Indian Journal of Fundamental and Applied Life Sciences ISSN: 2231– 6345 (Online)
An Open Access, Online International Journal Available at www.cibtech.org/sp.ed/jls/2015/01/jls.htm
2015 Vol.5 (S1), pp. 5090-5098/Fahandari and Ghanbari
Review Article

IMPROVING SPEED REGULATION PMSM SYSTEM BASED ON THE COMBINATION OF THE TERMINAL SLIDING MODE CONTROL METHOD AND GENETIC ALGORITHM

Mahnaz Hatami Fahandari[1] and *Mahmood Ghanbari[2]
[1]*Department of Electrical Engineering, AliAbad Katoul Branch,*
Islamic Azad University, AliAbad Katoul, Iran
[2]*Young Researchers and Elite Club, AliAbad Katoul Branch,*
Islamic Azad University, AliAbad Katoul, Iran
**Author for Correspondence*

ABSTRACT
Synchronous machines are the one of useful machines that they are used in industry and specially in the plant, Since the Dynamical equations of these machines are nonlinear so There is the possibility of detection complex behaviors and cause to create some problems, this paper is examined the problem of speed regulation system of permanent magnet synchronous motor servo (PMSM) based on the combination of the terminal sliding mode control method (TSMC) and genetic algorithm. With the help of non-singular terminal sliding mode (NTSM), a terminal sliding mode controller is designed for speed loop. This controller can converge to an inertia point in a limited time, so the controller can take the motor speed with the better tracking precision and faster convergence to reference value in the limited time. In addition we deal to improving the performance of the system to adjust the controller parameters by using of genetic algorithm that due to tend the error becomes zero, It also makes that the output terminal sliding mode controller combined has a fewer rise and settling time and it also doesn't have the steady-error, so it does faster than the traditional sliding mode controller and also non Singular sliding mode controller.

Keywords: *Permanent Magnet Synchronous Motor, Vector Control, Traditional Sliding-mode Control, Nonsingular Terminal Sliding-mode Control, Genetic Algorithm*

INTRODUCTION
PMSMs have been widely used in factory automation, Household electrical appliances, computer related, Equipments, CNC machines, robots, high-speed aerospace, drives and high-technology tools used for outer space exploration in the past decades, because of their good performances, such as high power density, high efficiency, fast dynamics, good compatibility and maintenance free, etc. compared to other kinds of motors, such as DC motors (French *et al.*, 1996).
It is difficult to accomplish the high-performance control of PMSM by using the conventional PID-type control methods. So far, many methods have been proposed for improving the performances of PMSM systems (Begovic *et al.*, 2013). Among these methods, the use of a system by variable structure with sliding mode in the nonlinear systems is considered.This controller by use of a very fast and convenient switching leads the under control process state track to a selective surface in the state space And keeps the state track on this level for the next times (Shihuna *et al.*, 2011).
Since the sliding mode control is critical to parameter variations, external disturbances injection and fast dynamic response, therefore, it is one of an effective control methods in theoretical research, SMC concept is used for solving the unstable and random system and successfully developed in recent year (Jikun *et al.*, 2011).
Among The sliding mode controllers, terminal sliding mode control has better stability against anarchy and instability rather than the traditional sliding mode control ensures, also it has the superior properties such as limited time convergence to the desired position (Jikin *et al.*, 2011). Designing the terminal sliding mode control is based on a particular choice of sliding surface and determines an allowed control law to stimulate the system position to remain on this level (Shihuna *et al.*, 2010).

Hence, in this study, from the terminal sliding mode control combined with genetic algorithm is used to improve the controlling of the permanent magnet synchronous motors (PMSM).

Mathematical Model of Permanent Magnet Synchronous Motor

The usual method of controlling the synchronous of permanent magnet machine, is turning the voltage and current equations in the form of synchronous (d, q) using the theory of synchronous reference machine, three-phase voltage and current and inductance of PMSM motor are taken to the two axis d, q, on the modeling of permanent magnet synchronous motor, we consider the following assumptions (Reddy *et al.*, 2013):

1- Of the hysteresis and eddy current losses are neglected.

2- Suppose that the magnetic potential in the air gap is distributed as sinusoidal.

