects like capture of power and dynamic characteristics when compared to standard control. The simulation results clearly show that there is no chattering in dynamic characteristics. Similarly, the performances of standard control applied to DFIG in comparison with proposed SMC strategy with MPPT are good and satisfactory.

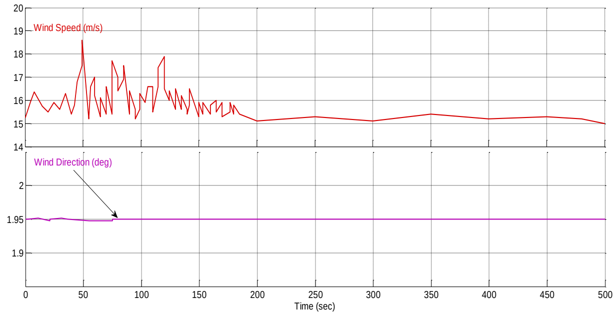
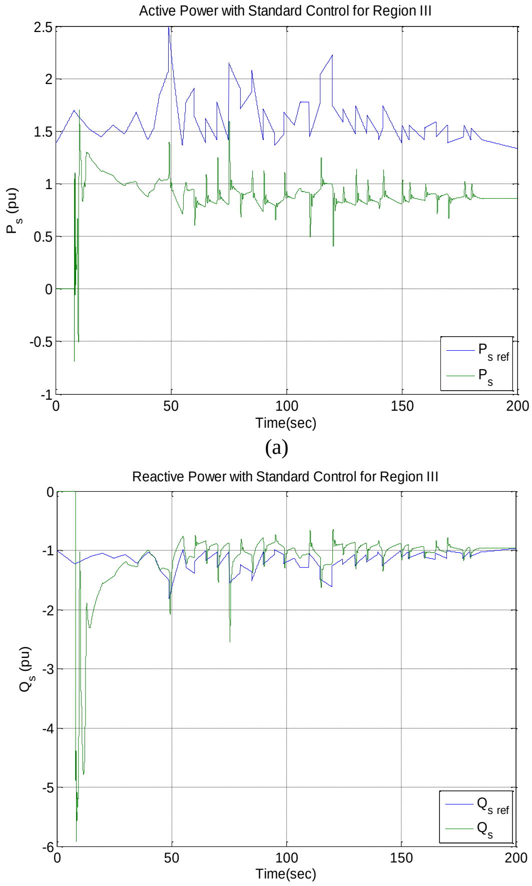


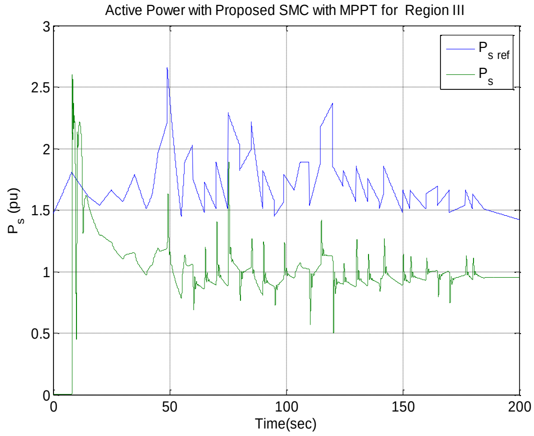
Figure 11. Wind speed profile for region III (Average wind speed is 15.87 m/s).



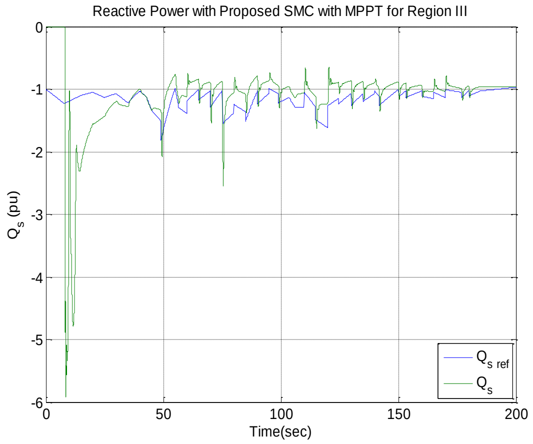
(a)

(b)

Figure 12. Standard control for Region III: (a) P_s (b) Q_s.

