Nonlinear Robust Control of a Variable Speed-Wind Turbine

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***Abstract*—This paper is aimed at designing a nonlinear robust control techniques for two mass model of variable speed wind turbine (VSWT) with better performance parameters and capability of rejection of disturbances. Sliding Mode Control (SMC) is the most widely used robust controller. The control scheme based on SMC ensures that system state (rotor speed) of VSWT will converge to a desired speed in finite time. However, in conventional SMC the system is robust against matched uncertainties only. Therefore an integral SMC is presented that eliminate the effect of both match and mismatch uncertainties. Integral SMC (ISMC) is presented to track the speed of rotor of VSWT with an improved performance of the system at the cost of eliminating the effect of mismatch uncertainties.**

***Index Terms*—Wind turbine, Robust Control, Uncertainties, Sliding mode control and Integral Sliding Mode Control**

I. Introduction

Generation of electrical energy is hazardous for global warming because of emission of CO_2. The energy demand for both domestic and industrial sectors is increasing day-by-day. Nevertheless, the conventional source for energy never meets these demands. Due to these issues, an inclination of producing electrical energy from renewable energy sources exists. Renewable energy is more appealing due to environment friendly nature. One of the important renewable energy sources is wind energy. Until 2006, 0.6% of whole energy produce across the world is wind energy. However, according to European Wind Energy association, the consumption of wind energy increases by 151% over last 4 years. Furthermore, as predicted by 2030, almost 20% of electrical energy will be produced through wind [1]. Improvement in this area required multidisciplinary work and advancement of new technologies in several fields. One of the issues that needed to be addressed is the development of robust control schemes for VSWT, that can eliminate the effect of match and mismatch uncertainties [2].

Wind turbine systems (WTS) have attracted many researchers for the last two decades. The research community has designed and implemented different control schemes for VSWT. These schemes have different merits and demerits. The models of wind turbine are mostly nonlinear in nature, so designing a linear controller will result in poor performance. Many researchers have designed and simulated a nonlinear controller for one mass model of VSWT. K. E. Johnson et al proposed an adaptive nonlinear control scheme for one mass model of VSWT [3]. But it doesn't capture all the dynamics of the system. In [4], a robust controller is designed and simulated for WTS that ensured the maximization of power, captured for below rated wind-speed. In [5], B. Boukhezzar et al provided a dynamic feedback linearization based solution and implemented a robust control scheme for VSWT. Flexibility and Stiffness have been taken into account while modeling the system that capture all the system's dynamics accurately. However, their solution exists for the specific system model. For maximizing the power production for the wind below rated-speed, a fuzzy logic based control method (FLC) is designed and simulated for VSWT [6]. Wind speed was estimated from known aerodynamic torque and rotor's speed of the turbine. However, the stability of the system is difficult to ensure, which is the drawback of FLC scheme. In [7], Linear Quadratic Regulator (LQR) based solution provides, along with the combination of Kalman filter and Newton Rapshon method that are used to estimate the states of system and wind speed respectively [7]. The pitch angle of VSWT was regulated for above rated wind-speed. In [8],a sensor-less control scheme has been proposed for VSWT, that estimate the aerodynamic torque used for determining the maximum reference of rotor's speed. In [9], Takagi-Sugeno FLC Scheme has been presented and linearized sub-models were derived using different linearization techniques (Taylor linearization/sector non-linear approach). The dynamics of wind turbine were considered and taken into account without noise. In [10], Proportional-Integral (PI) control scheme has been designed for wind turbine. The efficiency of the controller is lesser as compared to other nonlinear control schemes because it couldn't handle the nonlinearity arises due to wind. An Observer-Backstepping control scheme was presented by Roberto Galleazzi et al for two mass model of VSWT using generator torque as an input, for maximizing the power captured from the wind. The objective of this control scheme is to obtain optimal tip speed-ratio by tracking the speed of the rotor. The technique has a limitation in the sense that it is not a robust control technique. In [12], Backstepping-SMC based controller has been simulated for single mass model of VSWT, with generator torque as an input and rotor's speed as output. The main objective of method was to track the rotor's speed so that power is maximized at the cost of suppressing of oscillations in gearbox. The aerodynamic torque is estimated by Newton-Rapshon method. The performance of conventional SMC is compared with backstepping SMC. Due to single mass model, the flexibility in the low-speed shaft is not taken into account. H-infinity and PID has been presented for VSWT in [13]. PID based approach utilizes root locus whereas H-infinity control scheme utilizes M-synthesis, for the system's analysis. In case of H-infinity control scheme, lesser oscillations are observed . The performance of these schemes is compared when subjected to different reference inputs, for tracking the required output. The performance of PID is poor because it is linear control technique and it does not tackle mismatch uncertainties, while H-infinity is a linear robust control technique.