Under the above assumptions the state equations of permanent magnet synchronous motor in the d-q axis is defined as follow (6):

$$\begin{aligned} \dot{i}_d &= -\frac{R_s}{L_d} i_d + n_p w i_q + \frac{u_d}{L_d} \\ \dot{i}_q &= n_p w i_d - \frac{R_L}{L_q} i_q - \frac{n_p \psi_f}{L_q} w + \frac{u_q}{L_q} \\ \dot{w} &= \frac{n_p \psi_f}{J} i_q - \frac{B}{J} w - \frac{T_L}{J} \\ \dot{\theta} &= w \end{aligned} \quad (1)$$

Where u_d , u_q are the stator d and q axes voltages, i_q, i_d are the stator d and q axes currents, *Ld* , *Lq* are the stator d and q axes inductances *Ld* = *Lq* = *L*, *Rs* is the stator resistance, ω is the rotor angular velocity, n_p is the number of pole pairs, ψ_f is the flux linkage, T_l is the load torque, B is the viscous friction coefficient, J is the moment of inertia. Using these state equations we can simulate the PMSM system in the MATLAB, since our goal of designing the PMSM motor is adjustment the motor speed by terminal sliding mode control, we design the control system that consists three control loops, it made of a speed control loop and two-loop flow control and we can observe it in the figure (1), Here two PI controllers, which are used to stabilize the d-q axes current errors, are adopted in the two current loops respectively.In order to decouple the speed and currents, the vector control strategy Of $i_d^* = 0$ is used.

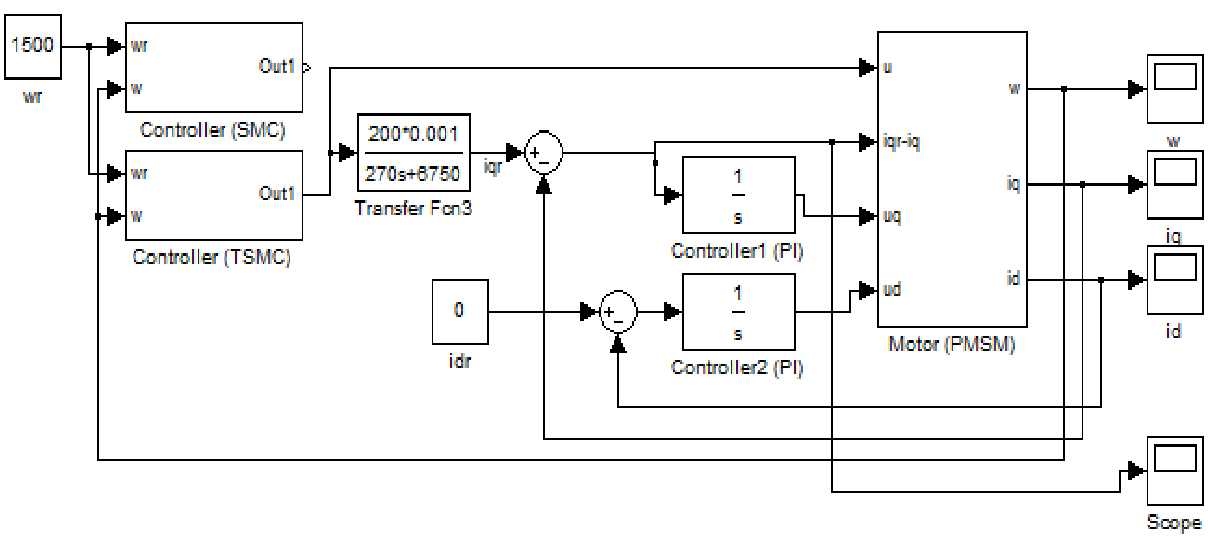

Figure 1: Schematic diagram of the PMSM system based on vector control

Controlling the speed of Permanent Magnet Synchronous Motor

The output of PMSM system is the speed w that we have it in equation 1 and it can be written as follows:

$$\dot{w} = b i_q - \frac{B}{J} w - \frac{T_L}{J} \quad (2)$$

It is in equation (2) $b = \frac{1.5 n_p \psi_f}{j}$ and For designing the speed loop controller, usually the q-axis stator current i_q is approximately replaced by the q-axis current supply that is i_q^* , In this simulation because the vector q current source corresponds to the vector q current is considered, therefore, equation (2) becomes the following equation:

$$\dot{w} = bi_q^* + a(t) \tag{3}$$

In the above equation where $(t) = -\frac{B}{J}w - \frac{T_L}{J} - b(i_q^* - i_q)$, can be considered as the system disturbances including friction, load disturbances and tracking error of i_q current loop. In (10), a second-order model between reference q-axis current and speed output is proposed, that its frequency domain is from equation (5):

$$\left(S^2 + \frac{\kappa_i}{\kappa_p}s\right)\Omega(s) = U(s) - \frac{b}{\kappa_p}sU_q(s) + \left(s + \frac{\kappa_i}{\kappa_p}\right)A(s) \tag{4}$$

where Ω(*s*), *Uq*(*s*) and *A*(*s*) are the Laplace transformation of w, uq and و a(t), respectively, *kp* and *ki* are the proportional and integral gains of PI controller in the current loop of i_q, respectively; U (s) is defined as:

$$U(s) = b(s + {}^{\kappa_i}/_{\kappa_p})I_q^* \tag{5}$$

where I_q^* is the Laplace transformation of reference q-axis current. The inverse Laplace transformation of (3) is

$$\ddot{w} = -\alpha\dot{w} + d(t) + u \tag{6}$$

Where $a = \frac{\kappa_i}{\kappa_p}$, $d(t) = -\frac{b}{k_p}\dot{u}_q + \dot{\alpha}(t) + \frac{\kappa_i}{\kappa_p}\alpha(t)$ can be considered as the lumped disturbances of the system, U is the control signal that should be designed firstly. the speed output for PMSM system is described by (6)

Designing the Speed Controller Based on Sliding Mode

In the speed controller the state variables can be defined as follows (Shihuna *et al.*, 2010):

$$\begin{cases} x_1 = w_r - w \\ x_2 = \dot{x}_1 \end{cases} \tag{7}$$

So the state space equation system for pmsm engine defines as follows:

$$\mathcal{X}1 = \mathcal{X}2 \quad ,\dot{\mathcal{X}}2 = \ddot{w}_r + \alpha\dot{w} - d(t) - u \tag{8}$$

Assuming the control goal is reset to zero the state variables x_1 and x_2, the sliding variable defines as the sum of system weighted errors are defined as follows:

$$s = x_2 + \lambda x_1 \tag{9}$$

Where in that λ used for weighting x_1 to x_2.

The sliding variable dynamic created by deriving of s:

$$\dot{s} = \dot{x}_2 + \lambda\dot{x}_1 = f(x) + g(x)u + w + \lambda x_2$$

That is a first-order dynamics and the controller can be designed using Lyapunov method. The controller u is designed in such a way that the sliding variable s reaches to zero.

To design u by using of Lyapunov method we have (2,8,10):

$$v = \frac{1}{2}s^2$$

In the Lyapunov method should be established the following conditions:

$$\dot{v} = s\dot{s} \leq 0$$

Make a reservation at the Best state $\dot{v} < 0$ leads to the asymptotic stability.

To achieve the stability limited time is defined the sliding condition as:

$$-\eta|s| \quad \dot{v} = s\dot{s} \leq$$

With the integration of both sides of the sliding condition we have:

$$s\frac{ds}{dt} \leq -\eta|s| \square \rightarrow \frac{s}{|s|}ds \leq -\eta dt \rightarrow \int_{s_0}^{0} \frac{s}{|s|} \leq \int_0^{t_r} -\eta dt \rightarrow$$

$$\begin{cases} s > 0 \Rightarrow \int_{s_0}^{0} 1ds \le \int_0^{t_r} -\eta dt \Rightarrow s\Big|_{s_0}^{0} \le -\eta t\Big|_0^{t_r} \Rightarrow 0 - s_0 \le \eta t_r \Rightarrow t_r \le \frac{s_0}{\eta} \\ s < 0 \Rightarrow \int_{s_0}^{0} -1ds \le \int_0^{t_r} -\eta dt \Rightarrow s\Big|_{s_0}^{0} \le -\eta t\Big|_0^{t_r} \Rightarrow 0 + s_0 \le \eta t_r \Rightarrow t_r \le \frac{-s_0}{\eta} \end{cases}$$

Finally time to reach the sliding variables to zero will be as follows:

$$t_r \le \frac{|s_0|}{\eta} \quad (10)$$

So t_r is the time to zero or time to sliding variable into sliding surface that is adjustable with changing.