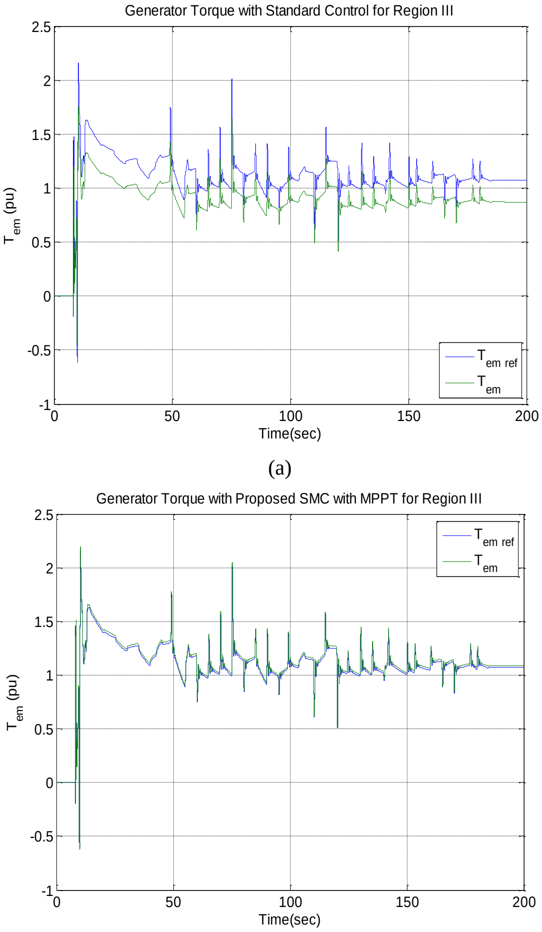


(a)



(b)

Figure 13. Proposed SMC strategy with MPPT for Region II: (a) P_s (b) Q_s.

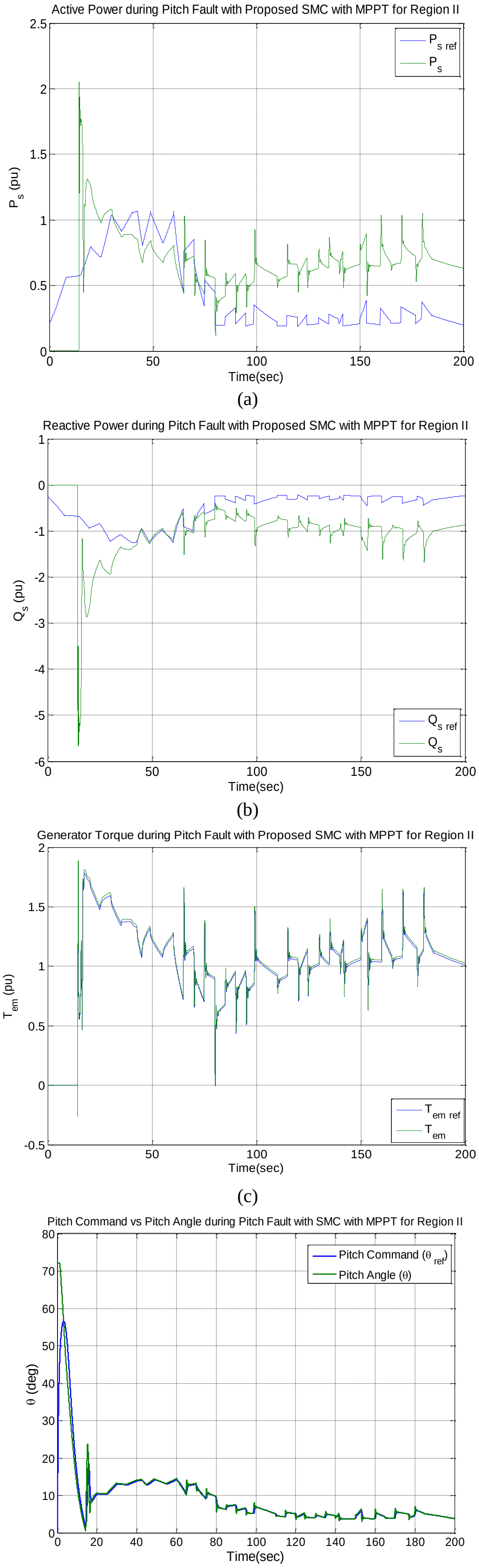


(a)