Motivated by (12) and (13), this work presents SMC and ISMC for two mass model for VSWT. The model under consideration include the damping effect of both the generator and rotor. Moreover the flexibility of the shaft is also taken into account. This Paper is structure as follows. In Section II, the model of VSWT is derived. The proposed model are implemented in section III. Finally section IV provides conclusion and recommendations for future work.

II. MATHEMATICAL MODEL

We cannot exactly model a real physical system of wind turbine due to their complex dynamics and unpredictability of wind, that can be treated as uncertainties. Such systems are referred as Perturbed systems whose modeling is a challenging task. Control system engineers employ different models of wind turbines. Each of these models has their own merits and demerits [14]. Among them, One-mass model is one of the simplest models of VSWT but it works in certain conditions and does not describe the dynamics of wind turbine completely. A two mass-model for VSWT represents the dynamics of wind completely, but it requires a complex controller than one-mass model. Two mass model for VSWT is considered in this paper. In this model, the flexibility in the gearbox is considered which is not possible while using the single mass model. The wind turbine consists of rotor blade, gear box and the generator. Fig. (1) shows the addressed two mass model of VSWT.

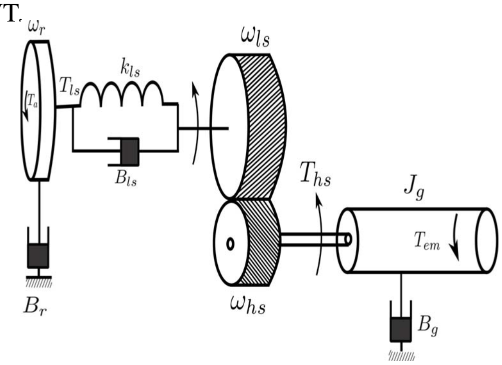

Fig. 1. Two Mass Model of VSWT

The following assumptions are made in the development of mathematical model of VSWT [15].

- The damping effect of rotor's blade as well as generator is considered.
- The stiffness of high-speed shaft is eliminated.
- The stiffness and damping of low speed shaft is considered .

Applying Newton's Law of rotation on rotor and gearbox, we get the following equations.

$$T_a - T_{ls} = B_r\omega_r + J_r\dot{\omega}_r \tag{1}$$

$$T_{ls} = B_{ls}(\omega_r - \omega_{ls}) + k_{ls}(\theta_t - \theta_{ls}) \tag{2}$$

Taking derivative of (2) and inserting the value of $\dot{\omega}_r$, we get

$$\dot{T}_{ls} = B_{ls}[\frac{1}{J_r}(-B_r\omega_r + T_a - T_{ls})] - B_{ls}\dot{\omega}_{ls} + k_{ls}\omega_r - k_{ls}\omega_{ls} \tag{3}$$

To compute $\dot{\omega}_{ls}$, consider gear box ratio n_g as:

$$n_g = \frac{T_{ls}}{T_{hs}} = \frac{\omega_g}{\omega_{ls}} \tag{4}$$

$$\omega_{ls} = \frac{\omega_g}{n_g} \tag{5}$$

Taking derivative

$$\dot{\omega}_{ls} = \frac{\dot{\omega}_g}{n_g} \tag{6}$$

$$\dot{\omega}_{ls} = \frac{1}{J_g n_g}(\frac{T_{ls}}{n_g} - T_{em} + B_g\omega_g) \tag{7}$$

