

# **SWITCHING SECTOR BASED SLIDING MODE CONTROL FOR VARIABLE SPEED WIND TURBINE SYSTEM**

A PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University  
in partial fulfillment of the requirements for the award of the Degree

of

Master of Technology

in

Electrical and Electronics Engineering

with specialisation in

*Industrial Instrumentation and Control*



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# DECLARATION

I undersigned hereby declare that the project report entitled "**Switching Sector Based Sliding Mode Control For Variable Speed Wind Turbine System**", submitted for partial fulfillment of the requirements for the award of degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by me under supervision of *prof.Salil N*, Assistant Professor, Department of Electrical and Electronics Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included. I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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## CERTIFICATE

This is to certify that the report entitled " **Switching sector based sliding mode control for variable speed wind turbine system** " submitted by **NAYANA M A** , (Reg. No. **TKM20EEII14**) of fourth semester to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering with specialisation in Industrial Instrumentation and Control, is a bonafide record of the project work done by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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# Abstract

Wind energy is prominently featured as a non-polluting, inexhaustible source of supplementary energy. However, its speed control is a major limitation, particularly when dealing with fast fluctuations in wind speed. The goal of wind energy systems is to maximize energy efficiency and controlling the wind turbine speed. Managing wind turbines with varying speeds is challenging due of the nonlinearities of identical mathematical models and the impacts of exogenous disturbances. The controller's primary goal is to extract the most power from the wind. Due to its simplicity design and efficient functioning, the PID controller design is a highly common technique for managing industrial processes. In fact, the practical systems operate with parametric variations and are affected by outside disturbances. PID controllers utilized in the industry don't have the proper settings, hence their performance is very suspect. The robustness of the sliding mode technique in terms of stability and performance against shocks makes it popular. So CSMC is implemented. A variable speed wind turbine with a sliding mode control mechanism to increase the amount of wind energy captured and reduce the transient loads driven by the frequent changes in wind speed. But the principal drawback of this strategy is the chattering phenomenon. So proposed the switching sector based sliding mode control technique that can be used to combat this issue. The effectiveness is simulated in MATLAB/Simulink and compared with controller conventional sliding mode controller for various wind speed profiles.

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# Abbreviations

CSMC	Conventional Sliding Mode Control
ERL	Exponential Reaching Law
PID	Proportional Integral and Derivative Control
SSC	Switching Sector Control
VSWECS	Variable Speed Wind Energy Conversion System

# Notations

$P_a$	aerodynamic power
$T_a$	aerodynamic torque
$T_{em\_eq}$	equivalent electromagnetic torque
$\omega_g$	generator speed
$T_{hs}$	high speed shaft torque
$T_{ls}$	low speed shaft torque
$\beta$	pitch angle
$C_p$	power coefficient
$\lambda$	tip speed ratio
$\omega_r$	turbine speed

# Chapter 1

## INTRODUCTION

### 1.1 Overview

The most critical challenge in the power industry today is obtaining energy without polluting the environment. Wind energy is a crucial player in this ecosystem, and it has emerged as one of the most popular renewable energy sources. However, several technical breakthroughs are still required to assure its security and increase the efficiency of energy generation. Because of the complicated construction and continual exposure to variable wind speeds, control systems are one of the most crucial factors in wind turbine development and maintenance. In this regard, several management strategies have been researched in this field during the last few years.[1]

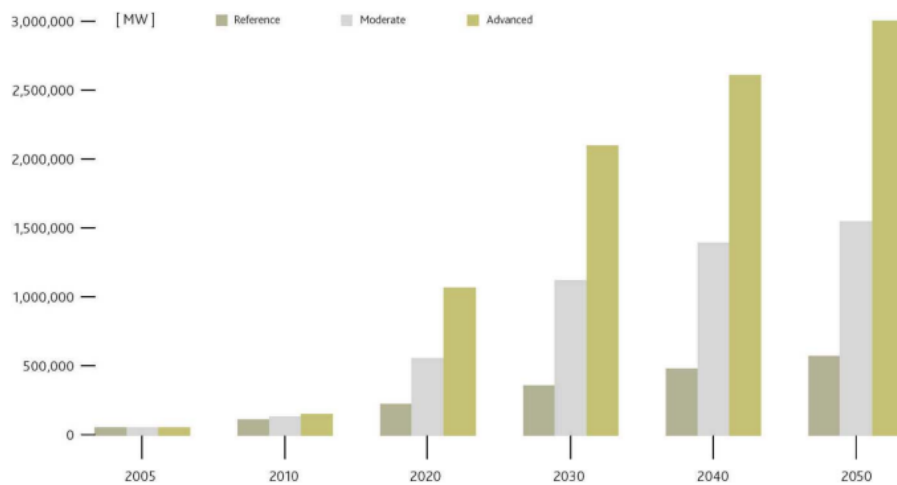


Figure 1.1: capacity of cumulative wind power

Variable-speed wind energy conversion systems (VS-WECS) are growing substantially their market share because they can maintain optimal power generation while tracking fluctuations in wind speed by modifying shaft speed. The more VS-WECS are studied, the more it becomes clear that the control approach being used has a substantial impact on their behaviour. The VS-WECS typically use power electronics and aerodynamic controls to control torque, speed, and power. When turbines get bigger, the aerodynamic control systems—typically variable-pitch blades or trailing-edge equipment—are more costly and complex. This circumstance provides an opportunity to consider other control measures.

Wind turbine efficiency improves when the rotor speed is optimised. A nonlinear controller that is sensitive to errors in the dynamic plant model and unexpected disturbances is proposed to improve rotor speed acquisition. It uses a nonlinear wind turbine model. Wind turbines with variable speeds rotate at a rate that varies with the speed of the wind. As a result, they maximize the use of aerodynamic power. Variable speed wind turbines are the most widely utilised wind turbines in the world due to less interruption in output and greater aerodynamic efficiency. On the other hand, the unpredictable and frequently variable wind speed, on the other hand, has presented various issues for control. Controlling the wind turbine rotor at different speeds has been a significant research area in recent years, as the wind industry began to embrace more complex control approaches due to the drawbacks of conventional control methods.[2]

The two-mass model of the complex nonlinear wind turbine system is frequently used due to its advantages. Wind turbulence and severe overshoot, on the other hand, are factors that stress wind turbines and may be mitigated by using an efficient speed management strategy. The first approach employed allows for the output and adjustment of PID controller settings in line with specified parameters. The second method is to use a sliding mode controller to obtain a chatter-free output. These two controllers are contrasted to show how the sliding mode controller corrects parameter uncertainty.

To deal with non-linearities existing disturbances/uncertainties of wind turbines, several linear and optimum control approaches have been established and utilized. The foundation for the construction of controllers is often the linearization of a mathematical model around an operating point of the actual system. However, linearization requires a mathematically exact model. In reality, actual systems are impacted by external disturbances and function with parametric fluctuations.

The sliding mode control is a non-linear control with a variable structure. Its success in control issues has been demonstrated since it was proposed in the early 1950s because it is equipped to deal with system uncertainties and external disturbances with good stability. This control provides a number of benefits, including high accuracy, quick dynamic response, stability, and ease of design and implementation. However, there is a significant issue with the phenomenon of chattering, which is a logical consequence of the real-time dynamic behaviour of the systems to be controlled and a result of a discontinuity in the control rules. One strategy for reducing chattering is to use the boundary layer method, which includes estimating the irregularities in the control law through softer variation functions such as the saturation function and hyperbolic tangent.[3]

## **1.2 Objective**

The wind turbine is dynamically modelled. Implement a wind turbine speed management method that eliminates the effects of wind turbulence and excessive overshoot and allows for improved performance. First of all a PID controller is implemented for trial and error. Then a conventional SMC is designed. It has the effect of chattering so modify the CSMC and a switching sector based sliding mode control controller is introduced and controller design approaches is to be tested in different wind profiles using MATLAB software.

## 1.3 Organisation of the report

The report is organised as follows:

- The background study of wind turbine components and its power curve are discussed in chapter 2.
- chapter 3 shows the dynamic modelling of wind turbine system.
- conventional sliding mode controller design is done in chapter 4.
- chapter 5 constitute modification of conventional siliding mode control-sector based approach for chatter free implementation.
- simulation result are presented and discussed in chapter 6.
- chapter 7 discuss the conclusion and future scope of the work.

# Chapter 2

## LITERATURE REVIEW

### 2.1 Overview

This chapter discusses about the structure,operation of wind turbine under various controllers.

### 2.2 Structure of wind turbine

The rotor blades of a wind turbine, which works similar to an aeroplane wing or a helicopter rotor blade, convert wind energy into electricity using aerodynamic force. The air pressure on one side of the blade falls as wind flows across it. Both lift and drag are produced by the different air pressure on the blade's two sides. The rotor spins because the force of the lift is greater than the force of the drag. If the generator is a direct drive turbine, the rotor is connected to it directly; otherwise, a gearbox that speeds up the rotation and permits a physically smaller generator is used. Electricity is produced as a result of the conversion of aerodynamic force into generator rotation.

A wind turbine system consist of an array of wind turbine tower, which is made of tubular steel, supports the turbine's structure. In order to appropriately orient the turbine with relation to the wind, the wind vane senses wind direction and interacts with the yaw drive.The controller receives wind speed information from the anemometer, which measures wind speed. Wind turbine system have three blades, which are typically constructed of fibreglass, are found on most turbines. The air pressure on one side of the blade falls as wind passes across it. The rotor, main bearing, main shaft, gearbox, and generator make up the drivetrain of a turbine with

a gearbox. The turbine's rotor's low-speed, high-torque spinning is converted into electrical energy by the drivetrain. The gearbox, low- and high-speed shafts, generator, and brake are all located in the nacelle, which is located atop the tower. When the wind direction changes, the yaw drive spins the nacelle on upwind turbines to keep them face the wind. The pitch system regulates the rotor speed by changing the blades' angle in respect to the wind. The hub, which is connected to the turbine's main shaft, is a component of the drivetrain. Turbine blades fit into the hub.

