

DIRECT TORQUE CONTROL BASED SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING NONLINEAR INFLEXIBLE SLIDING MODE TECHNIQUE

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Abstract: Now a days Permanent Magnet synchronous motors are widely used in industrial applications. In a reconfigurable assembling condition, control framework design needs creative ways to deal with face the fast changes in hardware and software modules. The control framework ought to have the capacity to naturally tune its parameters to upgrade machine exhibitions and powerfully adjust to various control destinations while preserving in the meantime stability and toughness properties. In this work, a powerful control framework for permanent magnet synchronous motors (PMSMs), together with an online self-tuning Nonlinear Inflexible Sliding Mode (NISM) technique, is exhibited. Mainly, a robust discrete-time Variable Structure Control (VSC) has been composed. An NISM approach has been then executed on a digital signal processor (DSP) to discover the VSC parameter set which limits a particular target work each time a different speed reference is given. The performance of Nonlinear Inflexible Sliding Mode methods was validated through simulation results. The design, analysis, and simulation of the proposed method are done using MATLAB Simulink environment. The simulation exhibitions alongside test consequences of the PMSM drive are considered for beginning, consistent state condition, speed inversion, and load perturbation. The test results demonstrate that the driving framework has an excellent unique reaction especially concerning torque swell and speed reaction..

Keywords: Field Oriented Control, Permanent Magnet Synchronous Motor, Nonlinear Inflexible Sliding Mode Controller, Matlab.

1.Introduction

The PMSM is a rotating electrical machine where the stator delivers a sinusoidal flux thickness circulation noticeable all around a hole, and the rotor has permanent magnets. From the most recent three decades AC machine drives are ending up increasingly mainstream, particularly PMSM Drives, however with some remarkable highlights, the PMSM drives are set up to meet refined necessities, for instance, quick, unique response, high power factor, and wide working rate run like world-class applications, as needs are, a moderate gain in the usage of PMSM drives

will undoubtedly be seen later on publicizing in low and mid power applications.

The execution of these motors in drive frameworks relies on the motor control and technique for observing in power converter. The method for motor control is noteworthy in the driving context. This is on account of the task of the PMSM under the impact of scalar control is experienced complicated coupling nonlinear dynamic execution. This issue can be unraveled by field arranged control (FOC) Field Oriented Control is the most well-known control method utilized with PMSMs. FOC procedure works quickly and gives the highest torque, full speed extends and fast increasing speed and deceleration by controlling the i_q and d_q streams for three-phase voltage supply in bringing down execution applications.

To change over the low voltage contribution to high voltage for motor coordination, the FOC is actualized with a voltage inverter. The ability of the inverter to modulate the voltage means the working scope of PMSM. The distinction in the information voltage pulse and the required modulation voltage are subject of PID controllers introduced in FOC controllers. There are many control strategies have been concentrated to control the speed of PMSM, for example, INFLEXIBLE control, PID control, wise control, and so forth. Vector control strategies have made conceivable the use of PMSM motors for elite applications where customarily just dc drives were connected.

The Vector control is otherwise called decoupling or field orientated control. Vector control decouples three phase stator current into two phase d-q hub current, one creating transition and other delivering torque. This permits coordinate control of motion and torque. So by utilizing vector control, the PMSM is equal into an independently energized dc machine. The model of PMSM is nonlinear. So by utilizing vector control, the

model of PMSM is linear. In this work to overcome the vector control issue by using NISM-VC technique. The rest of this work organized into five sections. In chapter one deals with introduction part followed by chapter two describes the literature survey about the PMSM control system. Proposed NISM three-phase PMSM control has discussed in chapter three, for section four briefly explain the result and discussion and finally section five deals with the conclusion.

2. Literature Survey: PMSMs have numerous favorable circumstances, for example, high effectiveness and power density, high torque-to-idleness proportion, and straightforward structure. The primary drawback of PMSMs is that flux and torque are inherent couplings, which makes them difficult to control. Many suggested control methods have been proposed to make PMSMs more practically identical. FOC and DTC are the two important control procedures for PMSM drives [1-2]. The FOC strategy is broadly utilized in PMSM drives. In any case, it performs not and additionally anticipated in consistent designing application because of the varieties of motor parameters and erroneous control mode [4]. In the 1980s, DTC algorithm [5] was right off the bat presented by ABB for induction motor drives. Decades past, it was at that point created and utilized for an assortment of motor drives.

Classical DTC approach, as a rule, embraces a proportional-integral (PI) speed controller, torque and flux hysteresis controllers, and heuristic switching table for creating a variable switching frequency [6-7]. This way, it can cause an inappropriate transient reaction with high overshoot, and also high torque and flux ripples when connected to PMSM drives. To tackle the previously mentioned issues of ordinary DTC, assortments of optimization techniques have been exhibited in the literature [8-10]. A considerable lot of them can get better outcomes in ripple decrease and settled switching frequency.