By substituting equation (5) and (7) in equation (3),we get the following equation

$$\dot{T}_{ls} = (k_{ls} - \frac{B_{ls}B_g}{J_r})\omega_r + (\frac{B_{ls}B_g}{n_gJ_g}\frac{k_{ls}}{n_g})\omega_g - (\frac{B_{ls}}{J_r} + \frac{B_{ls}}{J_gn_g^2})T_{ls} + \frac{B_{ls}}{J_gn_g}T_{em} + \frac{B_{ls}}{J_r}T_a \tag{8}$$

The model of generator is:

$$\dot{\omega}_g = \frac{1}{J_g}(T_{hs} - T_{em} + B_g\omega_g) \tag{9}$$

The system parameters used in mathematical model of VSWT is shown in table below.

TABLE I
SYSTEM PARAMETERS AND THEIR SYMBOLS

S.No	Parameters	Symbols	Units	Values
1	Gear box Ratio	n_g	-	43.165
2	Generator's Inertial Mass	J_g	kgm^2	34.4
3	Generator's Friction	B_g	$N.m.s/rad$	0.2
4	Rotor's Friction	B_r	$N.m.s/rad$	27.36
5	Shaft Stiffness	B_{ls}	$N.m/rad$	2691
6	Shaft Damping	k_{ls}	$N.m.s/rad$	9500
7	Rotor's Inertial mass	J_r	kgm^2	3250
8	Air density	p	$kg.m^3$	1.29
9	Rotor's Radius	R	m	21.65

To write equation (1), (8) and (9) in simplified form, we suppose the following constant as:

$$q_1 = \frac{-B_r}{J_r}, \quad q_2 = \frac{-1}{J_r}, \quad q_3 = \frac{T_a}{J_r}, \quad q_4 = \frac{B_g}{J_g},$$

$$q_5 = \frac{1}{J_g n_g}, \quad q_6 = \frac{-1}{J_g}, \quad q_7 = \frac{B_{ls} T_a}{J_g}, \quad q_8 = \frac{B_{ls}}{J_g n_g},$$

$$a = k_{ls} - \frac{B_{ls} B_r}{J_r}, \quad b = \frac{B_{ls} B_g}{n_g J_g} - \frac{k_{ls}}{n_g}, \quad c = \frac{-B_{ls}}{J_r} - \frac{B_{ls}}{J_g n_g^2}$$

By considering the above suppositions and choosing ξ_1, ξ_2 and ξ_3 as states of system, the state space model of VSWT is:

$$\dot{\xi} = \begin{cases} q_1\xi_1 + q_2\xi_3 + q_3 \\ q_4\xi_2 + q_5\xi_3 + q_6 u \\ a\xi_1 + b\xi_2 + c\xi_3 + q_7 + q_8 u \end{cases} \tag{10}$$

Where $\dot{\xi} = [\dot{\xi}_1 \quad \dot{\xi}_2 \quad \dot{\xi}_3]^T$. The input of the system is generating torque which is denoted by u, while the output of the system is rotor's speed of turbine which is denoted by ξ_1.

In the real world, physical systems are very sensitive to the uncertainties caused by parametric variations, external disturbances and error in the modelling. It is difficult to control dynamical systems having perturbations and uncertainties. The stability and the efficient control of such dynamical system requires applications of robust controller.

III. Non Linear Robust Control techniques

Systems that contain uncertain parameters are difficult to control in real environment and the controllers for such systems are termed as Robust Controllers. Control of so-called perturbed systems has been the focus of researchers for the last three decades. Among existing robust control techniques, SMC based techniques have attracted researchers due to its highly robust nature and simplicity. This technique has proved its importance by providing efficient controller for a system containing uncertainties [16-18].