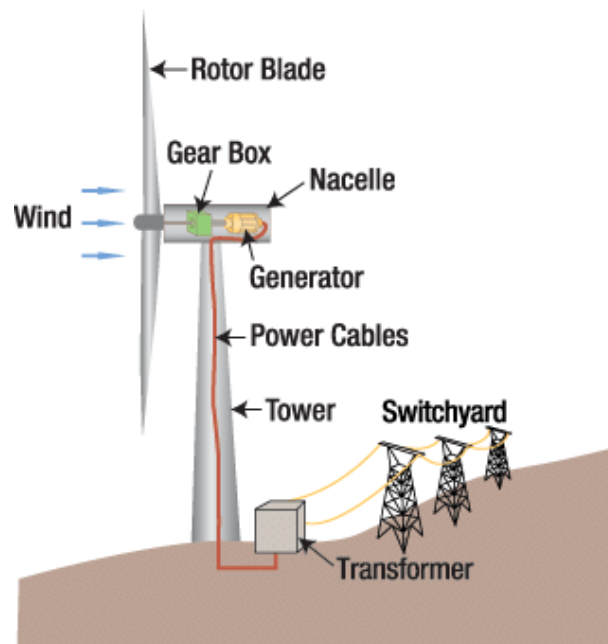


Figure 2.1: Wind turbine components

Given that we have no control over the power source (wind), a wind turbine is a difficult system to manage. Even from one second to the next, wind speed might fluctuate continuously. As a result, a turbine's power output must always be adjusted to the changing wind conditions. Pitch control is a feature that all new turbines have, meaning that the angle of the blades may be changed to maximise power output while minimising strain on the generator and the mechanical components of the blades, tower, and rotor shaft.

## 2.3 Models based on sliding mode control

Blade-pitch control is used by variable-speed, horizontal axis wind turbines to achieve predetermined goals for three operational regions. The controller design for the regime of constant power production is the main topic of this work. It is preferred to reduce both the actuator's motion and the rotor's departure from the intended speed. The PID controller's robustness is demonstrated, and ideal operating conditions are established. Similarities may be seen between the two linear models and the non-linear model's optimal regions selection. However, there is a small impact on the turbine performance due to the choice of the linearization point. It is feasible to determine the ideal set of controller parameters, simplifying the design of a PID controller. The large, flat surfaces show that a PID controller is particularly reliable in this application for variable-speed wind turbines.[4]

In this paper, the output frequency of a wind-turbine-driven self-excited induction generator (SEIG) that generates static load is adjusted. The fundamental relationships of wind energy conversion are shown. The wind turbine's dynamic modeling and linearization are derived. The PID controller, which is used for frequency regulation and turbine rotor speed control, is proposed. The Matlab-Simulink software programme simulates the block diagram of the proposed speed control system, which comprises of a speed controller, an actuator model, and a linearized turbine model.

Without wind speed readings and in below-rated wind circumstances, the challenge of constructing a nonlinear feedback control strategy for variable speed wind turbines was tackled. The goal is to run the wind turbines so that the most wind energy may be extracted while also reducing the mechanical loads. Two control strategies were suggested in an effort to improve performance. The first method makes use of a tracking controller to guarantee the rotor's ideal angular velocity. The Maximum Power Point Tracking (MPPT) method is used in the second technique. The first one combines a wind speed estimator and a sliding mode output feedback torque controller. To assure speed tracking, the second method uses a quasicontinuous high-order sliding mode controller. Comparing the suggested controllers to current control techniques and a FAST model based on the Controls Advanced Research Turbine is used to validate their performance (CART). The controllers work well in terms of removing load and extracting energy.[5]

In order to reduce mismatch between the generators and loads in the wind integrated power system, a new control method is presented in this study. Improved dynamic responsiveness and better coordination between traditional two-area and wind power systems are made possible by the suggested control technique. By creating a non-linear sliding mode control in a two-area thermal system, the goal is accomplished. The suggested controller achieves asymptotic stability by being able to adjust the closed-loop system damping property in response to uncertainties and load disturbances. Wind gusts, variations in wind speed, and inertia have no effect on the amount of wind power generated or the frequency regulation. A number of simulations are run on a two-area system with wind integration and an IEEE 39 bus system to show how well the suggested controller design works.[6]

The development of more potent control systems became necessary as wind turbine technology advanced. This is done to change the way wind turbines behave so they are more reliable and profitable. In order to maximise the electrical power produced by a wind turbine using a Doubly Fed Induction Generator (DFIG), for low wind speed, this research provides a novel control approach. The Bees algorithm, fuzzy maximum power point tracking MPPT, and nonlinear sliding mode control with exponential reaching law (ERL) are all used on the system to attain this goal. To get a decent reference tracking and to stop the chatter phenomena, the ERL and the Bees algorithm are utilised. The simulation results demonstrate the efficacy of this control method.[7]

The wind turbines' extremely nonlinear dynamics and their unpredictable operating conditions have presented various difficulties for their control approaches. This paper proposes a robust control technique for variable speed wind turbine speed tracking based on sliding mode and adaptive fuzzy disturbance observer. The dynamics of the variable speed wind turbine are first described by a nonlinear mathematical model, which is then developed. The control mechanism is then derived from this nonlinear model, and stability and robustness requirements are discovered. The control strategy is intended to follow the ideal wind speed that results in the most energy extraction. The Lyapunov stability theory was used to validate the stability condition. The method was validated by a simulation research, and its efficacy was assessed through a comparative analysis. The results demonstrated the devised methodology's great tracking capacity and robustness. When compared to a traditional control method, higher power extraction was also seen.[8]

With reference to three commercially available wind turbines, this research compares several methods for mathematical modelling of wind turbines with the use of a newly created algorithm. It has been discovered that modelling techniques based on the basic equations of wind power are difficult to apply and do not accurately mimic the behaviour of actual wind turbines. Although easy to use, models based on a presumptive power curve shape do not provide the requisite accuracy, but they do provide satisfactory results for higher yearly average wind speeds. Modeling techniques that use the actual power curve of a wind turbine to develop characteristic equations, such as the method of least squares and cubic spline interpolation, produce accurate results for turbines with smooth power curves; however, the method of least squares is best suited for turbines with less smooth power curves.

In order to address the issue of trajectory tracking for linear minimum or non-minimum phase systems, we integrate the sliding mode control (SMC) technique with monitoring functions and time-scaling in this study. Here, we deal with the tracking objective by assuming the plant is subject to parametric uncertainties and applying only output feedback, in contrast to other publications that generally assume full/partial state availability, the complete knowledge of the non-minimum phase plant parameters, or just handle the stabilization/regulation problem. Depending on the time-scaling parameter, we can anticipate that the reference model will track slowly when employing the time-scaling technique. This is the cost of taking into account a more comprehensive framework of uncertainty. The closed-loop system's global asymptotic stability with respect to compact sets is shown, and the output tracking error eventually shrinks to produce residual sets of any size. Results from simulations show how well our control algorithm performs.

One works with highly resonant, nonlinear dynamic systems subject to random excitation, i.e., wind turbulence, when designing control for variable-speed wind turbines. When combined with the increasingly popular "soft" concept of lightweight, flexible constructional components, it calls for thorough knowledge of the dynamics that need to be controlled. While this has cost advantages over more material-intensive rigid constructions, it also produces low frequency structural eigen frequencies, some of which may show up in the bandwidth of closed-loop operation. For the purposes of this paper, system-identification tests on a 400 kW, variable-speed, horizontal-axis wind turbine have been carried out utilising a variety of identification systems. The parameters in a physical model of the drive system now have numerical values thanks to the identification results. For the purpose of regulating wind turbine speed, a variety

of linear and nonlinear control schemes have been designed and evaluated using the acquired model.

In order to maximise the power conversion efficiency of a wind energy conversion system, this study investigates the application of second order sliding mode control techniques. The "sub-optimal," "twisting," "super-twisting," and "with a prescribed law of variation" algorithms are used to design and analyse four different controllers. These algorithms show finite-time convergence, robustness, chattering reduction, and mechanical stress reduction. They are also quite simple to operate and implement online. The performance of the controlled system may be understood for each of the controllers, and some comparisons can be made, utilising representative simulation results using a comprehensive model of the system under realistic operating conditions.

## **2.4 Concluding Remarks**

All significant wind turbine systems research is addressed in this chapter. It would be straightforward to undertake research in the developing domain of wind turbine system in light of the analysis that is offered above.

# Chapter 3

## Dynamic Modelling of Wind Turbine System

### 3.1 Overview

This chapter discusses about the dynamic modelling of the wind turbine.

### 3.2 Modelling

The conversion of wind energy to kinetic energy is described by aerodynamic behaviour. Through the transmission shafts, this energy is sent to the generator, where it is converted into electric energy. many models are put out in the literature that model mechanical subsystems with one mass, two masses, or several masses. The 2 mass model is frequently employed as acceptable trade between simplicity and efficiency.[9]

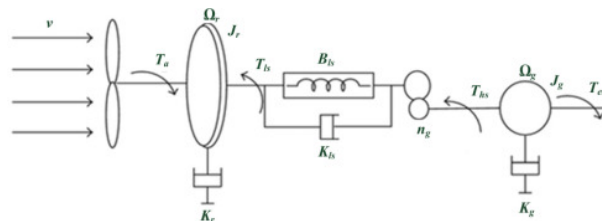


Figure 3.1: 2 mass model structure

For coupling the wind turbine and generator, pitch angle control at high wind speed, the two mass drive train models have been established. The gearbox and generator, which are essential

for a turbine to generate power, make up the drivetrain of a wind turbine. The gearbox is in charge of coupling the high-speed shaft connected to the generator to the low-speed shaft attached to the turbine blades.

A wind turbine's drive train is made up of a turbine, generator, and gearbox. The turbine and generator are primarily responsible for this system's inertia. Only a little portion is contributed by the gearbox's teeth wheels. Because of this, the inertia of the gear is frequently overlooked, and only the gear system's transformation ratio is taken into account. However, in this modelling, the gear ratio is set to 1. As seen in fig.3.1 , the drive train is thus represented as a two-mass model with a connecting shaft and all of the inertia and shaft elements.

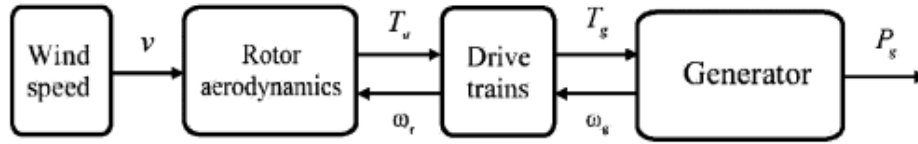


Figure 3.2: WECS global scheme

The global scheme for the VS-WECS is given by Fig.3.2. In addition to maximising power efficiency, the VS-primary WECS's control goal is to increase dynamic performance, which lowers drive train mechanical stresses and output power variations. The turbine tip-speed ratio should be maintained at its ideal value despite variations in wind speed to maximise power efficiency.

The rotor ability to capture aerodynamic power is governed by

$$P_a = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) v(t)^3 \quad (3.1)$$

Where  $\lambda, \beta$  function of the pitch angle and the tip speed ratio,  $v(t)$  is the wind speed, and  $C_p$  is the aerodynamic power coefficient. The wind turbine can only produce its maximum power under a given wind speed when it is operating at its maximum  $C_p$ .

The relationship between tip speed ratio and power coefficient is defined by

$$\lambda = R \frac{\omega_r}{v(t)} \quad (3.2)$$

By altering the rotor speed to keep the system at opt, a variable-speed wind turbine typically follows the  $C_p$ max to capture the maximum power up to the rated speed. When there is high

wind, it operates at its rated power with power regulation performed either passively or actively by controlling the pitch angle of the blades.