Be that as it may, the majority of them center around replacing hysteresis controllers [11,12], receiving space vector modulation (SVM) [7] and joining multilevel converter [13], hence including greater many-sided quality, computational weight, or equipment cost to DTC framework. Speed controller, more often than not been ignored, likewise assumes a critical job in DTC method for PMSM drives. A PI controller is broadly connected to in the external speed controller circle because of its relative necessary execution and adequacy [14]. In any case, the PI control approach can't perform adequately well in nonlinear PMSM drives framework with different vulnerabilities [15]. Moreover, it's time expanding and challenging to tune the proportional and integral gain parameters of

the PI controller. As of late, some new techniques have been proposed to supplant PID speed controller [16, 17].

DTC alongside Neuro-fuzzy control has been utilized for better execution and lessened flux and torque ripples [18]. The outcomes have been compared with customary DTC and DTC with Fuzzy logic control techniques [19]. The hysteresis torque limits and the flux reference for the proposed control methodology are produced utilizing the ANFIS control [20]. Permanent magnet synchronous motor (PMSM) is favored as a result of its better productivity, high torque to volume proportion, better over-burdening ability, and superb heat dissipation capacity over asynchronous motor [21]. It has found that the system has a problem of three-phase PMSM drive operation in all the above approaches So that a new advanced method has proposed in this work.

3. Materials And Method:

The block diagram of DTC utilized in this work appears in Figure. 1. Keeping in mind the end goal to encourage the examination of various control methodologies, speed control loop, and an NISM algorithm are used in the majority of the control plans incorporated into this work. The flux controller is a two-level comparator while the torque controller is a three-level comparator. As indicated by the stator flux position and the yield signals of hysteresis controllers, there exists an ideal voltage vector to be connected to the stator winding, which can limit the error of torque and stator flux in each control period. The determination of a perfect voltage vector is actualized, which requires three information sources and gives one yield. The three sources of info are desired stator flux variation, desired torque variation and the sector w that the real stator flux situated inside. The single output is the ideal voltage vector to be connected to the machine.

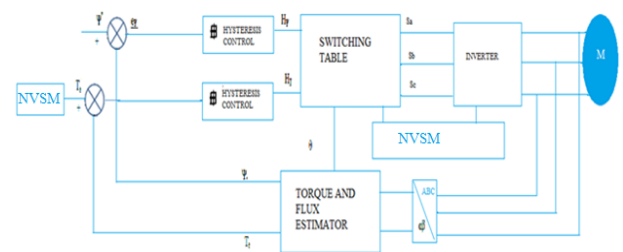


Figure 1: Block diagram of the proposed system

3.1 PMSM – Modelling : Permanent magnet synchronous motor has been generally contemplated for the two decades ago. In the greater part of strategies utilized for PMSM, there is an arrangement of conditions subject to rotor position. Speaking to the motor conditions in rotor

If that the point among stator and rotor field flux be kept at 90 Degree will have $i_d^*=0$. Along these lines, by this suspicion and $set_i_o=0$, deciding i_q prompts control the electrical torque specifically

$$T_e = \frac{3}{2} p \gamma_m i_q \dots (8)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \dots (1)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \dots (2)$$

Where

 $\theta =$ Rotor position. $\alpha, \beta = \text{Phase angle.}$

As indicated by what has specified over, and electromechanical conduct of the PMSM in the dq-outline is as per the following

$$V_q = Ri_q + \omega_r \gamma_d + \frac{d\gamma_q}{dt} \dots (3)$$

$$V_d = Ri_d + \omega_r \gamma_q + \frac{d\gamma_d}{dt} \dots (4)$$

$$V_o = Ri_o + \frac{d\gamma_o}{dt} \dots (5)$$

$$\gamma_q = L_q \dot{i}_q$$

$$\gamma_d = L_d i_d + \gamma_m$$

$$\gamma_o = L_o i_o$$

$$Te = \frac{3}{2}P(\gamma_m i_q + (L_d - L_q)i_d i_q) \dots (6)$$

$$\frac{d\omega_r}{dt} = \frac{P}{I} (T_e - B\omega_r - T_m) \dots (7)$$

3.2 PMSM – Speed Controller: The functional architecture of proposed NISM based PMSM speed control is demonstrates in following figure 2. This functional architecture different blocks like hysteresis current controller, stator current estimator, Voltage Source Inverter and Torque Limiter.