Now we gain the controller with the enforcement of sliding condition. With the enforcement of this condition we have:

$$\dot{v} = s\dot{s} = s(f(x) + g(x)u + w + \lambda x_2) \le -\eta|s|$$

Such as linear feedback method, we deleted definite nonlinear sentences. The controller must be composed of two parts below (12).

$$u = u_{eq} + u_r$$

Where u_{eq}or equivalent control for removing of definite sentences to be determined as follows:

$$u_{eq} = \frac{1}{g(x)}(-f(x) - \lambda x_2)$$

Now, for this part of the controller, again we form the sliding condition:

$$s(g(x)u_r + w) \le -\eta|s|$$

u_r Called the supplier that is considered the following general form:

$$u_r = -ksign(s)$$

Finally the controller will be as follows:

$$u = (\ddot{w}_r + \alpha\dot{w} + c\dot{x}_2 + ksgn(s) + \lambda x_2) \quad (11)$$

Speed Controller Design Based on non-singular Terminal Sliding Mode

In order to achieve good performances, such as fast convergence and better tracking precision, a non-singular terminal sliding mode manifold is designed as (8). In the nonsingular terminal sliding mode control the sliding surface is same as the following equation:

$$s = x_1 + \frac{1}{\beta} x_2^{p/q} \quad (13)$$

Where $\beta > 0, p, q$ are positive odd integers,$1 < p/q < 2$ .the terminal sliding mode control can be designed as:

$$u = \left(\ddot{w}_r + \alpha\dot{w} + \beta\frac{q}{p}x_2^{2-p/q} + ksgn(s) + \lambda x_2\right) \quad (14)$$

Where $k > 0$ is the switching gain, and $sgn(0)$ is the standard signum function.

According to the above design procedure, a non-singular terminal sliding mode control scheme based on the second-order model of PMSM speed regulation system is shown in Figure 2. Note that the generalized plant in Figure 2, represents the two current loops which include PMSM and other components the same as that of Figure 1 (10).

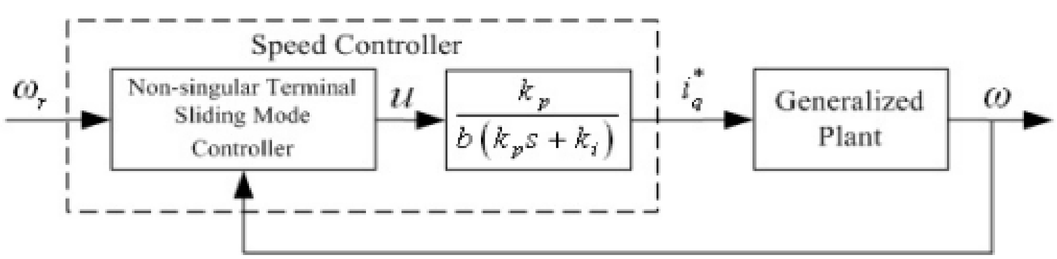

Figure 2: Designing of speed controller based on the combination of non Singular terminal sliding mode and Genetic Algorithm

Review Article

Setting control parameters to improve performance by using a genetic algorithm is designed to improve the performance of designed controller (in the above description) is as follows:

$u = \alpha\dot{w} + \ddot{w}_r + \beta\frac{q}{p}x_2^{2-\frac{p}{q}} + \lambda x_2 + ksgn(s)$

$x_1 = w_r - w$

$s = x_1 + \acute{\beta}x_2^{2-\frac{p}{q}}$

The following parameters are regulated by genetic algorithm

$$\acute{\beta}, \beta, p, q) \quad x = [k, \lambda,$$

So six unknown parameters are defined as follows:

X(1)=k
X(2)= λ
X(3)= $\acute{\beta}$
X(4)= β
X(5)=p
X(6)=q

Now should be defined the cost function as a measure to determine the performance of the controller. so The same LQG cost function is defined below:

$$J = \sum_{k=1}^{N}(w_r - w(k))^2 + \sum_{k=1}^{N}(u(k))^2 \quad (16)$$

With minimizing of above Relationship the tracking error is reduced and at the same time the control signal will be in accepted limit.