Power captured by the wind turbine is defined by:

$$P_a = T_a \omega_r \quad (3.3)$$

And the aerodynamic torque produced by the wind turbine  $T_t$  is defined by,

$$T_t = \frac{P_t}{\omega_t} = \frac{\rho \pi R^3 v^2 C_p(\lambda, \beta)}{2\lambda} \quad (3.4)$$

aerodynamic force  $T_t$  will drive the windturbine at the rate  $\omega_r$ . The rotor is subjected to a braking torque by the low-speed torque  $T_{ls}$ . The high-speed torque  $T_{hs}$  drives the generator, and the electromagnetic torque  $T_{em}$  restrains it. To acquire the generator speed  $\omega_g$  through the gearbox, the rotor speed is increased by the gearbox ratio  $n_g$  while the low-speed torque is increased.

The transmission ratio for an ideal gearbox is given by,

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} = \frac{\theta_g}{\theta_{ls}} \quad (3.5)$$

Figure 3.1 depicts the two-mass model structure, and the following set of equations serves as a representation of the corresponding dynamic model.

$$\begin{cases} \dot{\Omega}_r = a_{11}\Omega_r + a_{12}\Omega_g + a_{13}T_{ls} + d_1T_a + b_1T_{em} \\ \dot{\Omega}_g = a_{21}\Omega_r + a_{22}\Omega_g + a_{23}T_{ls} + d_2T_a + b_2T_{em} \\ \dot{T}_{ls} = a_{31}\Omega_r + a_{32}\Omega_g + a_{33}T_{ls} + d_3T_a + b_3T_{em} \end{cases} \quad (3.6)$$

$$\begin{aligned} a_{11} &= -\frac{K_r}{J_r}; & a_{12} &= 0; & a_{13} &= -\frac{1}{J_r}; & a_{21} &= 0; & a_{22} &= -\frac{K_g}{J_g}; \\ a_{23} &= \frac{1}{n_g J_g}; & a_{31} &= B_{ls} - \frac{K_{ls} K_r}{J_r}; & a_{32} &= \frac{K_{ls} K_g}{n_g J_g} - \frac{B_{ls}}{n_g}; \\ a_{33} &= -K_{ls} \frac{J_r + n_g^2 J_g}{n_g^2 J_g J_r}; & d_1 &= \frac{1}{J_r}; & d_2 &= 0; & d_3 &= \frac{K_{ls}}{J_r}; \\ b_1 &= 0; & b_2 &= -\frac{1}{I_\alpha}; & b_3 &= \frac{K_{ls}}{n_r I_g} \end{aligned} \quad (3.7)$$

### 3.3 Power curve

A wind turbine is a machine that transforms wind energy from kinetic to electrical. In order to minimise energy costs and lessen reliance on fossil fuels, wind turbines are becoming a more significant source of intermittent renewable energy. For effective power output and to keep the turbine components within speed and torque restrictions, rotation speed must be managed.[10] This arrangement is susceptible to overspeed because the centrifugal force on the blades grows with the square of the rotational speed. Turbines must withstand far larger wind loads than those from which they generate power since power increases as the cube of the wind speed.[11]

Table 3.1: Simulation Parameters

SL.NO	PARAMETER	SPECIFICATION
1	Air Density	1.29Kg/m <sup>3</sup>
2	Turbine Radius	21.65m
3	Gearbox Ratio	43.165
4	Turbine Inertia	325000Kg·m <sup>2</sup>
5	Generator Inertia	34.4Kg·m <sup>2</sup>
6	Shaft Stiffness Coefficient	269100Nm/rad
7	Shaft Damping Coefficient	9500Nm/rad/s

The two types of wind turbines can be distinguished by the fact that variable speed turbines can be controlled to change speed while fixed speed turbines can only be adjusted to a specific speed. The development of the wind turbine's rotor efficiency, which is performed by generator torque management, will determine the rotor speed. The variable speed wind turbine can cap-

ture more energy than the fixed speed wind turbine, which is the main distinction between the two. The disadvantage of variable speed systems is their high cost and need for sophisticated control methods. Fixed speed wind turbines have the advantage of being simple, robust, and inexpensive, but they are electrically and aerodynamically inefficient. The mechanical (which consists of the shaft, aeroturbine, gearbox) and electrical (which consists of power converters and induction generator) subsystems of wind turbine machine can be separated.

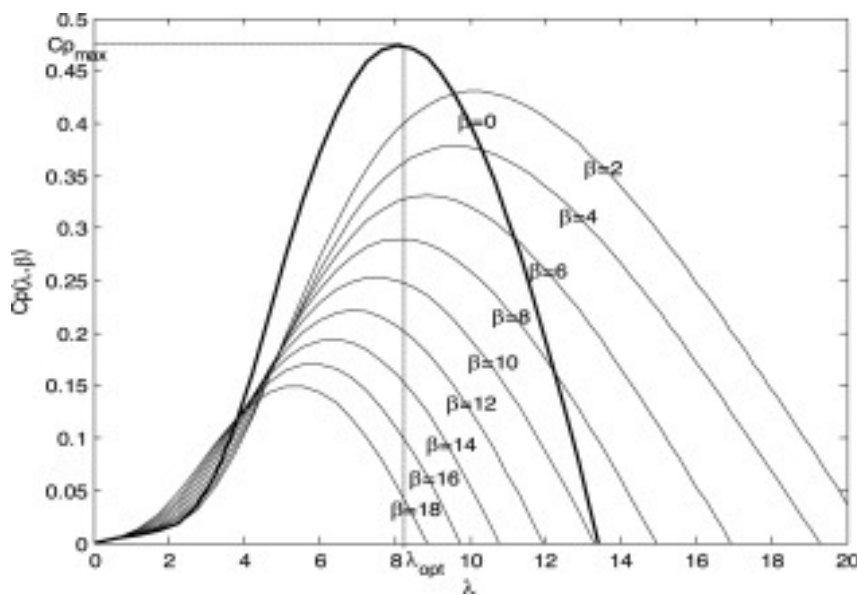


Figure 3.3: power co efficient

A particular wind speed range, divided into 3 different zones, governs the operation of wind turbines. According to Fig. 2: The ultimate control goal in zone I is to capture much possible wind power because the wind turbines only run at partial loads. The unique maximum value of the power coefficient should be maintained. In zone II, the wind turbine runs under transient loads with low to high wind speeds. Therefore, stabilising power generation and lowering aerodynamic loads are the goals of control. Switching control strategies are typically used to accomplish this. The wind turbine runs at full loads in zone III. Here, maintaining the output power at its rated value is the control goal. Typically, this is accomplished by altering the pitch angle while maintaining a constant generator torque.[12]

Figure 1.2 below demonstrates how the power extracted varies with wind speed; this is caused by the rotor efficiency, a key design parameter. The speed of the rotor, the speed of the wind, and the blade pitch angle of the rotor blades are all factors that affect rotor efficiency, which is

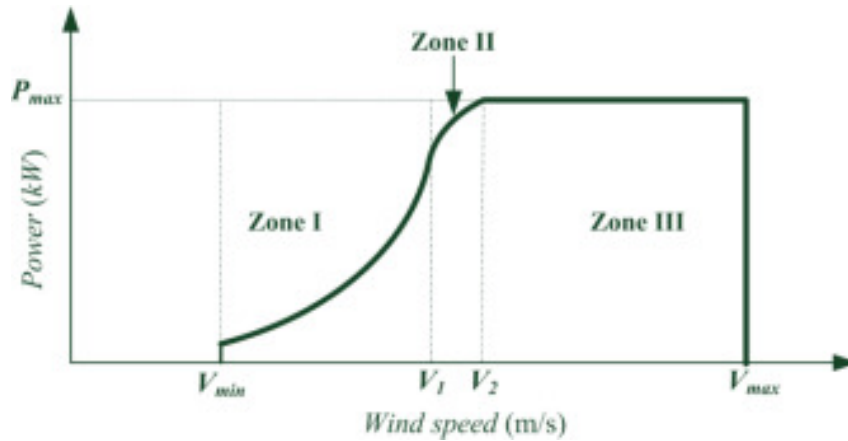


Figure 3.4: extracted power curve

extremely nonlinear.

The extraction of energy from the wind explains how wind turbines work. The torque placed on the system by the wind's impact on the blades is then transformed to rotational energy at the rotor shaft. A gear box is required to make efficient use of the generator because the torque is too great for a typical generator. The generator receives the mechanical power after being sent through the gearbox. The generator is responsible of transforming mechanical energy into electrical energy.

### 3.4 Conclusion Remarks

This chapter discussed about the dynamic modelling of wind turbine system. conventional sliding mode controller is mentioned in the following chapters.

# Chapter 4

## SLIDING MODE CONTROLLER

### 4.1 Overview

This chapter studies about the sliding mode controller and the sliding mode controller design.

### 4.2 Conventional sliding mode controller

One of the effective methods for designing reliable controllers for sophisticated, high-order, nonlinear dynamic systems that operate in unpredictable environments is the sliding mode control approach. About 40 years ago, in the former Soviet Union, research in this field began. Over the past 20 years, the sliding mode control methodology has attracted significantly greater interest from the global control community. Sliding mode's main benefit is its low sensitivity to changes in plant parameters and other disruptions, which removes the need for precise modelling. Sliding mode control makes it possible to separate the motion of the entire system into separate, lower-dimensional partial components, which lowers the complexity of the feedback. Sliding mode control (SMC) is a nonlinear control technique used in control systems that modifies a nonlinear system's dynamics by enforcing a discontinuous control signal that drives the system to "slide" over a cross-section of its usual behaviour. By applying a discontinuous control signal that forces the system to "slide" over a cross-section of its typical behaviour, sliding mode control (SMC), a nonlinear control approach used in control systems, alters the dynamics of a nonlinear system.[13]

For the state-feedback control law, time is not a continuous function. Instead, it can switch from one continuous structure to another depending on where it is in the state space. Therefore, sliding mode control is a technique for managing a flexible structure. The fact that there are multiple structures means that the final trajectory won't be entirely confined by any of them because trajectories always move in the direction of a region with a different control structure. Instead, it will slide along the edges of the control structures.

Dynamical systems governed by ordinary differential equations with discontinuous state functions in the right-hand sides may exhibit the "Sliding Mode" phenomena.