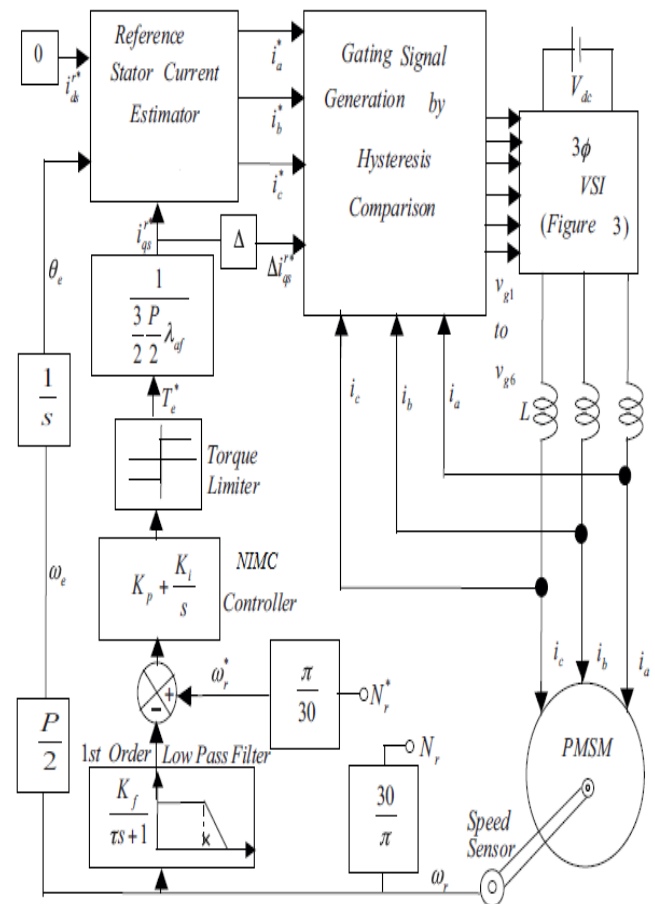


Figure 2: Block diagram of Speed Control system

To measuring the rotor speed based on NIMC controller response, the first order low pass filter is used remove the noise of rotor's output signal and in this proposed speed control system the reference speed value and rotor speed value is almost same. The steady error was calculated based on reference speed (w_r^*) and rotor speed (w_r) values. The output of NIMC which conformed to control the upper and lower restrains of the torque, in this manner was deliver perfect torque response (T_e^*). To complete the operation of Direct Torque Control by using NIMSC,

the reference coordinate axis current i_{ds}^* is zero, the i_{ds}^* and i_{qs}^* are gone through the backwards Park change block to create the stator three phase current references. Electrical rotor position θ_c feedback acknowledged by incorporating the electrical rotor speed ω_e is required with a specific end goal to produce the phase current references as appeared in Equation (9).

$$\begin{aligned} i_a^* &= i_{qs}^* \cos \theta_c + i_{ds}^* \sin \theta_c \\ i_b^* &= i_{qs}^* \cos \left(\theta_c - \frac{2\pi}{3} \right) + i_{ds}^* \sin \left(\theta_c - \frac{2\pi}{3} \right) \\ i_c^* &= i_{qs}^* \cos \left(\theta_c + \frac{2\pi}{3} \right) + i_{ds}^* \sin \left(\theta_c + \frac{2\pi}{3} \right) \dots (9) \end{aligned}$$

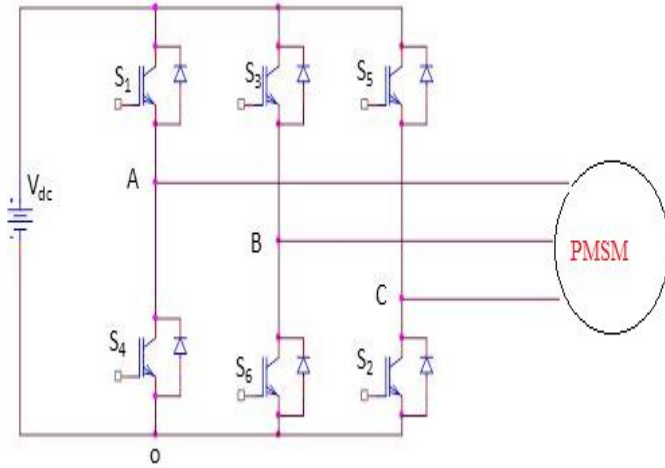


Figure 3: Voltage source Inverter of PMSM

The parameter Δ is the hysteresis band that moderates i_{qs}^* as appeared in Figure 2. The above figure 3 shows the circuit diagram of Voltage source inverter, in this inverter have six mosfet switches. Based on the gate pulse of this switches the motor speed was perfectly controlled through NISM based PWM generation. The PWM generation and algorithm steps of NISM is discussed in following section 3.3.

3.3 Nonlinear Inflexible Sliding Mode Technique For Three Phase PMSM Control:

In regular FOC, some facilitate changes are expected to change over PMSM current amount from AC to DC. The DC amount is considerably simpler to be controlled by NISM controller and be comprehended by instinct than AC amount. Park and Clarke's changes are utilized to change over AC amount to DC amount in regular FOC. In regular FOC, PMSM provided by three-stage AC voltage (ABC-stage) that will be transformed into two-stage AC voltage ($\alpha\beta$ -stage) by utilizing Clarke change. Stop change is expected to alter $\alpha\beta$ stationary organize into dq rotational facilitate. From Park change result, the two-stage AC amount is changed to two-stage DC amount. In ordinary FOC, two change processes, as well as the

inverses from the two changes for the fundamental control and input process, are utilized. The change procedure is enormous and takes a considerable measure of recollections in the calculation procedure.