A. Sliding Mode Control

SMC is a nonlinear control method used to ensure system's trajectories at the sliding surface in a finite time interval, even in the presence of perturbations. In this scheme, the system is constrained to lie within a neighborhood of the switching function called as sliding surface. The sliding surface is designed so that the system's trajectories slides over the so-called sliding surface [19]. Once the system's trajectories reach on the sliding surface, the control law keeps the states on the close neighborhood of the states. It is two steps controller designed problem. In the first step, sliding surface is designed. A typical sliding surface σ can be expressed as follows.

$$\sigma = (\frac{d}{dt} + \lambda_1)^{r-1} e \tag{11}$$

Where r is the relative degree of the system and λ_1 is the tuning parameter. The choice of parameter λ_1 is arbitrary and it defines the poles of reduced dynamics of the system in sliding mode. The parameter r is the relative degree of the system.

In the second step, control law is designed to make switching surface attractive to the system states. Its major advantage is that the closed response becomes totally insensitive to some particular uncertainties. However, there is a drawback of this scheme called chattering. It is the high frequency switch across a sliding surface that can be dangerous for actuator of the system [20].

1) Relative Degree: Relative degree is an important concept in control system. It is denoted by r. Let us consider a SISO system.

$$\dot{\xi} = f(\xi) + g(\xi)u \tag{12}$$

$$y = h(\xi) \tag{13}$$

If the Lie-derivative L_f^{r-1} of the function $f(\xi)$ along the input vector $g(\xi)$. i.e $L_g L_f^{r-1} h(\xi)$ is not equal to zero, i.e.

$$L_g L_f^{r-1} h(\xi) \neq 0 \tag{14}$$

then the system has relative-degree r.

Consider a mathematical model of VSWT derived in equation (10). The output of the system is

$$y = h(\xi) = \xi_1 \tag{15}$$

where as

$$f(\xi) = \begin{bmatrix} q_1\xi_1 + q_2\xi_3 + q_3 \\ q_4\xi_2 + q_5\xi_3 \\ a\xi_1 + b\xi_2 + c\xi_3 + q_7 \end{bmatrix} \tag{16}$$

$$g(\xi) = \begin{bmatrix} 0 \\ q_6 \\ q_8 \end{bmatrix} \tag{17}$$

To compute the relative degree of the VSWT, first we calculate the Lie-Derivative of zero order.

$$L_g L_f^0 h(\xi) = L_g h(\xi) \tag{18}$$

$$L_g h(\xi) = \frac{\partial(h)}{\partial\xi} g(\xi) \tag{19}$$

$$L_g h(\xi) = 0 \tag{20}$$

This means that relative degree of the system is not equal to 1. Now to calculate $L_g L_f h(\xi)$, first we compute $L_f h(\xi)$

$$L_f h(\xi) = \frac{\partial(h(\xi))}{\partial\xi} f(\xi) \tag{21}$$

$$L_f h(\xi) = q_1\xi_1 + q_2\xi_3 + q_3 \tag{22}$$

$$L_g L_f h(\xi) = \frac{\partial(L_f h(\xi))}{\partial(\xi)} g(\xi) \tag{23}$$

By computing, the following result is produced

$$L_g L_f h(\xi) = q_2 q_6 \tag{24}$$

Hence $L_g L_f h(\xi) \neq 0$, this means that relative degree of the system is 2.

2) SMC Controller for VSWT: Consider the general sliding manifold with relative degree of 2,

$$\sigma = \frac{d}{dt}e + \lambda_1 e = \dot{e} + \lambda_1 e \tag{25}$$

By substituting the value of e and $\dot{e}$, we get

$$\sigma = \lambda_1 \xi_1 - \lambda_1 \xi_d + q_1 \xi_1 + q_2 \xi_3 - \dot{\xi}_d \tag{26}$$

Taking derivative

$$\begin{aligned}\dot{\sigma} =& (\lambda_1 + q_1)(q_1 \xi_1 + q_2 \xi_3 + q_3) + q_2(a\xi_1 + b\xi_2 + c\xi_3 + q_7 \\ &+ q_8 u) + \dot{q_3} - \ddot{\xi}_d - \lambda_1 \dot{\xi}_d\end{aligned} \tag{27}$$