Simulation and Analysis

The parameters of the PMSM used in the simulation are shown in Table 1 (10).

Table 1: Parameters Of Pmsm

Rated Power P_N	750W
Rated Voltage U_N	200V
Rated Speed n_N	3000rpm
Stator Resistance R_s	1.74 Ω
Stator Inductances L	4mH
Rotor Flux Linkage ψ_f	0.402wb
Moment of Inertia J_n	$1.78\times10^{-4}\, kg\cdot m^2$
Viscous Friction Coefficient B	7.403×10^{-5} N · m · s/rad
Number of Pole Pairs n_p	4

The speed regulation system of the PMSM is simulated by MATLAB. To have a fair comparison, the switching gains of SMC and NTSM are both selected as k = 400. The PI parameters of both current-loops are the same, i.e., the proportional gains are $k_p = 200$, the integral gains are $k_i = 5000$.

The reference speed is *1500RPM*, and the disturbance load torque $T_l = 4N.m$ is added at *t=1s*. The results of the simulation are shown in Figures 3 and 4.

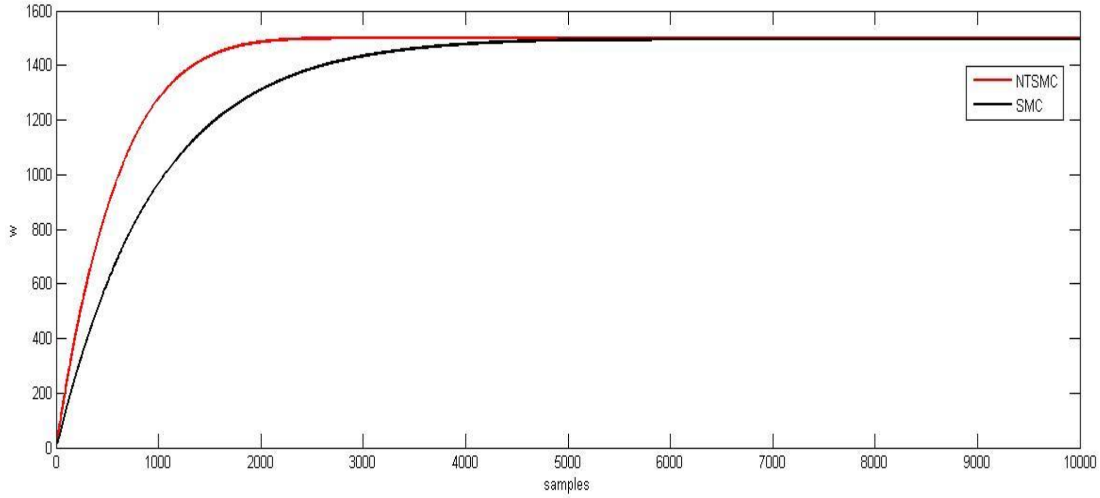

Figure 3: Responses of PMSM system under the SMC and NTSM control methods

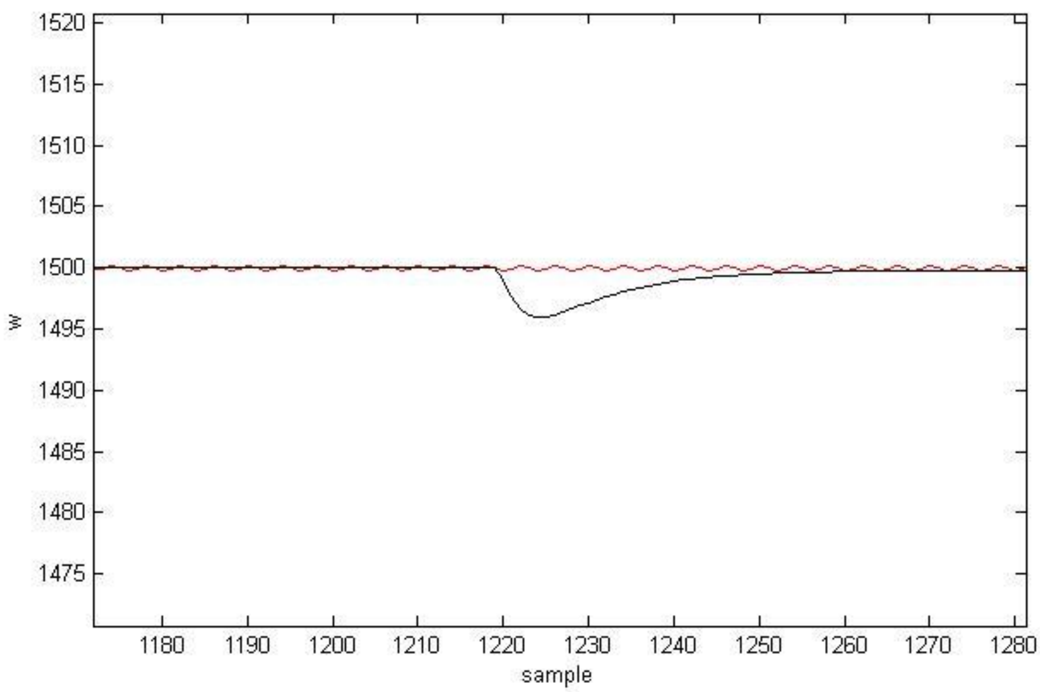

Figure 4: Responses with a sudden load under the SMC and NTSM control methods

The speed responses of PMSM speed regulation system from 0 to 1500RPM are shown in Figure 3. It can be seen that the NTSM control scheme has a shorter settling time, and both methods show small overshoots. Simulation results about load disturbance rejection properties of the two control schemes are shown in Figure 4, Turbulence applys as the load torque and at the 0.5 second and It can be seen that the speed response of PMSM system under the NTSM control scheme has a less speed drop and a better disturbance rejection ability when the disturbance load is added suddenly.