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta & -\sin \theta \\ \cos \left(\theta - \frac{2\pi}{3} \right) & -\sin \left(\theta - \frac{2\pi}{3} \right) \\ \cos \left(\theta - \frac{4\pi}{3} \right) & -\sin \left(\theta - \frac{4\pi}{3} \right) \end{bmatrix} \dots (10)$$

$$\begin{bmatrix} a \\ b \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} -\sin \theta \\ -\sin \left(\theta - \frac{2\pi}{3} \right) \end{bmatrix} [q] \dots (11)$$

In vector control the organize change is remarkably decreased under the supposition of the d axis current, which is noted as the rotor flux component, is set to be zero. The Vector control idea can be gotten from both opposite Clarke and Park changes mix which is appeared as Equation (10) and decreased into Equation (11) when i_{ds} are set to be zero.

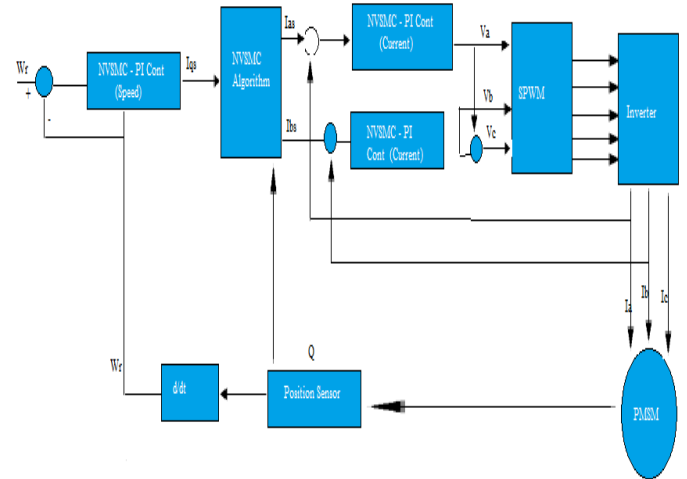


Figure 4: NISM of PMSM

The above Figure 4 demonstrates the NISM based PMSM motor speed control block diagram. The NISM method was decided for its great tracking ability and requests on the controllers. A short investigation of the NISM technique for plan of the current and speed controller has been made and the algorithm steps of NISM are discussed below

Step 1: Initialize weight matrices Q, R, P, and phase p.

Step 2: Measure the current state $x(k)$, i.e., $I_d(k)$, $I_q(k)$, and $\omega_r(k)$.

Step 3: Set phase $m = 1$.

Step 4: Choose candidate branch u_j in order from the discrete control set $\{S_0, S_1 \dots S_6\}$, where $j = 1, 2 \dots 7$, then calculate predictive node $x_j(k + m)$ by equation (11), finally $m = m + 1$.

Step 5: If $m < p$, go back to step 4); else, go to next step.

Step 6: Calculate the function $L(x, u)$ for each candidate branch u_j ($k + m - 1$) in order by equation (21), where $j = 0, 1 \dots 7$, then calculate the cost function J_{k+m} on the basis of $L(x, u)$ and previous $J * k+m+1$ (if $m = p$, $J * k+m+1 = 0$). Minimize J_{k+m} to select the optimal input u^* ($k + m - 1$) and determine suboptimal control signal sequence U^* ($k + m - 1$). Finally, $m = m - 1$.

Step 7: If $m \geq 1$, go back to step 6); else, go to step 8).

Step 8: Apply the first optimal input u^* (k) to the PMSM system.

End this algorithm.

3.4 EFFICIENCY ESTIMATION OF NISM

The efficiency of proposed NISM method based direct torque controlled PMSM was calculated by following equation.

$$G = \frac{\text{Output_Power } (P_{out})}{\text{Input_power } (P_{in})} \dots (12)$$

Input Power of the PMSM can be computed by the immediate currents and voltages, as indicated by the accompanying condition.

$$\text{Input}_{power} = \text{Input_Current} \times \text{Input_Voltage} \dots (13)$$

$$\text{Output}_{power} = T_{shaft} \times \text{Rotor_Speed} \dots (14)$$

Output power was calculated based on rotor speed and shaft responses and the mathematical expression of the output was estimated as in above equation 14.

4. RESULTS AND DISCUSSION:

In this results and discussion section give the performance analysis and simulation results of nonlinear Inflexible sliding mode based PMSM speed control. The simulation was developed by using Matlab software and the Specification of Permanent Magnet Synchronous Motor is listed in Table.1 and the following figure 6-10 shows the simulation results of PMSM speed control system.