The control input that will track the desired speed is given below:

$$\begin{aligned}u =& -\frac{1}{q_2 q_8}[(\lambda_1 + q_1)(q_1 \xi_1 + q_2 \xi_3) + q_2(a\xi_1 + b\xi_2 + c\xi_3) \\ &+ \dot{q_3} - \ddot{\xi}_d - \lambda_1 \dot{\xi}_d + k_1 sign(\sigma) + k_2 \sigma)]\end{aligned} \tag{28}$$

Where λ_1, k_1 and k_2 are the tuning parameters, i.e λ_1, k_1 , $k_2 > 0$.
Substituting equation (28) into equation (27), we get

$$\dot{\sigma} = (\lambda_1 + q_1)q_3 + q_2 q_7 - k_1 sign(\sigma) - k_2 \sigma \tag{29}$$

3) Stability Analysis: According to Lyapunov theorem, the stable system should satisfied the following conditions.

Choosing the lyapunov-function $V(\xi)$, such that it must be positive definite i.e. $V(\xi) > 0$ and $V(0) = 0$. The following lyapunov function is considered for the VSWT system.

$$V(\xi) = \frac{1}{2}\sigma^2 \tag{30}$$

The derivative of lyapunov-function $\dot{V}(\xi)$ must be negative definite, i.e $\dot{V}(\xi) < 0$

$$\dot{V} = \sigma\dot{\sigma} \tag{31}$$

Substituting equation (29) in equation (31), we get

$$\dot{V} = \sigma(\lambda_1 + q_1)q_3 + q_2 q_7 - k_1 sign(\sigma) - k_2 \sigma] \tag{32}$$

$$\dot{V} = (\lambda_1 + q_1)q_3 \sigma + q_2 q_7 \sigma - k_1 \sigma sign(\sigma) - k_2 \sigma^2] \tag{33}$$

$$\dot{V} \leq -[-(\lambda_1 + q_1)q_3 - q_2 q_7 + k_1]|\sigma| - k_2|\sigma|^2 \tag{34}$$

$$k_1 - (\lambda_1 + q_1)q_3 - q_2 q_7 > 0 \tag{35}$$

$$k_1 > (\lambda_1 + q_1)q_3 + q_2 q_7 \tag{36}$$

In the above equation, $\dot{V}$ is always negative definite for the derived k_1, so the system will be stable for the derived input. The speed of rotor and desired speed of VSWT using SMC is shown in Fig. (2).

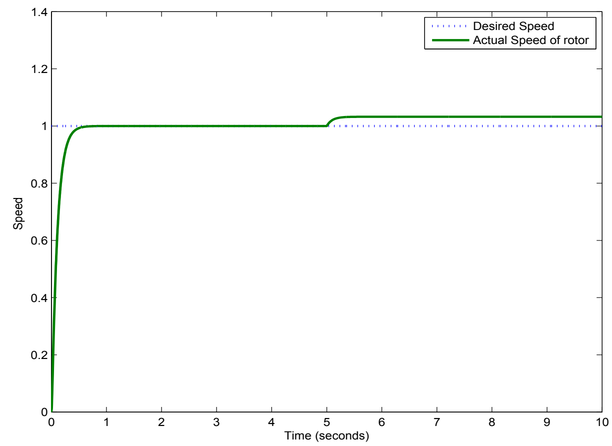

Fig. 2. Tracking rotor speed of VSWT

Remarks: It is evident from the simulation results that the system's states initially converge to a specific desired speed for a constant aerodynamic torque. After 5 seconds, the aerodynamic torque changes and system's states converges but does not track the desired speed. It is due to the fact that SMC eliminates only matched uncertainty. The system under consideration has mismatch uncertainty (T_a), so SMC technique is not suitable for the system having mismatch uncertainty. The difference between the desired speed and actual speed is considered as an error. The error plot for the VSWT is shown in figure below. Initially there is an error because controller takes time to track the desired speed. After approximately 1 second, the error has been reduced to zero. But when due to uncertain behaviour, the aerodynamic torque changes, the error again increases and it cannot be eliminated by this SMC scheme.