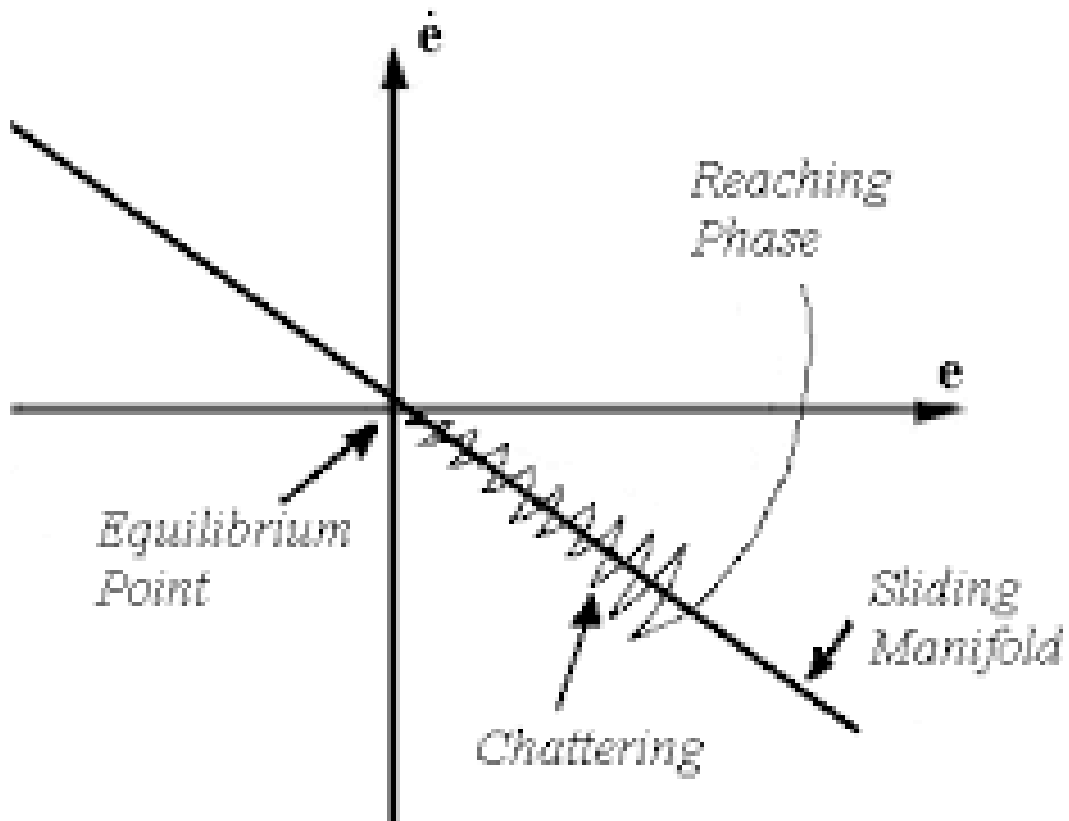


Figure 4.1: sliding surface

The geometric region comprised of these boundaries is known as the sliding surface, and the sliding motion of the system along these boundaries is known as a sliding mode.

The so-called Equivalent Control Method, which aims to derive sliding mode equations in manifolds with  $s = 0$ , can be supported by boundary layer regularisation.

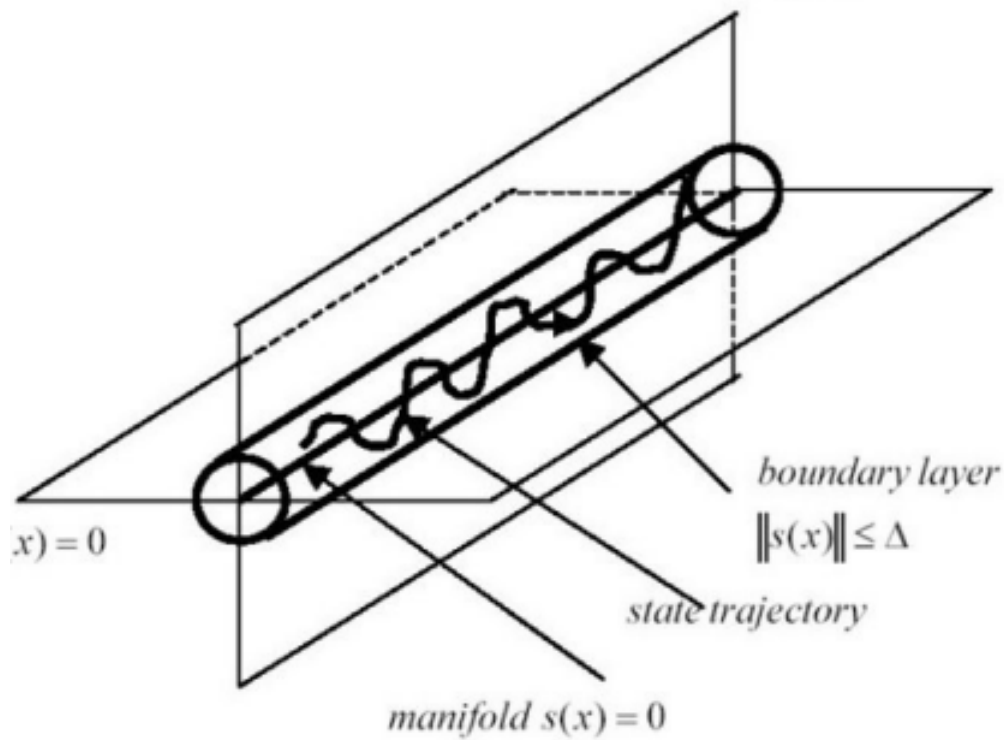


Figure 4.2: boundary layer

In the circumstances of modern control theory, the variable systems, such as a system operating under SMC, can be observed as a specific case of a dynamical hybrid system because it alternates between many discrete control modes and a continuous state space.

Figure 4.1 depicts the system's trajectory. When system trajectories finally reach the surface of sliding, which is determined by  $surface=0$ , the sliding mode starts along the surface.

In the theoretical explanation of sliding modes, the system stays constrained to the sliding surface and simply has to be conceived of as sliding along the surface. In actual sliding mode control implementations, which replicate this theoretical behaviour with a high-frequency and typically non-deterministic switching control signal, the system "chatters" at a close vicinity to the sliding surface. Chattering can be eliminated by utilising boundary layers or deadbands around the sliding surface, as well as other compensating techniques.[14]

### 4.3 Sliding mode control design

Sliding Mode Control (SMC) is a nonlinear discontinuous control technique that uses a relay as its fundamental control element and can be applied to the design of reliable controls. Reduced order dynamics, insensitivity to constrained shocks and uncertainties, non-uniqueness of solutions, and chattering are some of the characteristics supplied by sliding mode control.

The integrator system is taken into consideration in order to explain the fundamental characteristics of sliding mode control. For this system, the dynamics are defined by the first order differential equation

$$\dot{x} = u + d \quad x(t_0) = x_0 \quad (4.1)$$

where  $u$ ,  $d$  and  $x$  are the control input, disturbance and the output system respectively. The goal is to manage  $x$  by the control law will be  $u = c$ , and it will involve adjusting  $u$  with a feedback law that minimises the effect of disturbance on output.

The sliding surface for higher order dynamical systems can be a point, plane, or hyperplane for linear switching functions, and manifolds for nonlinear switching functions.

There are two tasks in the SMC design.

- Choosing an appropriate switching function  $s(x)$  depending on the desired reduced order dynamics

$$s(\mathbf{x}) : \mathbb{R}^n \rightarrow \mathbb{R}^m \quad (4.2)$$

- Create a control law that, in a finite amount of time, causes  $s(x)$  to equal 0 and therefore limits the states of a sliding surface. Since the design of linear switching functions is well established and the design of nonlinear switching functions is challenging, linear switching functions are used in several applications. The control law design that manage the trajectory in its sliding surface, and the next is the declaration of the stability criteria that guarantees chatter-free implementation. The tracking related error and the relative system degree are combined to create the sliding surface.[15]

From the tracking error, the sliding surface and the relative degree is synthesized. The control law forces output of the system  $\Omega_r$  to track its reference  $\Omega_{ropt}$  by minimizing the error due to

tracking can be defined by:

$$\begin{aligned}
h_1 &= \Omega_r - \Omega_{\text{ropt}} \\
h_2 &= \dot{h}_1 \\
\dot{h}_2 &= f(h, t) + g(h, t)T_{\text{em}}
\end{aligned}$$

where  $f(h, t)$  and  $g(h, t)$  are: (4.3)

$$\begin{aligned}
f(h, t) &= (a_{11}^2 + a_{13}a_{31})\Omega_r + a_{13}a_{32}\Omega_g + \\
&(a_{11}a_{13} + a_{13}a_{33})T_{ls} + (a_{11}d_1 + a_{13}d_3 \\
&T_a + d_1\dot{T}_a - \ddot{\Omega}_{\text{ropt}}
\end{aligned}$$

The surface of sliding can be denoted as:

$$S = h_2 + \kappa h_1$$

where  $\kappa$  is a positive valued constant.

$$P(s) = s + \kappa$$

## 4.4 Basic Block Diagram of SMC

The variable structure system's sliding mode is a unique way of operation. With system uncertainties and outside disruptions infecting the process, it was a huge progress in late years due to how simple and robust its deployment was.

There are three sections to sliding mode control. The initial step is to create a sliding surface that, in the state variable space, mimics the desired closed-loop performance.

The control must be created so the trajectories of the system state is pointed in the direction of the sliding surface and remain there when we establish the condition of convergence.

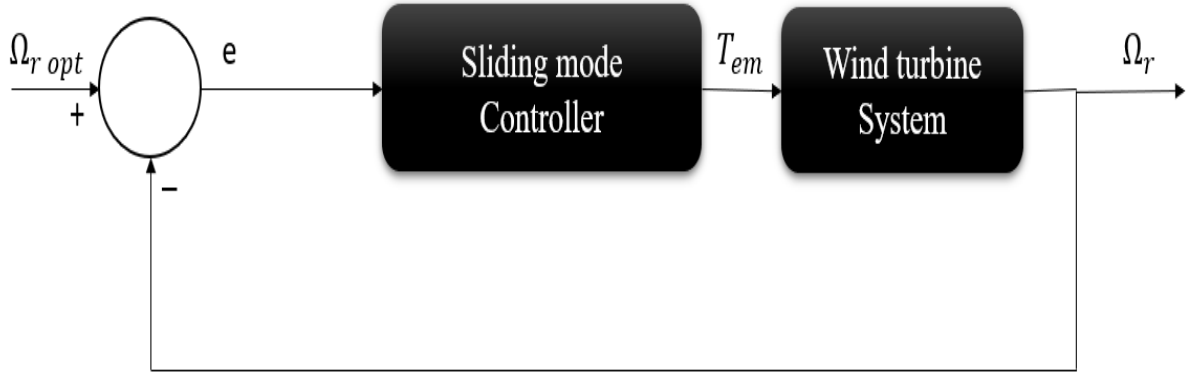


Fig 4.2 : wind turbine with SMC

## 4.5 Control law designing

To confirm that the surface has the sliding mode Assuming that we can reach this surface in finite time, The below statement needs to be contented:

$$\dot{S}S < 0 \quad (4.4)$$

There is an equivalent electromagnetic control torque that can hold the system on the sliding surface if sliding mode is present.[16] It can be determined using  $\dot{S} = 0$

$$T_{em\_eq} = \frac{-1}{g(h,t)} (f(h,t) + \kappa h_2) \quad (4.5)$$

$T_{em\_eq}$  is a control equivalent that can keep the system on its surface of sliding. In practise, the parameters are uncertain, making it impossible to fully understand the dynamics of the entire system. It is only possible to estimate the equivalent control  $T_{em\_eq}$ .  $T_{em\_eq}$  does not guarantee convergence to the switching surface, hence the corresponding control typically includes a relay term:

$$T_{em} = T_{em\_eq} - \alpha \text{sign}(S) \quad (4.6)$$

where the switching gain is  $\alpha$ . The above control law only serves as reference value for the controller and control method used by the power converter; it does not directly control the turbine rotor speed.