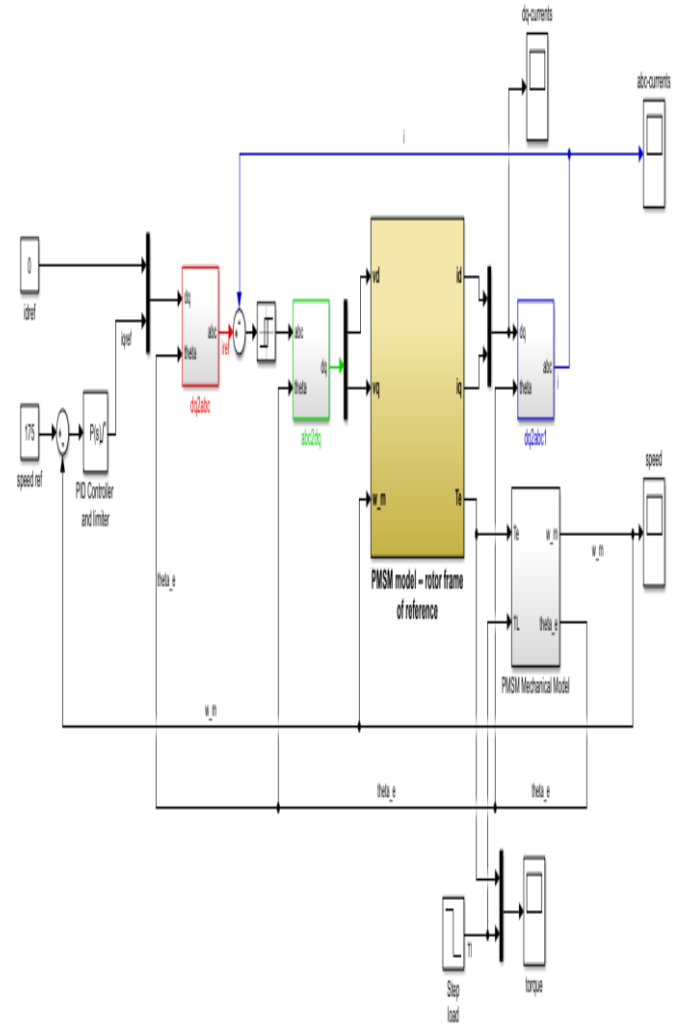


Figure 5: Simulink model of the proposed system

The above Figure 5 exhibits the Simulink model of the vector controlled a Permanent Magnet Synchronous Motor utilizing nonlinear Inflexible sliding mode control strategy. The accompanying Figures 6 to 9 delineates the simulation reaction of the proposed NISM framework.

Symbol	Description	Value
Rm	A resistance of the stator winding	12.01 ohm
Ld	D axis inductances	0.3119 henry
Lq	Q axis inductances	0.3119 henry

ϕ_m	A flux of permanent magnets	0.297ϕ
Pm	Pole pairs	4

Table 1: Parameters of PMSM

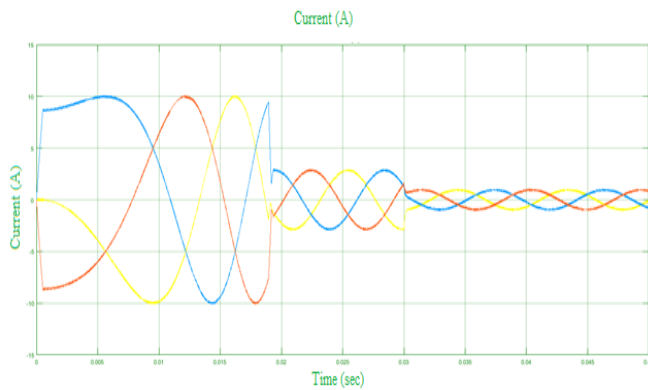


Figure 6: Current Response to the Proposed System

The above Figure 6 shows the rotor current reaction of the proposed Nonlinear Inflexible sliding mode based permanent magnet synchronous motor speed control drive framework.

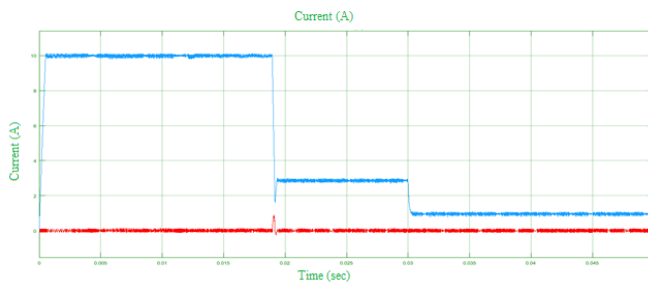


Figure 7: dq – Current response

The above Figure 7 shows the d-q axis currents response of the proposed PMSM control system using Nonlinear INFLEXIBLE Sliding mode control method.