(b)

Figure 14. Electromagnetic torque, T_{em}: (a) Standard control for Region II (b) proposed SMC strategy with MPPT for Region II.

Fig. 15 illustrates that the proposed model is robust to even for a pitch fault. The simulation results of active and reactive powers and dynamic characteristics versus the reference values show that the proposed strategy is the ideal solution for model uncertainties like pitch fault, and even robust for other uncertainties like electric grid disturbances. The comparison between pitch command and angle is also shown in Fig. 15.



(a)

(b)

(c)

(d)

Figure 15. Sliding mode control for Region II with pitch fault: (a) P_s (b) Q_s (c) T_{em} (d) comparison of pitch command and angle.

In this paper, the proposed control strategy and standard control are validated by NREL FAST code [4], [5], [9]. Fig. 16 shows the FAST wind turbine block which contains S-Function, this simulink function is embedded with FAST equations of motion.

The proposed control strategy with MPPT and the standard control has been validated by using the same simulated wind turbine of 2.6MW base power. The wind data shown in Fig. 7 is used as FAST wind data for performance of validation tests. The validation is successful only when the FAST is terminated normally. For both the cases the validation was successful and the result was "FAST terminated normally", which shows that the system simulation results are worth encouraging.

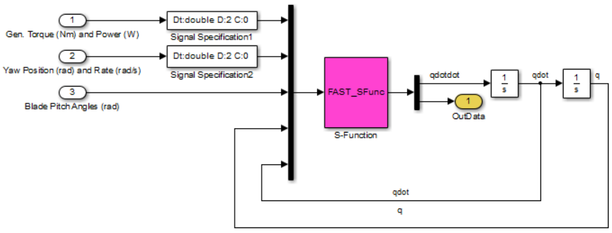


Figure 16. FAST wind turbine block.

V. CONCLUSION

The proposed SMC strategy in comparison to the standard mode of control applied to variable speed wind energy conversion systems with DFIG has more advantages like simplicity, robustness for parameter uncertainties of turbine and generator during fault conditions, modeling inaccuracies, good conversion efficiency, the lower drive train mechanical complexity leading to stability, good power regulation in both operating zones, providing the ideal feedback control solution.

The simulation results show that the proposed control strategy applied to DFIG has better performance in terms of capture and regulation of power when compared with standard control. The system model is validated by using FAST which shows that system simulation results are worth encouraging.

APPENDIX NOMENCLATURE

B_g	Generator external stiffness (N-m rad^{-1}-s^{-1}).
B_r	Rotor external stiffness (N-m rad^{-1}-s^{-1}).
$C_p\ (\lambda,\theta)$	Power coefficient.
$C_q\ (\lambda,\theta)$	Torque coefficient.
J_g	Generator inertia (kg-m^2).
J_r	Rotor inertia (kg-m^2).
K_g	Generator external damping (N-m rad^{-1}-s^{-1}).
K_r	Rotor external damping (N-m rad^{-1}-s^{-1}).
n_g	Gearbox ratio.
P_a	Aerodynamic power (W).
P_g	Generated power (W).
r'	Rotor radius (m).
T_a	Aerodynamic torque (N-m).
T_{em}	Generator electromagnetic torque (N-m).
T_g	Generator torque in the rotor side (N-m).
T_{hs}	High-speed torque (N-m).
T_{ls}	Low-speed torque (N-m).
λ	Tip speed ratio (TSR).
v	Wind speed (ms^{-1}).
ρ	Air density (kgm^{-3}).
ω_r	Rotor speed (rads^{-1}).
ω_g	Generator speed (rads^{-1}).

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