B. Integral-Sliding Mode Control

The robust property of SMC scheme having parameter variation and external disturbances can be guaranteed after the existence of sliding surface in the state space. Prior to sliding phase, there occurs a reaching phase in a general SMC scheme and the system can be affected by uncertain parameters and external disturbances which affects the performance. ISMC has an extra integral term in the sliding manifold that eliminates the reaching phase. This result in an important feature of ISMC and the system remains robust against parameter variations and disturbances. The second advantage of of ISMC is that the order of a system is equal to the order of ISMC , this results that the system operates with full states in ISMC as compared to the reduced order of system in general SMC. In spite of the fact that ISMC is a robust technique against system with uncertainties, it requires the information of upper bound of uncertainty. It is a difficult task to guess the upper bound and usually this is overestimated that results in excessive gain which may cause damage to actuators

1) ISMC Design: In order to design a controller using ISMC scheme, consider a system.

$$\dot{\xi} = f(\xi) + B(\xi)u + h(\xi, t) \tag{37}$$

where ξ is vector which represents states , u represents the control input , and $h(\xi, t)$ represents disturbances. The present control law consists of two terms.

$$u = u_0 + u_1 \tag{38}$$

u_0 represents continuous control and u_1 represents discontinuous control is used to reject uncertainties. So equation (37) becomes

$$\dot{\xi} = f(\xi) + B(\xi)u_0 + B(\xi)u_1 + h(\xi, t) \tag{39}$$

The sliding manifold 'S' for ISMC can be selected as

$$S = \left(\frac{d}{dt} + \lambda_2\right)^{n-1} \int edt \tag{40}$$

The sliding manifold contains the integral term which reduces chattering in input. while the remaining terms are same as in conventional SMC. Here n is equal to the order of the system.

2) ISMC for VSWT: Consider the sliding manifold 'S' with n=3, we obtain

$$S = {\lambda_2}^2 \int edt + \dot{e} + 2\lambda_2 e \tag{41}$$

Taking derivative of sliding manifold,

$$\dot{S} = {\lambda_2}^2 e + \ddot{e} + 2\lambda_2 \dot{e} \tag{42}$$

The difference between the speed of rotor and the desired speed is considered as an error, mathematically

$$e = \xi_1 - \xi_d \tag{43}$$

Taking derivative,

$$\dot{e} = q_1\xi_1 + q_2\xi_3 + q_3 - \dot{\xi}_d \tag{44}$$

$$\begin{aligned}\ddot{e} =&(q_1^2 + aq_2)\xi_1 + (bq_2)\xi_2 + (q_1q_2 + cq_2)\xi_3 + \\ &(q_1q_3 + q_2q_7) + q_8u - \ddot{\xi}_d\end{aligned} \tag{45}$$

By putting the values,

$$\begin{aligned}\dot{S} =&({\lambda_2}^2 + q_1^2 + aq_2 + 2\lambda_2q_1)\xi_1 + (bq_2)\xi_2 + (q_1q_2 \\ &+ cq_2 + 2\lambda_2q_2)\xi_3 + (q_1q_3 + q_2q_7 + 2\lambda_2q_3) \\ &- {\lambda_2}^2\xi_d - 2\lambda_2\dot{\xi}_d - \ddot{\xi}_d + q_2q_8u\end{aligned} \tag{46}$$

The control input that will stable the given system:

$$\begin{aligned}u =& -\frac{1}{q_2q_8}[({\lambda_2}^2 + q_1^2 + aq_2 + 2\lambda_2q_1)\xi_1 + (bq_2)\xi_2 + \\ &(q_1q_2 + cq_2 + 2\lambda_2q_2)\xi_3 + (q_1q_3 + q_2q_7 + 2\lambda_2q_3) \\ &- {\lambda_2}^2\xi_d - 2\lambda_2\dot{\xi}_d - \ddot{\xi}_d + \eta_1 sign(S) + \eta_2(S)]\end{aligned} \tag{47}$$

Where λ_2, η_1 and η_2 are the tuning parameters,i.e
λ_2, η_1 , $\eta_2 > 0$.
The speed of rotor of VSWT obtained after implementation of system using ISMC technique is shown in Fig. (3). The error signal and control input is shown in Fig. (4) and Fig. (5) respectively.