The below-mentioned **Figure 8** determines the simulation outcomes of speed reaction in PMSM based on recommended Nonlinear INFLEXIBLE Sliding Model Controller

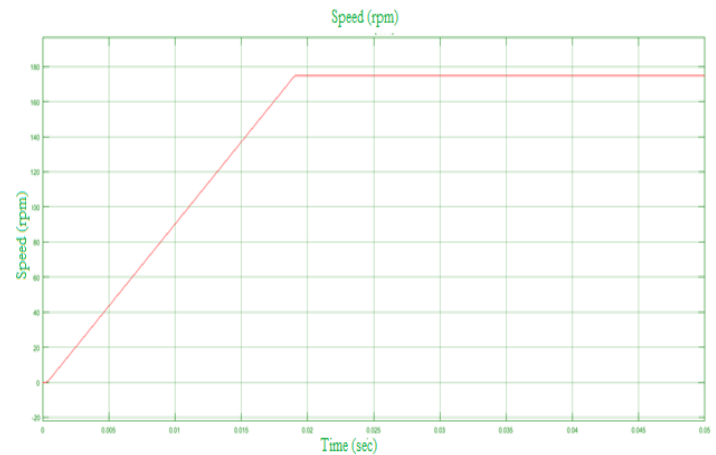


Figure 8: Speed Response of proposed NISM

The above-mentioned **Figure 8** determines the simulation outcomes of speed reaction in PMSM based on recommended Nonlinear INFLEXIBLE Sliding Model Controller

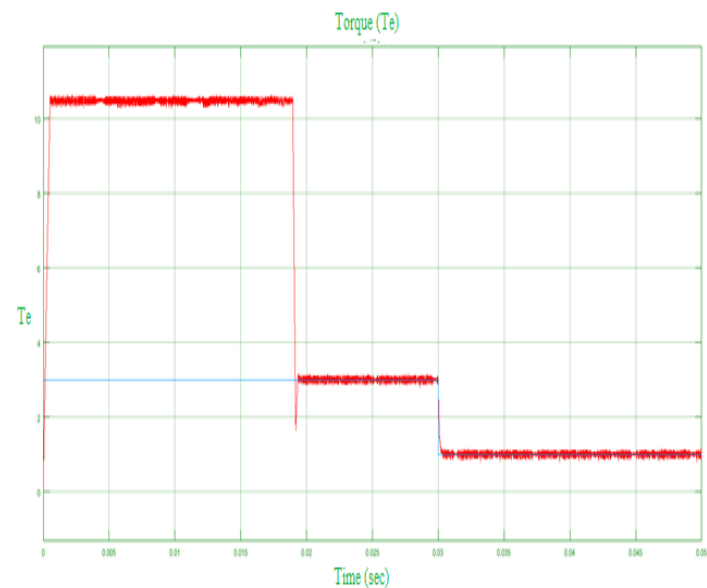


Figure 9: Torque response of PMSM

The speed response of PMSM with load change from full load to no load and control system parameter for both cases are provided in Table 2. When sudden load rejection occurs, speed will get increased and rise in speed is witnessed for all controllers except proposed controllers. For realistic load variation conditions, fuzzy online gain tuned for various controllers among this proposed NISM controller is performing the best controller than the other considered controllers.

