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Adaptive Neuro-Fuzzy Sliding Mode Controller (ANF-SMC) to control speed, electromagnetic torque (EMT), Stator Current, and Back EMF using PMBLDCmotor(PMBLDCM) in Electric Propulsion of Electric Vehicles

***Abstract**. In present days conventional vehicles were replaced by electric vehicles due to their low maintenance and eco-friendly nature with PMBLDCM motor due to its simple design, long-term usage, low noise, speed response, stability, and high efficiency. In electric vehicles, the speed control method is still difficult with PMBLDC motor to produce the desired high torque and to deal with uncertainty problems due to dynamic loads which cannot apply in conventional vehicles. To overcome these problems, we proposed the usage of Adaptive Neuro-Fuzzy Sliding Mode Control (ANF-SMC) which also handles electromagnetic torque (EMT), back EMF and stator current, nonlinear and uncertainties in the electric propulsion subsystem of electric vehicles by applying adaptive neuro-fuzzy sliding mode control for effective speed regulation and parameter tuning of the fuzzy system based on performance index of PMBLDC motor in the absence, presence and variable speed conditions. The simulation was done using the designed approach with MATLAB/Simulink R2020b with a Fuzzy tool kit and the performance of the proposed controller was compared with existing PID, SMC, FSMC, and AFSMC controllers to validate its success in improving the system characteristics. Simulation results infer that the proposed ANF-SMC controller with no overshoot and less rise, peak, and settling time than that of existing systems under different loads and variable speed conditions.*

***Streszczenie.** W dzisiejszych czasach pojazdy konwencjonalne zostały zastąpione pojazdami elektrycznymi ze względu na ich niskie koszty utrzymania i przyjazny dla środowiska charakter z silnikiem PMBLDCM ze względu na jego prostą konstrukcję, długotrwałe użytkowanie, niski poziom hałasu, szybkość reakcji, stabilność i wysoką wydajność. W pojazdach elektrycznych metoda sterowania prędkością jest nadal trudna w przypadku silnika PMBLDC do wytworzenia pożądanego wysokiego momentu obrotowego i radzenia sobie z problemami niepewności wynikającymi z obciążeń dynamicznych, których nie można zastosować w konwencjonalnych pojazdach. Aby przezwyciężyć te problemy, zaproponowaliśmy wykorzystanie Adaptacyjnego Neuro-Fuzzy Sliding Mode Control (ANF-SMC), który obsługuje również moment elektromagnetyczny (EMT), wsteczną siłę elektromotoryczną i prąd stojana, nieliniowość i niepewności w podukładzie napędu elektrycznego pojazdów elektrycznych poprzez zastosowanie adaptacyjne sterowanie trybem ślizgowym neuro-fuzzy w celu efektywnej regulacji prędkości i strojenia parametrów systemu rozmytego na podstawie wskaźnika wydajności silnika PMBLDC w warunkach nieobecności, obecności i zmiennej prędkości. Symulacja została przeprowadzona przy użyciu zaprojektowanego podejścia z MATLAB/Simulink R2020b z zestawem narzędzi Fuzzy, a wydajność proponowanego kontrolera została porównana z istniejącymi kontrolerami PID, SMC, FSMC i AFSMC, aby potwierdzić jego sukces w poprawie charakterystyki systemu. Wyniki symulacji wskazują, że proponowany sterownik ANF-SMC nie ma przeregulowania i ma krótszy czas narastania, wartości szczytowej i ustalania niż w istniejących systemach przy różnych obciążeniach i warunkach zmiennej prędkości.* (**Adaptacyjny kontroler trybu ślizgowego Neuro-Fuzzy (ANF-SMC) do sterowania prędkością, momentem elektromagnetycznym (EMT), prądem stojana i wsteczną siłą elektromagnetyczną za pomocą silnika PMBLDCmotor (PMBLDCM) w napędzie elektrycznym pojazdów elektrycznych**)

Keywords: Adaptive Fuzzy SMC, Adaptive-neuro Fuzzy SMC, Fuzzy SMC, Permanent Magnet Brushless DC Motor.
Słowa kluczowe: kontroler adaptacyjny, logika rozmyta, bezszczotkowy silnik prądu stałego.