In designing of system by combination of genetic algorithm for minimizing of the cost function for the equation (16) of the function (ga) MATLAB is used that the algorithm settings are selected as default of MATLAB and as fowling table:

Table 2: Options genetic algorithms in MATLAB

Generation mutation Coefficient	Coefficient crossover	The number of variables	Number of generations	Total Population
0.2	0.8	6	100	20

To run of this algorithm is used the following command:
options=gaoptimset('InitialPopulation',x0,'Display', 'iter', 'Generations', 100);
x=ga(@opt,6,options)
That the Opt function has the task of running simulink and calculate the cost function. In accordance with the above code in each generation of algorithm running the amount of cost to be displayed in Matlab. The simulink runs about one hundred generation and twenty in each generation or in other word the simulation runs two thousand to get optimum value for parameters and finally the optimum value of controller parameters and the least cost value are shown in the MATLAB environment and the results have been told as follows:
Genetic algorithms is used for adjusting the parameters of sliding mode terminal controller through the optimization of the expressed cost function in the reporting and the fowling figure shows the reduction of cost value in every generation.

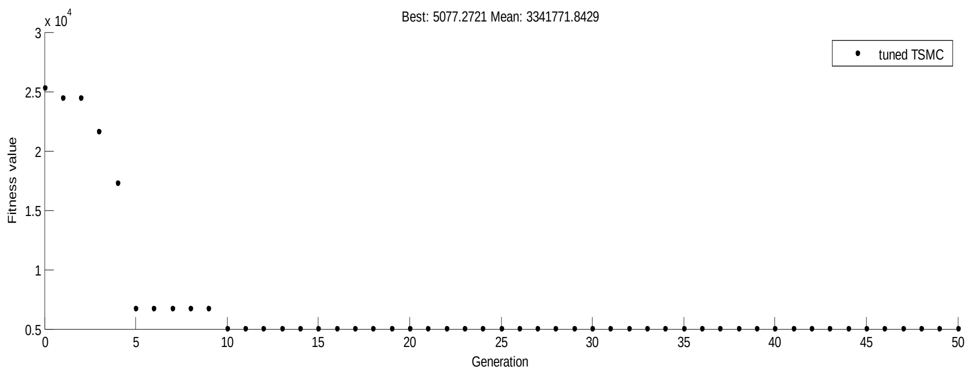

Figure 5: Chart cost of NTSMC

It is seen that the cost value has decreased from 25100 to 5076 levels. The same method is used to set the parameters of the sliding mode controller (classic) and the cost function curve can be seen below. It is seen that the least cost value algorithm is come to 23019.5 that was very larger than cost value for previous controller that is pointer the advantage of controller type of terminal.