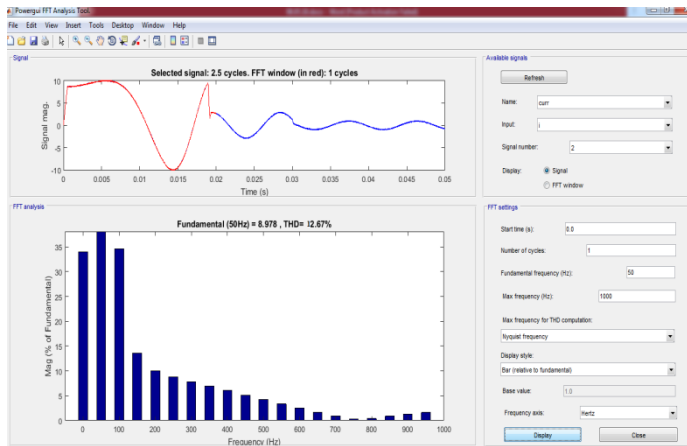


Figure 10: THD Result of Proposed System

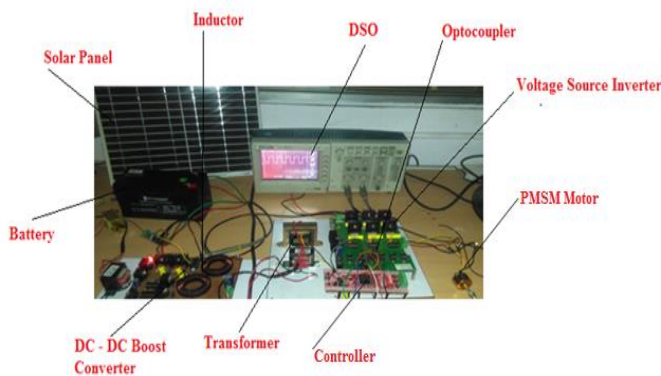
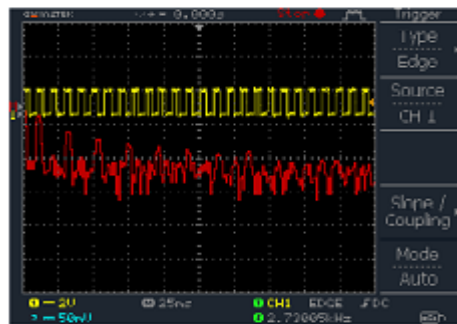
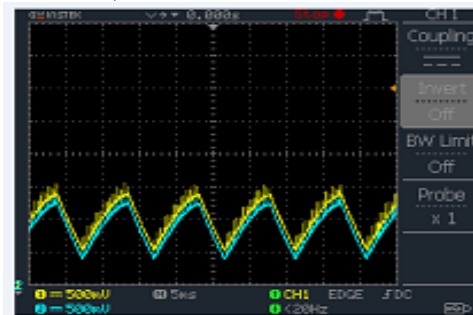


Figure 11: Hardware setup



a) Gate Pulse of MOSFET



b) Result of VSI

Figure 12: Hardware Result

The above figure 12 shows the FPGA based real-time implementation result of proposed NISM based PMSM control system. In this figure 12a shows the switching pulse response and 12b shows inverter response.

Methods	Peak time(sec)	Peak value(rpm)	Peak Overshoot (%)	Recovery time(sec)	Steady state error(rpm)	Steady state error (%)
PID	0.4417	1519.5	1.3025	0.46	10	0.666
FUZZY	0.4010	1516.5	1.1255	0.44	10.5	0.7
ANFIS	0.4002	1501.2	0.120	0.46	2.8	0.186
NVSM	0.842	750	0.0123	0.42	5.6	0.142

Table.2: Performance comparison for different methods

From the simulation results with different methods, the comparison was tabulated in **Table 2**. In this comparison result is clearly says that NISM based controller was produce the perfect result for example less rise time, settling time and maximum overshoot value.

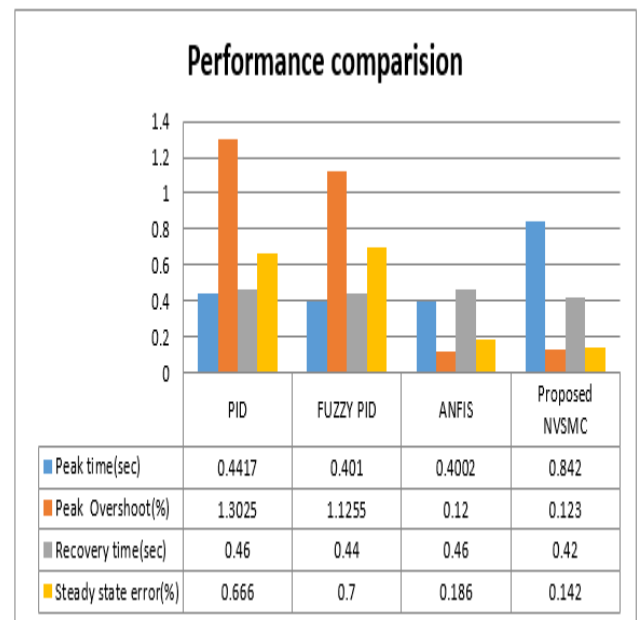


Figure 13: Performance comparison

The above figure 13 and table 2 shows the performance analysis result of proposed NISM based PMSM speed control system. Also, these controllers have produced less

steady state error than the other controllers. The proposed NISM controllers have outperformed the other considered controllers. In the controllers proposed for a PMSM, NISM controller has shown superior performance under all operating conditions.

5. CONCLUSION

Direct torque control is an effective method for controlling the operation of flux and torque without changing the reference speed. The Voltage source Inverter with DTC of PMSM can accurately control the flux and torque for this work using NISM method. In this examination work, Nonlinear Inflexible Sliding Mode controller can be utilized to fulfill the confinements on speed and torque. It very well may be inferred that DTC can be connected for the PMSM and is helpful for an extensive variety of speed. Applications which require great dynamic execution request DTC as it has a more prominent preferred standpoint over other control strategies on account of its property of quick torque reaction. The design, analysis, and simulation of the proposed method are done using MATLAB Simulink environment. The simulation exhibitions alongside test consequences of the PMSM drive are considered for beginning, consistent state condition, speed inversion, and load perturbation. The simulation and hardware results demonstrate the proposed NISM based controller was produce perfect result for all operating conditions. In this work perfectly increase the performance of simulation and hardware results produce for example less rise time, less settling time, maximum overshoot value and this system is produce the low steady sate error value of 0.146%.