1. Introduction

Drastically change in vehicle technology is essential due to the crisis of the automotive industry because of high oil prices and outdated designs. Electric and hybrid electric vehicles are optimal solutions due to advancements in electric machines, power electronics, and artificial intelligence control mechanisms. More significance is given to research on Power Propulsion systems in electric vehicles in the automobile industry. In EV driving systems irrespective of model, parameter variation and any load disturbances the motor speed should follow a specified reference trajectory. In addition to this, it should also cover constant torque and power regions. In electric vehicles where space and weight place an important role, the use of Permanent Magnet Brushless DCMotor (PMBLDCM) is the best choice and also more suitable for high power density design. PMBLDCM motors with greater influence because of their simple design, long-term usage, low noise, and electromagnetic interference, speed response and stability, high efficiency, and high applied output torque. PMBLDC motor works with high efficiency in electric vehicle propulsion systems achieved due to the elimination of secondary losses and with simpler rotor cooling. PMBLDC motor drive and its controller plays a crucial role to reduce cost and weight in the conversion of existing conventional vehicles to electric vehicles [1, 2, 3, 4, 5], and in designing new electric vehicles. The usage of PMBLDC motors in electric vehicles is not optimal due to varied set points when passing the incline. Many existing controllers such as PID [6, 7, 8 to 10], NAFLC, and AFLC were referred to improve the PMBLDC motor drive performance. In dynamic load conditions quick response, and settling time with zero overshoot are important characteristics of a good controller, which cannot be achieved with conventional controllers. In the case of conventional controllers such as PI and PID, the response will be slower with a variable set point. These controllers were inefficient in case of higher order, nonlinear, time delay, and complex systems without an accurate mathematical model. Disadvantages of conventional controllers were overcome with the usage of SMC, NAFLC, AFLC, and NNC using individually or hybrid together. To deal with inaccurate mathematical models' fuzzy logic control (FLC) is used for speed control of the PMBLDC motor by generating required control commands. However, to solve the fuzzification and defuzzification processes of FLC time requirement is greater than conventional controllers. In the case of neural network control (NNC), performance results of PMBLDC motor speed were affected by uncertainty and load disturbances. To overcome these disadvantages Sliding Mode Control (SMC)is widely used in the control of PMBLDC motors because of its simple structure, easy implementation, fast response, and ability to handle parametric uncertainties. To achieve low overshoot, small rise, and settling time, performance with a better steady response system in PMBLDC motor hybrid control techniques were widely used. In previous studies Fuzzy tuned PID (FPID) or NAFLC, AFLC, ANFIS [11, 12], Sliding Mode Control, FSMC [13], Adaptive], and NFSMC control schemes were used in BLDC motor for generating fast response and high efficiency[14 to 16]. In the case of Fuzzy PID control speed response obtained during load variations exhibit over and undershoot. Incontroller, to train the FLSC reference plant model is needed. In the study of existing controllers, the simulation and experimental results indicate the parameters especially concentrated on load disturbances. To overcome limitations faced by existing conventional controllers, the proposed method PMBLDC motor is used to predict back electromagnetic force and to reduce uncertainty under dynamic load conditions. Adaptive Neuro-Fuzzy Sliding Mode Controller (ANF-SMC) to PMBLDC motor proposed in this work by taking salient features of ANN, FL with SMC to reduce uncertainty and load disturbance generated by PMBLDC motor in EVs. The proposed ANF-SMC controller is used to compensate limitations of SMC, to enhance the online adaption ability of the system with the minimum number of user-defined rules, and to overcome the uncertainty problem. In the implementation of the work the mentioned steps were done:

- To design ANF-SMC toPMBLDC motor in EVs.
- Simulate dynamic responses of the proposed ANF-SMC for different load conditions.
- Comparing simulation results obtained speed, EMT, stator current, and back EMF values by the proposed controller with existing conventional controllers used in EVs.
- Validating the proposed ANF-SMC controller in the improvement of the system.