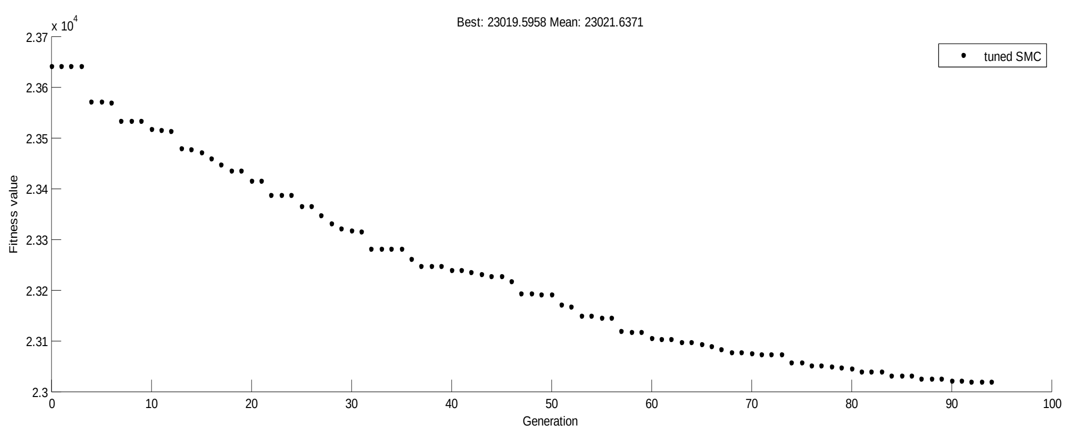

Figure 6: Chart the cost of the SMC

CONCLUSION

Parameters obtained for 4 types of controllers are described in the following table.

	K1	K2	K3	K4	p	q
Terminal sliding mode	1.36	1002.8	300.1	50000	0.45	0.91
Terminal sliding mode	400	1000	3000	50000	15	13
Sliding mode	100	500	10000			
Sliding mode	102.833	473.22	9.999			

After applying the above values, the following results are obtained.