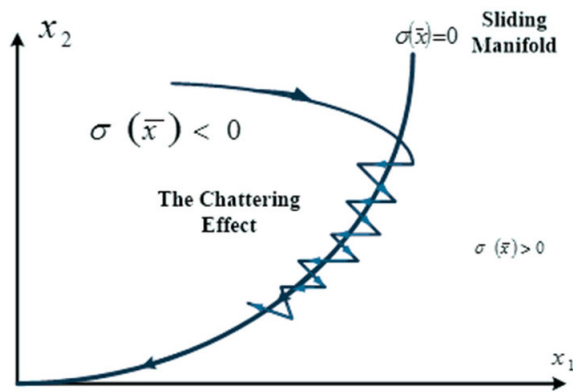
The designed control law that maintains the trajectory on its sliding surface and the assertion of stability conditions that guarantees chatter-free execution. Since it can effectively handle system uncertainties and outside disturbances, its success in control problems has been demonstrated. High fidelity, dynamic quick response, stability, and ease of designing and implementation are only a few benefits of this control. The aspect of chattering, which is a logical aftereffect of the actual dynamic behaviour of the systems to be managed and a result of the discontinuity in the control rule, presents a significant challenge, though. The high frequencies of the controlled system may be harmed by this phenomena, which involves rapid, sudden shifts of control signal. The sliding mode technique has been used in a lot of research projects. Using this approach, the problem can only be resolved in systems with modest disturbances.

## 4.6 Chattering Phenomenon

Chattering is primarily the state trajectory's high-frequency oscillation around the sliding surface and results in system output oscillations around the reference values, is the most significant drawback of SMC. The existence of component which has discontinuous switching in the derivative of sliding variable and switching delay are both potential causes of chattering. A delay in switching can happen for a number of reasons, including

- Discretization
- Non-ideal relay (Relay with Hysteresis, Dead zone, etc.)
- Unmodeled dynamics

Chattering happens as a result of the controller's discrete time implementation, which results in finite frequency switching where the frequency is determined by the sampling period (i.e. simulation step size  $T$ ). The sliding variable and controlled variables oscillate around their steady-state values as a result of this switching at a finite frequency. Discretization chattering is the term for this. As  $T$  rises, the chattering becomes more obvious and the switching delay increases.



*The Chattering Effect*

Figure 4.3: chattering effect

Even if continuous time implementation is used, switching delays still create chattering in practical situations. Relays typically display hysteresis behaviour because, in practise, they are unable to switch at infinite frequency. As a result, there will be some switching delay. As seen in Fig. 4, a relay with a switching delay may exhibit hysteresis behaviour.

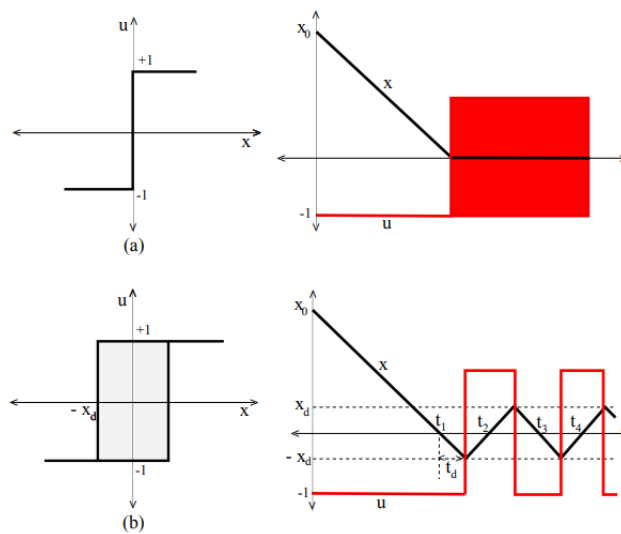


Figure 4.4: (a) Ideal relay (b) Relay with delay.

and which leads to finite frequency switching and chattering phenomenon. Fig. 4.2 displays the response with the perfect relay for  $x_0 > 0$ . (a). Now, the response will look like Fig. 4.2 if there is a switching delay (b). Despite the fact that  $x$  crosses zero at each  $t_i$  due to the  $t_d$  delay, control switching happens at  $t_i + t_d$ . This causes the variables to chatter as they oscillate around their steady-state position. There is no chattering for a perfect relay since  $x_d$  is 0 and  $t_d$  is 0.[17]

Even with the perfect relay with no switching delay, chattering may still occur. This is a result of the dynamics that are not included in the model, especially the faster dynamics of actuators or sensors that are disregarded during modelling. This unmodeled dynamics causes switching to take longer than it should and causes chattering.

## **4.7 Concluding Remarks**

This chapter discussed about the conventional sliding mode controller design and about the chattering phenomenon. The next chapter deals with the switching sector based sliding mode control design.

# Chapter 5

## SWITCHING SECTOR BASED SLIDING MODE CONTROLLER

### 5.1 Overview

In this chapter, switching sector based control scheme is proposed for the elimination of chattering phenomenon.

### 5.2 Robustness of system and chatter-free implementation

The requirement of the system's trajectory that must stay on the surface of switching causes the control law of sliding mode approach to demand greater switch gain, which is in the existence of significant speed changes and, as a result, to generate more chattering. But in the presence of slow switching rate, this requirement is too expensive. The trajectory might be able to move continuously if the switching sector takes the place of the switching surface. The idea is to compel the trajectory to oscillate within the switching sector on the switching surface ( $S = 0$ ),  $[S_1 = 0, S_2 = 0 \dots S_r = 0]$  with system's relative degree.

### 5.3 Design Of SSC

In order to model the SSC method of the system, 2 switching surfaces are denoted by

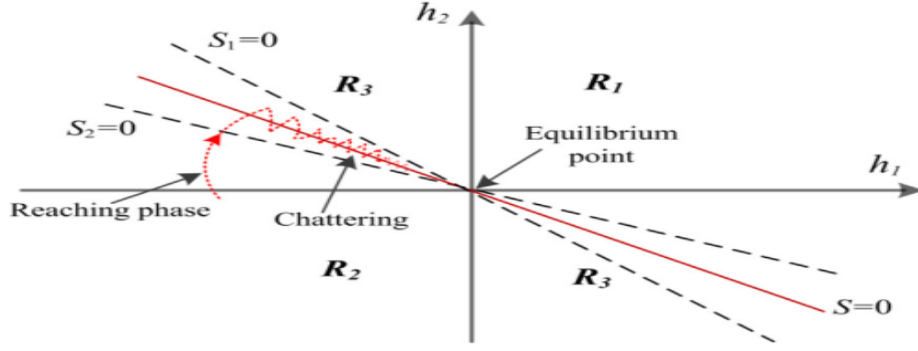


Figure 5.1: Switching sectors of relative degree,  $r = 2$

two switching surfaces are defined by

$$\begin{cases} S_1 = h_2 + \kappa_1 \cdot h_1 \\ S_2 = h_2 + \kappa_2 \cdot h_1 \end{cases} \quad (5.1)$$

The state space of the two switching surfaces is shown in Fig. 5.1. Three regions— $R_1$ ,  $R_2$ , and  $R_3$ —can be distinguished in equation 5.1, with  $R_3$  serving as the switching sector.

$$R_1 = \{h \mid S_1(h) > 0 \& S_2(h) > 0\} \quad (5.2)$$

$$R_2 = \{h \mid S_1(h) < 0 \& S_2(h) < 0\} \quad (5.3)$$

$$R_3 = \{h \mid S_1(h) \cdot S_2(h) \leq 0\} \quad (5.4)$$

The control law is modified and Eq. (4.6) becomes:

$$T_{em} = T_{em-eq} + u_d$$

The new additive term  $u_d$  is expressed by:

$$u_d = \begin{cases} -\frac{\alpha}{g(h,t)} \cdot \text{sign}\left(\frac{S_1+S_2}{2}\right) & \text{if } h \in R_1 \cup R_2 \\ -\frac{\alpha}{g(h,t)} \cdot \frac{S_1+S_2}{|S_1|+|S_2|} & \text{if } h \in R_3 \end{cases} \quad (5.5)$$

The intermediate switching sector in Fig. 5.1 can be visualised as the following surface.

$$S = \frac{S_1 + S_2}{2} = h_2 + \kappa \cdot h_1 \quad (5.5)$$

$$\kappa = (\kappa_1 + \kappa_2) / 2. \quad (5.5)$$

The following quadratic Lyapunov function validates the robustness analysis of the proposed approach based on the stability.

$$V = \frac{1}{2} S^2 \quad (5.5)$$

The system dynamics along with the Lyapunov function time derivative.

$$\dot{V} = S\dot{S} \quad (5.5)$$

$$\dot{V} = S(\dot{h}_2 + \kappa \cdot \dot{h}_1) \quad (5.5)$$

$$\dot{V} = S \cdot g \cdot u_d \quad (5.5)$$

outside of the switching sector  $R_1 \cup R_2$  :

$$\dot{V} = -S \cdot \alpha \cdot \text{sign}\left(\frac{S_1 + S_2}{2}\right) \quad (5.5)$$

When S is the midpoint between "S1, S2," then

$$\dot{V} = -\alpha \cdot \left(\frac{S_1 + S_2}{2}\right) \cdot \text{sign}\left(\frac{S_1 + S_2}{2}\right) \quad (5.5)$$

The derivative of time  $\dot{V}$  value in every time is negative for zero, which indicates switching sector continues to be the system's trajectory.

The switching sector, specifically in region  $\epsilon R_3$ :

$$\dot{V} = -S \cdot \alpha \cdot \frac{S_1 + S_2}{|S_1| + |S_2|} \quad (5.5)$$

$$\dot{V} = -\frac{1}{2} \cdot \alpha \cdot \frac{(S_1 + S_2)^2}{|S_1| + |S_2|} \quad (5.5)$$

at the bounds of the switching sector, we have

$$\alpha \cdot \text{sign}\left(\frac{S_1 + S_2}{2}\right) = \alpha \cdot \frac{S_1 + S_2}{|S_1| + |S_2|} \quad (5.5)$$

The absolute value of the discontinuous term decreases as the system trajectory gets closer to the switching sector's middle ( $S=0$ ), which ensures a chatter-free implementation.