In this paper section 1 deals with an introduction, section 2 describes the used electric drive train, mathematical model, and speed controller simulation of PMBLDC, section 3 explanation on the design of the proposed controller, section 4 deals with simulation and comparative simulation results under different load conditions and conclusion part in section 5.

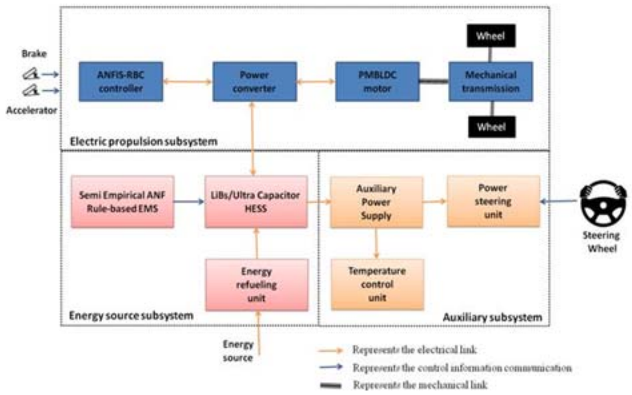


Fig. 1. Description of electric drive train used in EV configuration

2. PMBLDCM Motor

2.1 Explanation of used electric drive train

The used electric drive train is represented in Fig. 1.which consists of an electric propulsion subsystem with ANF-RBC controller, power converter, Permanent Magnet BLDC motor with ANF-SMC controller, and mechanical transmission. The energy source subsystem consists of Lithium Ion Battery [2] /Electro Chemical Double Layer Capacitors Hybrid Electrical Energy Storage System (LiBs/ECDLCs-HEESS), an energy refueling unit, and a semi-empirical Adaptive Neuro-Fuzzy Rule Based Energy Management System. The auxiliary subsystem consists of temperature control, power steering, and an auxiliary power supply unit. Based on input from the brake and accelerator in EVs, the ANF-RBC controller produces a control signal to the used power converter by regulating power flow in between the PMBLDC motor and used hybrid electrical energy storage system (LiBs/ECDLCs-HEESS). In the electric propulsion subsystem to reduce uncertainty and load disturbance generated by the PMBLDC motor, a hybrid control approach is used in the ANF-SMC controller. This hybrid electrical energy system possesses the ability to accept regenerated energy with the cooperation of the proposed controller.

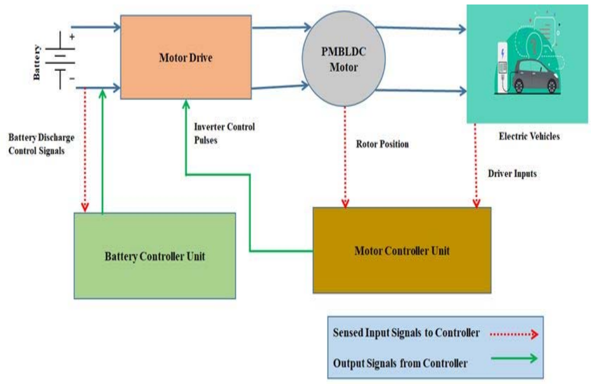


Fig. 2. Block diagram of PMBLDC Motor Driving

2.2 PMBLDC Motor Mathematical Model

PMBLDCM is a three-phase synchronous machine with PM rotor wiring distributed with 120^0 in connection stator with Y connection and equal resistance R in each phase has trapezoidal back EMF [17, 18, 19] waveform. Fig. 2. represents PMBLDC Motor Driving System.
PMBLDC motor phase voltage represented by equation 1