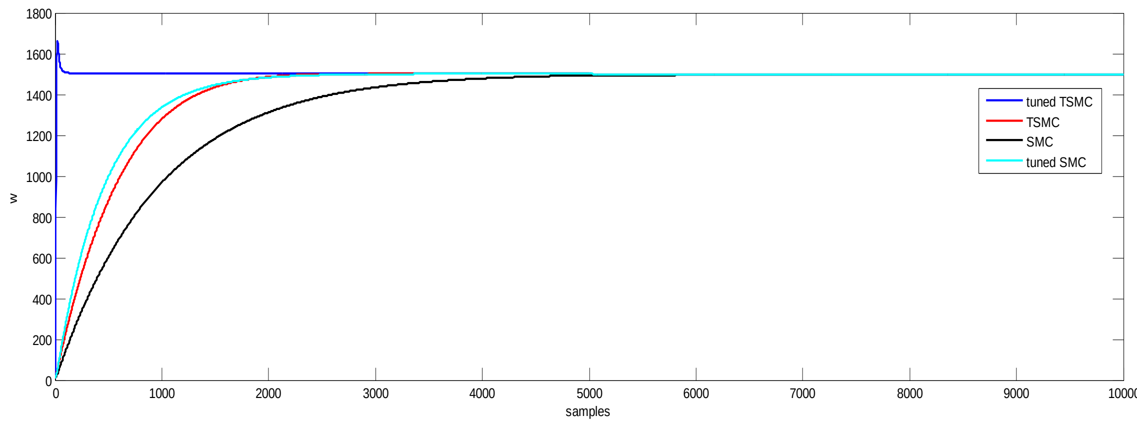

Figure 7: Output system w for 4 controller

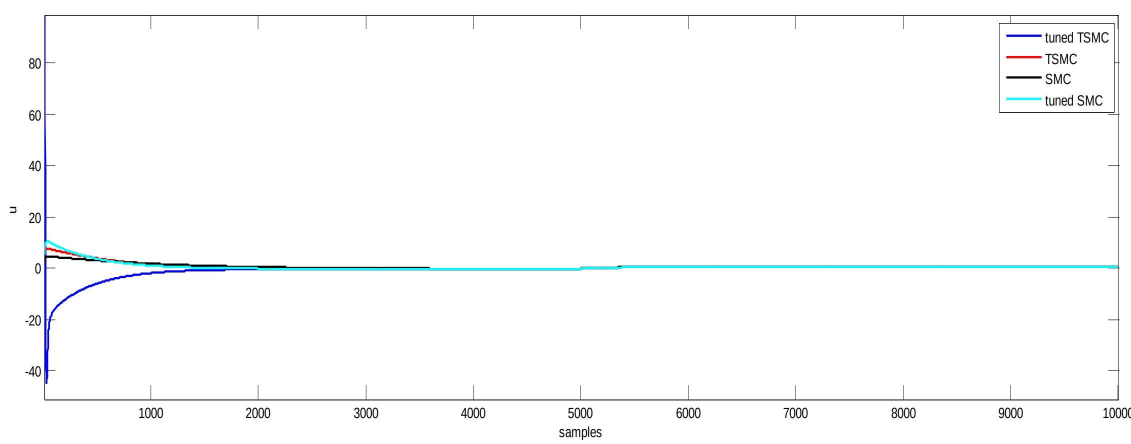

Figure 8: Control signal 4 controller

From the above results it is evident that the output of terminal sliding mode controller is configured to have fewer rising and settling time and also have no persistent error, so it is faster than three types of controller, but it has jump and larger control signal.

Obtained cost value for the controllers also indicates that the adjusted terminal controller has the cost far less. (The cost function is defined as LQG), therefore it shows that the adjusted controller is better, of course by increasing the number of algorithm iterations or changing the cost value likely can be achieved to the better responds.

REFERENCES

Fossard AJ and Floque T (2002). An Overview of Classical Sliding Mode Control.

French C and Acarnley P (1996). Control of permanent magnet motor drives using a new position estimation technique. *IEEE Transactions on Industry Applications* **32**(5) 1089–1097.

Hongyu S, Feng Y and Yu X (2010). Adaptive backstepping hybrid terminal sliding-mode control for permanent magnet synchronous motor. *In: Proceedings of the 11th International Workshop on Variable Structure Systems* 26–28.

Jamshidi Nima, Farzad Atousa and Pedar Behrad (2010). *Applied Guide to Simulink*, Paperback **23**.

Jinkun Liu and Xinhua Wang (2011). *Advanced Sliding Mode Control for Mechanical Systems*, ISBN: 978-3-642-20906-2 (Print) 978-3-642-20907-9.

Liang Qi and Hongbo Shi (2013). Adaptive position tracking control of permanent magnet synchronous motor based on RBF fast terminal sliding mode control. *Neurocomputing* **115** 23–30.

Nagasekhar Reddy P (2013). Modeling and Simulation of Space Vector Pulse Width Modulation based Permanent Magnet Synchronous Motor Drive using MRAS. *International Journal of Science and Modern Engineering (IJISME)* ISSN: 2319-6386 **1**(9).

Shihua Li, Mingming Zhou and Xinghuo Yu Fellow (2013). Design and Implementation of Terminal Sliding Mode Control Method for PMSM Speed Regulation System. *IEEE Transactions on Industrial Informatics* **9**(4).

Shihua LI, Mingming ZHOU and Xinghu YU (2011). Disturbance Observer Based Terminal Sliding Mode Control Method for PMSM Speed Regulation System. *Proceedings of the 30th Chinese Control Conference*, Yantai, China.

Shirzadi A (1389). The strucutre of transverse flux permanent magnet synchronous system and its application in propelling ships and submarines. *The Twelfth Conference on Maritime.*

Slotine Jean-Jacques E and Weiping LI (1991). *Applied Nonlinear Control* (Prentice Hall).

Yong Feng, Member Jianfei Zheng, Xinghuo Yu and Nguyen Vu Truong (2009). Hybrid Terminal Sliding-Mode Observer Design Method for a Permanent-Magnet Synchronous Motor Control System. *IEEE Transactions on Industrial Electronics* **56**(9).