## 5.4 Control scheme

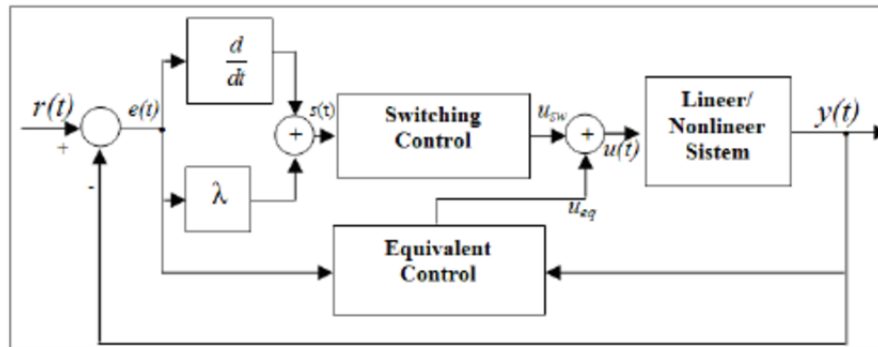


Figure 5.2: Block diagram for a SSC.

The output of the system is the turbine speed and to control this speed controlling the electromagnetic torque. The difference between the output from the wind turbine system and the reference input is the called error. Reduced tracking error is given to the controller for proper control action.

## 5.5 Concluding Remarks

This chapter discussed about the switching sector based sliding mode control is discussed. Next chapter shows the simulation results.

# Chapter 6

## SIMULATION RESULTS

### 6.1 Overview

In this part, the MATLAB software simulator was used to evaluate the efficiency of the proposed approach. The wind turbine characteristics and parameters indicated in Table 1 are used in the numerical simulations, which are run in variable wind speed.

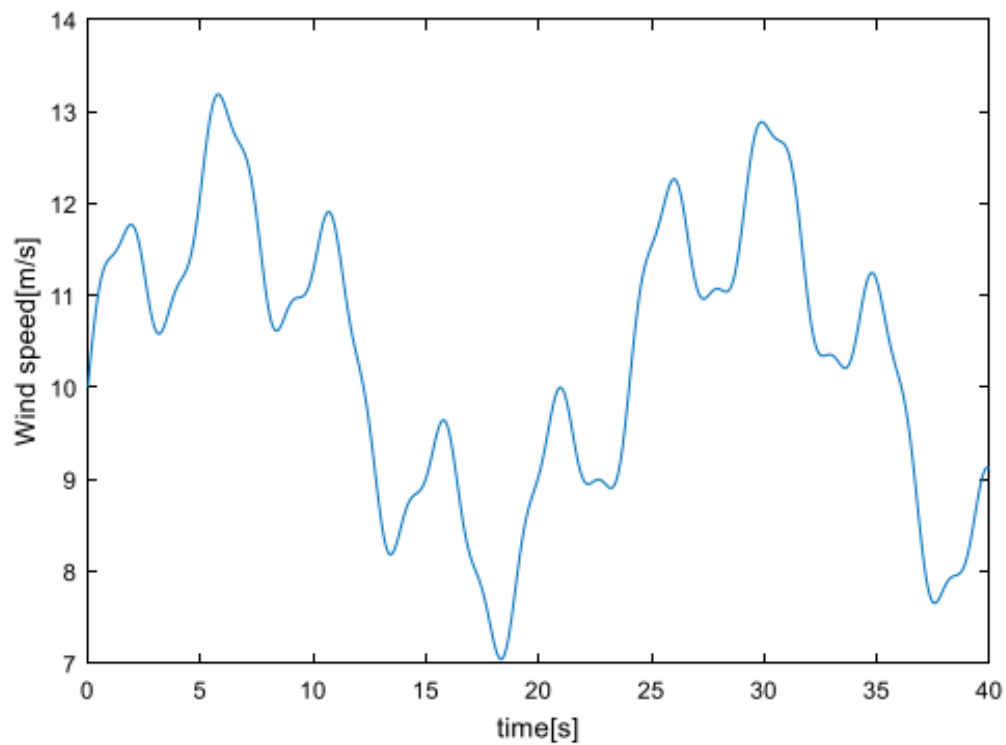


Figure 6.1: wind speed profile

## 6.2 Graphical results

Simulations was performed on both CSMC and SSC along with closed loop model of wind turbine system. simulation done to verify the effectiveness and chatter free implementation.

The characteristics plotted are

1. Comparison of SMC controllers and SSC controllers for the speed tracking of turbine with switching gain  $\alpha = 0.07$ .
2. Comparison of SMC controllers and SSC controllers for the speed tracking of turbine with switching gain  $\alpha = 0.5$ .
3. Time progression of electromagnetic torque,  $\alpha = 0.07$ .
4. Time progression of electromagnetic torque,  $\alpha = 0.5$ .
5. The time progression  $\alpha = 0.07$ .
6. The time progression  $\alpha = 0.5$ .
7. The zoomed in portion with  $\alpha = 0.07$  .
8. The zoomed in portion with  $\alpha = 0.5$ .

### 6.3 Results

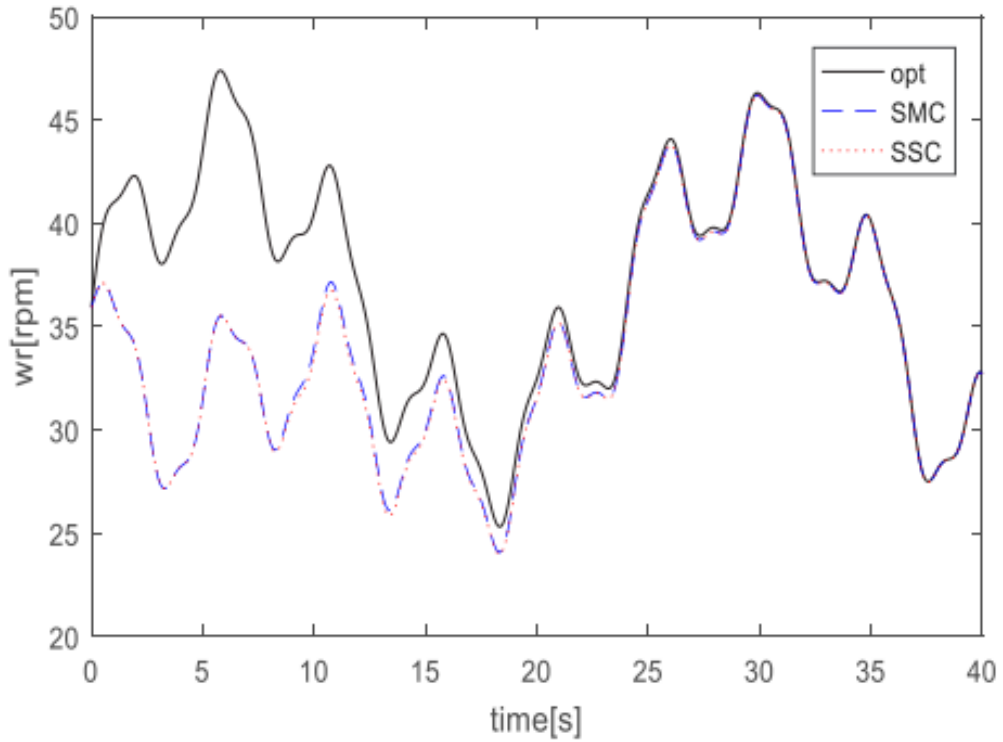


Figure 6.2: comparison of smc and ssc controller for turbine speed with  $\alpha=0.07$

In this part, the MATLAB software simulator was used to validate the efficiency of the approach. Wind turbine characteristics and parameters indicated in the table 3.1 are used in the numerical simulations, which are run with changing wind speed. The wind speed is divided into two main parts by the equation  $v = v_m + v_t$ , where  $v_m$  is the maximum speed of wind and  $v_t$  the turbulent speed.

The designed sector based control was compared to the traditional SMC strategy in order to assess its performances and robustness. For same switching gain values, both control strategies will be evaluated with relation to the turbine control aim. The goal is to maximise energy obtained from the speed of wind while minimising the transient load experienced by the shaft. To do this, the torsion of the rotor shaft decreased, which is comparable to decreasing the generator shaft's torsion change.[18]

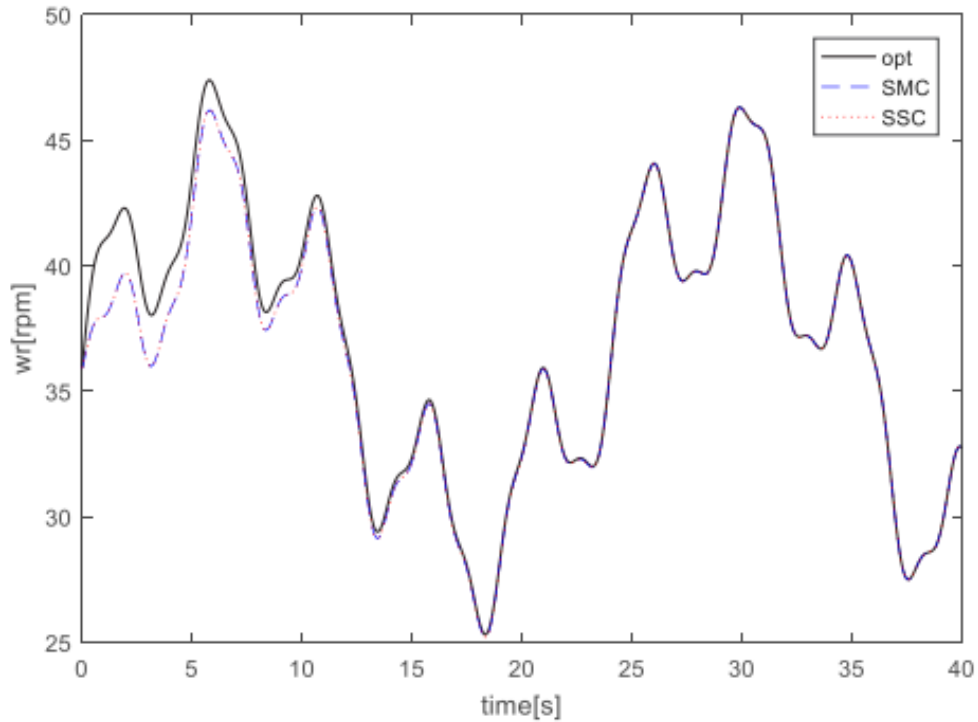


Figure 6.3: comparison of smc and ssc controller for speed of turbine with  $\alpha=0.5$

The torque of generator is found to be inside the constraint of 162kNm based on the data obtained. In Fig. 6.2 and 6.3 the tracking performance is depicted. It is evident that the suggested control approach appears to have very little impact on rotor speed tracking. As a result, the new approach maintains the conventional approach's performance in terms of power extraction. Fig. 6.4 and 6.5 shows how resilient the controller is against the chattering issue. It is apparent that the SSC strategy's control law is free of chatter.