(1) $$V = R * I + S * \frac{d}{dt} * I + E$$

Phase voltage applied (V)= $[V_a V_b V_c]^T$
Stator Resistance (R)=*diag*[R]
Phase Current (I) = $[I_a I_b I_c]^T$ and
back EMF voltage (E) = $[e_a\ e_b\ e_c]^T$ for PMBLDCM respectively.
Inductance matrix S is represented as equation 2

(2) $$S = \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix}$$

Where self-inductance (L) and mutual inductance (M) of PMBLDC motor.
Based on phase current and Back EMF, the EMT of PMBLDC is represented by equation 3

(3) $$T_{emf} = \frac{e_a I_a + e_b I_b + e_c I_c}{w_m}$$

Where T_{emf} is the EMT of the PMBLDC motor and ω_m is the angular velocity
Mathematical model of PMBLDC motor found by using T_{load}, J, and $V_{fr.}$
Motor motion is represented as equation 4

(4) $$T_{emf} - T_{load} = J \frac{d\omega_m}{dt} + V_{fr}$$

The mechanical speed of the rotor (ω_m) is calculated as in equation 5

(5) $$\omega_m = \int \frac{T_{emf} - T_{load} - V_{fr\omega_m}}{J} dt$$

Current to the stator windings are shown as equation 6

(6) $$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} \sin(\omega_r t + \alpha) \\ \sin\left(\omega_r t + \alpha - \frac{2\pi}{3}\right) \\ \sin\left(\omega_r t + \alpha + \frac{2\pi}{3}\right) \end{bmatrix} I_{max}$$

Where maximum current applied (I_{max}), angle difference (α) and rotor electrical speedω_r.

2.3 PMBLDCM Motor Speed Controller and Simulation Description

Fig. 3.described the PMBLDCM speed control simulation using an ANF-SMC controller. The described circuit has a closed loop to control the speed using DC bus voltage with the inverter. The control signal and switching logic given to the three-phase voltage inverter generated a signal of feedback error and reference speed given to the controller block.

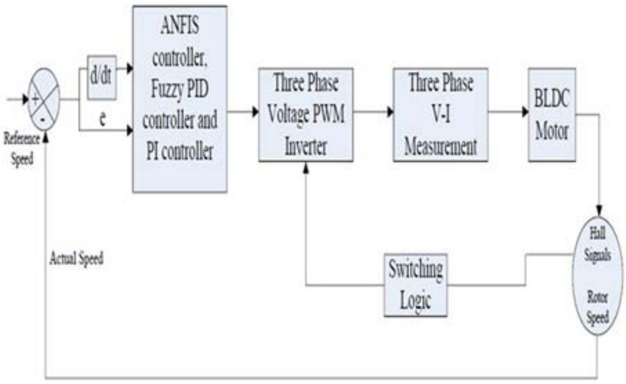


Fig. 3. Description of PMBLDC Motor Speed Controller simulation

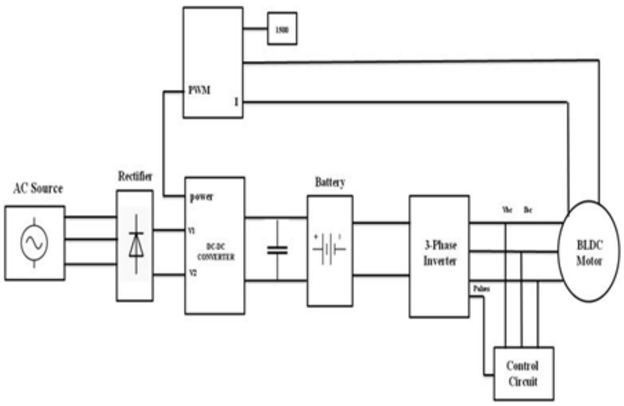


Fig. 4. Description of PMBLDC motor simulation

Fig. 4. described PMBLDCM simulation using an ANF-SMC controller. The described circuit has a closed loop to control speed, EMT, back EMF, and stator current using PMBLDCM with the source of current, controller, rectifier, and three-phase inverter and their connections as shown in the figure.