REFERENCES:

1. Ke Song (2008): "Permanent Magnet Synchronous Motor Field Oriented Control and HIL Simulation" IEEE Vehicle Power and Propulsion Conference, Harbin and Pages:6-8
2. Y. Choi (2016): "Feedback linearization direct torque control with reduced torque and flux ripples for IPMSM drives " IEEE transaction on Power Electronics Drives, Volume: 31, Issue:5 and Pages:3728-3737
3. Y. Cho, K.-B. Lee, J.-H. Song, and Y.-I. Lee "Torque-ripple minimization and fast dynamic scheme for torque predictive control of PMSMS" IEEE transaction on Power Electronics Drive, Volume:30, Issue: 4 and Pages: 2182–2190
4. J. Kang, W.J. Meng, A. Abraham, H.B. Liu, An adaptive PID neural network for complex nonlinear system, Neuro computing 135, 79–85.(2014)
5. Xin Wang C. Steve Suh "Time-frequency based field oriented control of permanent magnet synchronous motors" International Journal of Dynamics and Control, June 2018, Volume 6, Issue 2, pp 663–678
6. Chai S(2013): "Model predictive control of a permanent magnet synchronous motor with experimental validation" Journal of Energy Control Practice, Volume: 21 ,Issue:11 and Pages: 1584–1593
7. Ananthamoorthy NP, Baskaran K (2015) High performance hybrid fuzzy PID controller for permanent magnet synchronous motor drive with minimum rule base. J Vib Control 21(1):181–194
8. Sivaprakasam A, Manigandan T (2015) An alternative scheme to reduce torque ripple and mechanical vibration in direct torque controlled permanent magnet synchronous motor. J Vib Control 21(5):855–871
9. Wang X, Suh CS (2016) nonlinear time-frequency control of PM synchronous motor instability applicable to electrical vehicle application. Int J Dyn Control 4(4):400–412
10. T. Tudorache, M. Popescu, "Optimal Design Solutions for Permanent Magnet Synchronous Machines", Advances in Electrical and Computer Engineering Journal, Vol. 11, No. 4, pp. 77-82, 2011.
11. J M. Bourogaoui, H. Ben AttiaSethom , I. SlamaBelkhodja. Real-time encoder faults detection and rotor position estimation for permanent magnet synchronous motor drives fault tolerant sensorless control using digital signal controller. Mathematics and Computers in Simulation, Vol 131, January 2017, pp. 253-267.
12. T.Orlowska (2014):" DTC and sliding-mode observer with a magnetizing reactance estimator for the field-weakening of the induction motor drive "Journal of Mathamatics and Simulation ,Volume :98 and Pages:31-44
13. M. Antchev, A. Tomova-Mitovska" Comparative Analysis of Hysteresis and Fuzzy-Logic Hysteresis Current Control of a Single-Phase GridConnected Inverter",American Journal of Electrical Power and Energy Systems, Vol 4, Issue 6, ,Dec. 2015,pp. 8-12.
14. Xin Cao, Qin Sun, Chenhao Liu, Heng Zhou, Zhiquan Deng, "Direct control of torque and levitation force for dual-winding bearing less switched reluctance motor",Electric Power Systems Research, Volume 145, April 2017, pp. 214-222
15. O. Ouledali, A. Meroufel, P. Wira, S. Bentouba, "Direct Torque Fuzzy Control of PMSM based on SVM "Energy Procedia, Vol 74, August 2015,pp. 1314-1322.
16. H.Bouzeriaa C.Fetha "Fuzzy Logic Space Vector Direct Torque Control of PMSM for Photovoltaic Water Pumping System" Energy Procedia, Volume 74, August 2015, Pages 760-771
17. B.Bossoufim (2011): "DTC control based artificial neural network for high performance PMSM drive" Journal of Theoretical and Applied Information Technology ,Volume :33 ,Issue:2 and Pages: 165-176

18. Moulay Tahar Lamchich, "Torque Control," Publisher: InTech, chapters published February 10, 2011 under CC BY-C-SA 3.0 license.
19. Sampath Kumar, A & Vivekanandan, P 2018, 'Gene Selection Using Multiple Queen Colonies In Large Scale Machine Learning', Journal of Electrical Engineering, vol. 18, no. 4, pp. 97-111. ISSN: 1582-4594
20. Frank L. Lewis, PHD. "Neural network control of nonlinear discretetime systems" Published by CRC Press Taylor & Francis Group, 2006.
21. Bennassar, A Abbou, M Akherraz, and M. Barara, "A comparative study of I P, fuzzy logic and sliding mode controllers in a speed vector control of induction motor" International Review on Modelling and Simulations, vol. 6, n. 6, pp. 1865-1871,2013.