Fig. 6.6 shows it if the switching gain has increased, whereas in the case of the conventional technique, the chattering magnitude has increased. Based on Figs. 6.6 and 6.7, In the case of switching sector based control, the trajectory slowly enters the switching sector, gradually approaches the switching surface, and then smoothly moves to the surface = 0. As opposed to the conventional SMC, where the trajectory reaches the switching surface directly and more quickly than the SSC, once there it oscillates about the surface  $S = 0$  and causes the phenomenon of chattering. Primary distinction between the three control strategies is the control activity.

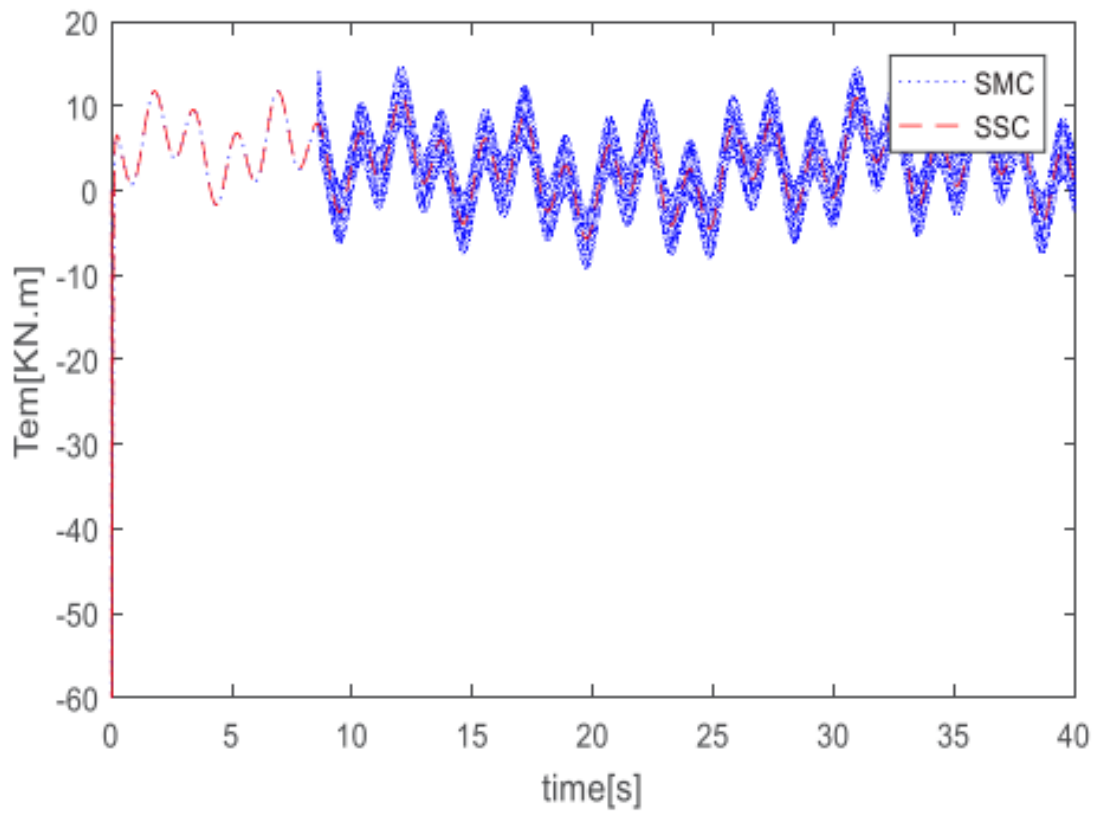


Figure 6.4: Time progression of the electromagnetic torque,  $\alpha = 0.07$ .

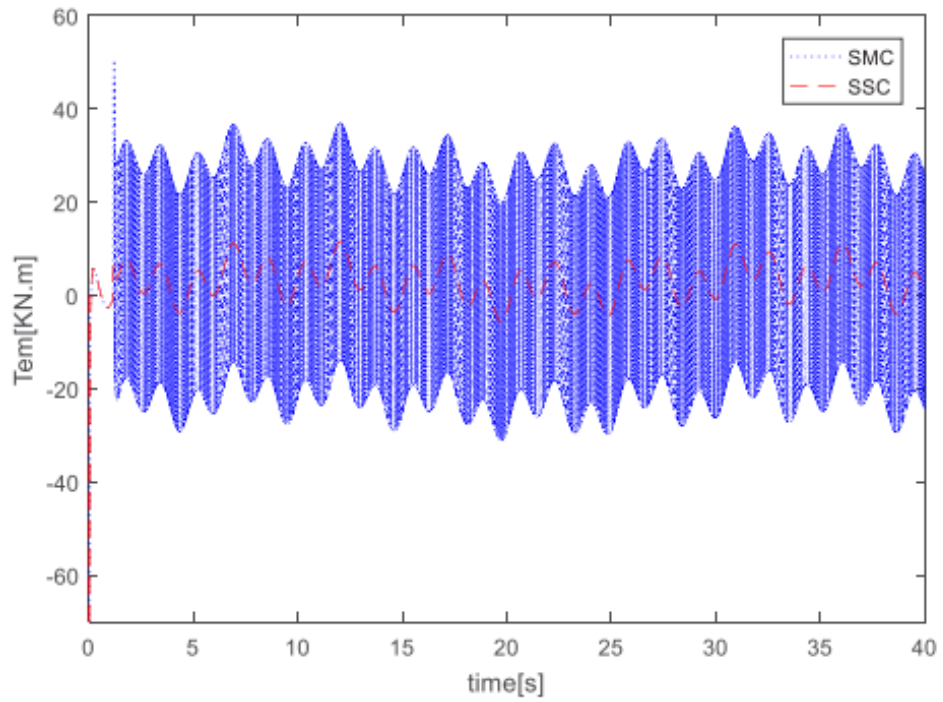


Figure 6.5: Time progression of the electromagnetic torque,  $\alpha = 0.50$

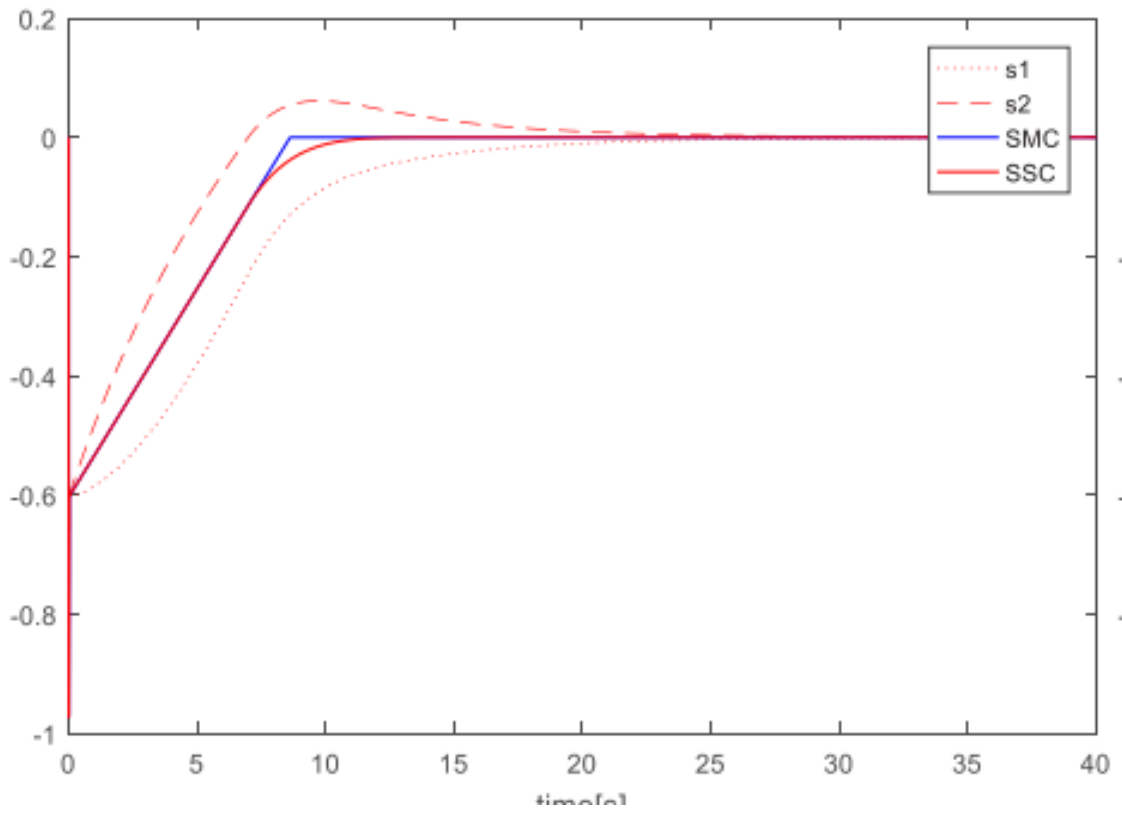


Figure 6.6: Time progression with  $\alpha = 0.07$ .