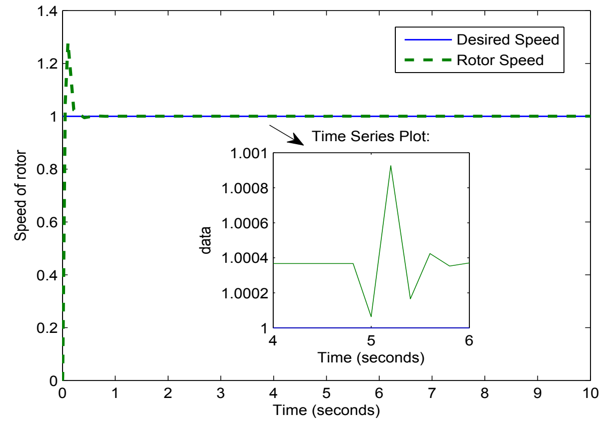

Fig. 3. Tracking of Rotor Speed of VSWT

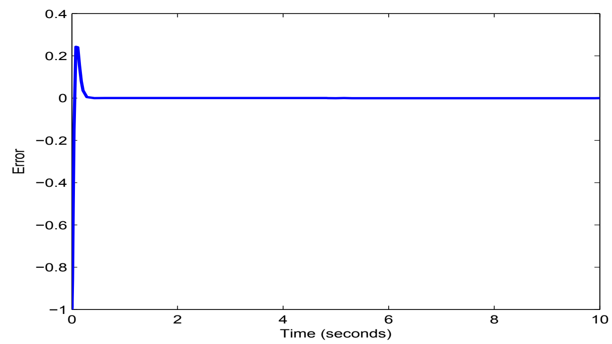

Fig. 4. Error signal

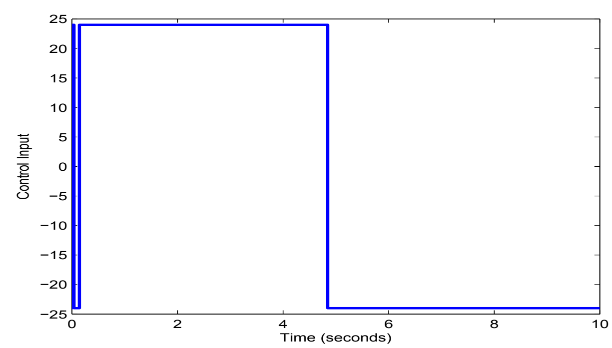

Fig. 5. Control input using ISMC

Remarks: The rotor's speed of VSWT tracks the desired speed in the presence of uncertainties. The integral term used in sliding manifold is responsible for elimination of reaching phase. It has been ensured that rotor's speed tracks the desired speed with better performance in the presence of uncertainties. Moreover, the chattering effect in control input is reduced to considerable level. The system ensures stability and the states of the system are driven towards the sliding surface from initial conditions.

TABLE II
PERFORMANCE PARAMETERS OF SMC AND ISMC

Techniques	Settling time	Steady state error	Chattering
SMC	0.5	0.0323	Significant
$ISMC$	0.3	0.001	Low

IV. CONCLUSION AND FUTURE WORK

In this paper, two mass model of VSWT was presented. SMC and ISMC based solution have been provided to track the rotor's speed of VSWT. The advantage of designing a controller using SMC is that it eliminated the effect of match uncertainty in the system only. The shortcomings of SMC scheme were eliminated by as ISMC. Moreover, ISMC eliminated both match and mismatch uncertainties, which results into convergence of rotor's speed of VSWT in a finite time. Based on the controllers designed in this paper, the most suitable future directions for researchers is to use Disturbance Observer along with ISMC so that the performance can be improved at the cost of reducing tracking error.

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