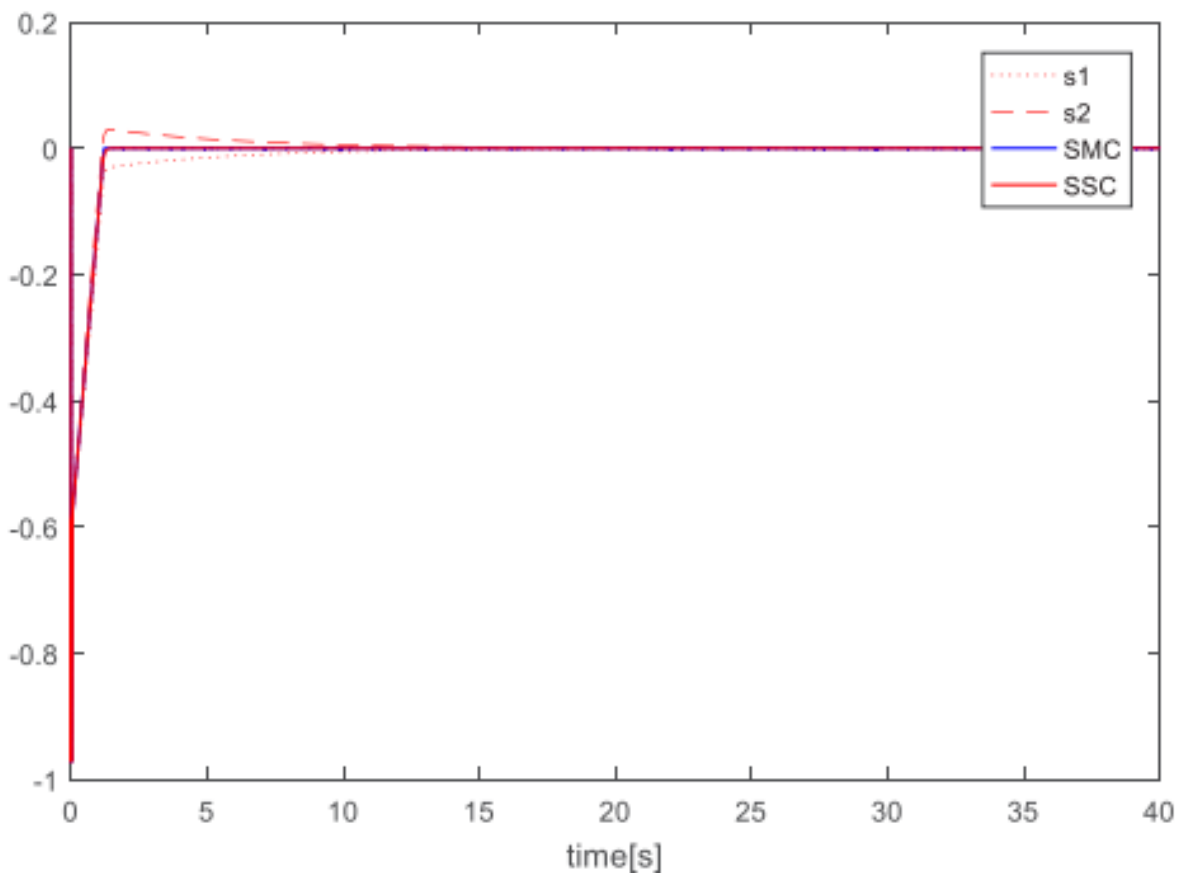


Figure 6.7: Time progression with  $\alpha = 0.5$

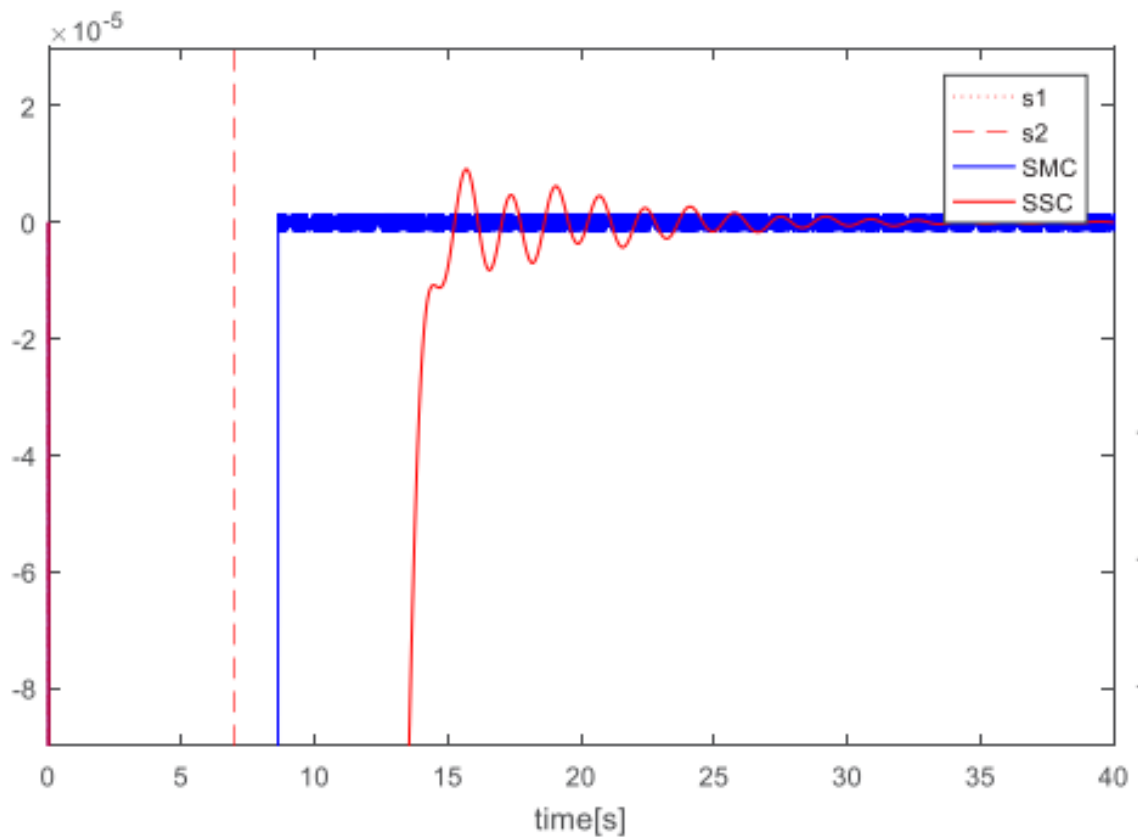


Figure 6.8: The zoomed in portion with  $\alpha = 0.07$

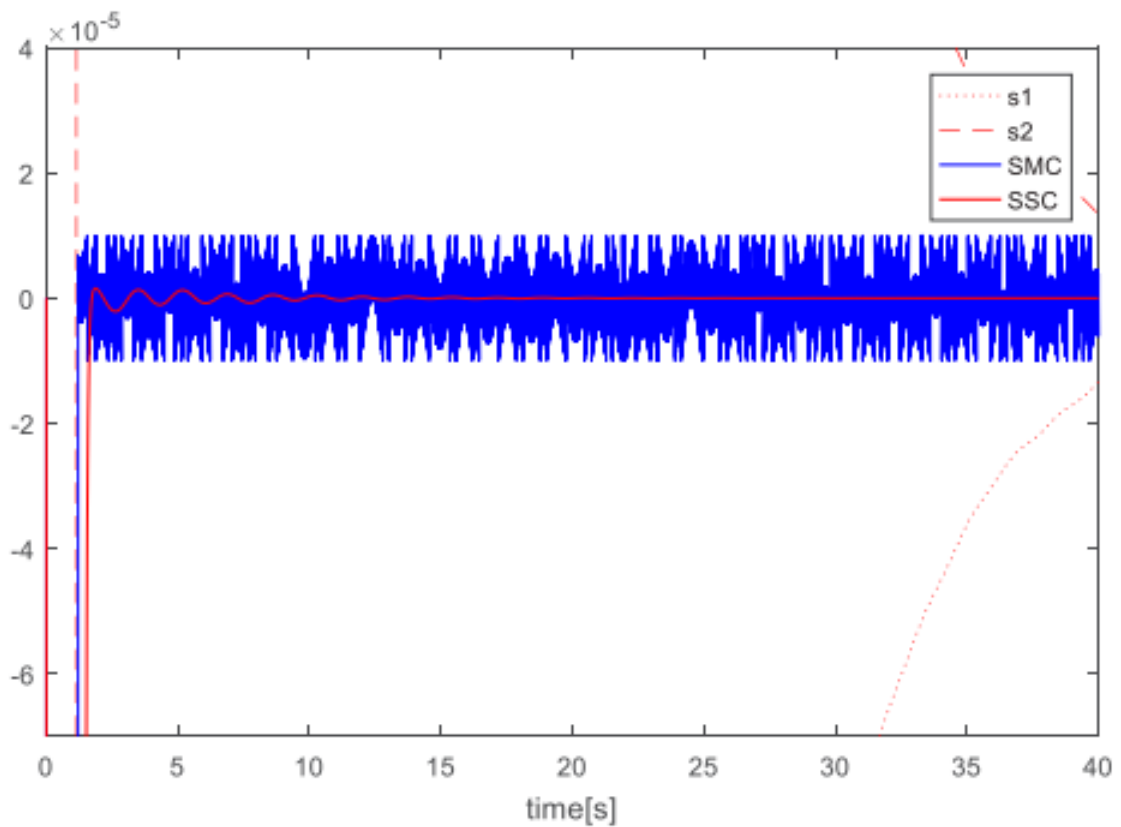


Figure 6.9: The zoomed in portion with  $\alpha = 0.5$

The primary difference in the 2 control approaches is its control activity. Despite the fact that the typical SMC requires heavy controller action and has a high level of robustness, it also creates significant vibrations in the transmission shafts (chattering). By lowering the control gain, which increases the reaching phase and consequently lowers the system's response velocity, the chattering can be reduced. If the designed control law is based on the sliding-sector, used in place of the sliding-surface, the chatter reduction is considerable with similar control gain.

## **6.4 Analysis of result**

- Because the coefficient is kept at its optimal value, the simulation results shows that the switching sector based SMC performs superior than conventional sliding mode control.
- SMC is used because it can correct parameter uncertainty and unexpected external disturbances.
- The capacity to track is equivalent between the two control strategies. The most significant aspect of traditional sliding mode is thus carried over into the sliding sector approach.
- When the sliding sector approach is used, the control system's robustness with regard to chatter-free implementation is accomplished.
- The system trajectory's convergence to its reference signal is greatly influenced by switching gain. However, in the case of severe disturbances and unpredictability, the control law demands a higher switching gain, which results in more chattering than in the case of a conventional strategy.
- Comparing the 2 controllers, sector-based sliding mode controllers have important characteristics including chatter-free operation and parameter uncertainty avoidance.

## **6.5 Concluding remarks**

This chapter verified the effectiveness of switching sector based sliding mode controller over conventional sliding mode controller.

## **Chapter 7**

### **CONCLUSION AND FUTURE SCOPE**

The work presented in the paper benefits the sector based sliding mode controller is how much effective than the conventional sliding mode controller . Two control approaches used to a nonlinear model of wind turbine. In zone I the turbine operates at partial load, so that the fundamental principle is to acquire the optimum amount of wind power. The problem of identify or rectify the external disturbances or parameter uncertainty due the fast fluctuations of wind is the control objective. Therefore focused on SMC sector based design that can be treated as the expansion of conventional sliding mode method by changing the surface of switching to a sector. The system's control preserves the robustness of the conventional technique while offering a smoother control law. The control law makes sure that the sector is within the trajectory of the system in a certain amount of time. The proposed control system has even chattering limitations and is relatively stable. Whenever external disturbances are present, herein strong and wind speed fluctuates. The future scope of the project includes the zones II and III region of operation.

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# List of Publications

- [1] Nayana M A and Salil N, "Switching sector based sliding mode control for variable speed wind turbine system," communicated to *International Conference on Edge Computing and Applications (ICECAA)*, 2022.
- [2] Nayana M A and Salil N, "Speed Control of Variable Speed Wind Turbine using SSC," communicated to *IEEE 19th India Council International Conference (INDICON)*, 2022.