3. Control Design

3.1 PID Architecture

PID Control is linear and symmetric with constant parameters and employs feedback by combining advantages of dependent, independent, and inconsistent systems governed by nonlinear differential equations as shown below gives a quicker response time which is represented in Fig. 5. The main limitation of SMC controller is that we cannot use when the system has two elements competing, noise is present in controllers' response.

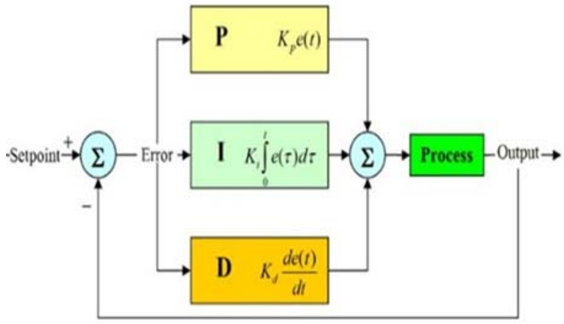


Fig. 5. PID Control Simulation Diagram

InTable1. And Table 2. truth tables of Gates used; Decoders used in the PID controller were shown respectively.

Table 1. Truth-Table of Gates used in PID Controller

emf_a	emf_b	emf_c	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

Table 2. Truth-Table of Decoder used in PID Controller

ha	ha	ha	emf_a	emf_b	emf_c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	+1	0
0	1	1	-1	0	+1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	+1	-1
1	1	1	0	0	0

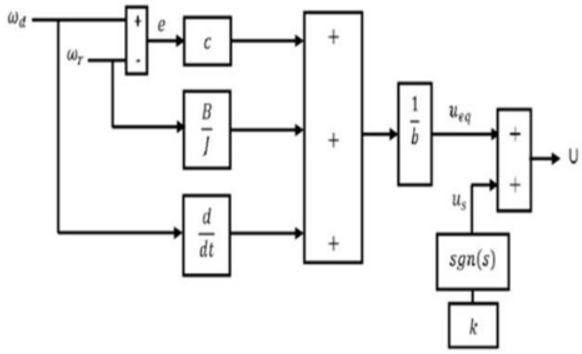


Fig. 6. SMC Control Simulation Diagram

3.2 SMC Architecture

Sliding Mode Control is a nonlinear discontinuous approach governed by ordinary differential equations characterized by various parameters and designed by considering sliding hypersurface and suitable control law. The main aim of this controller is to control the speed of the PMBLDC motor for desired value tracking even in presence of disturbances; it also combines maximum torque with vector control strategy represented in Fig. 6.and its sub-system in Fig. 7. The main limitation of SMC controller is the chattering problem. The figure describes the simulation and sub-system of SMC control.

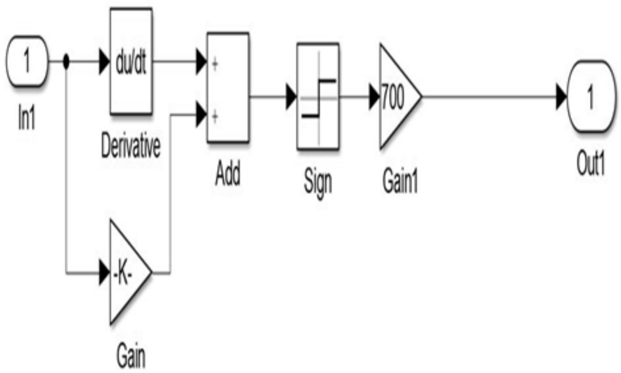


Fig. 7. Sub System of SMC Simulation

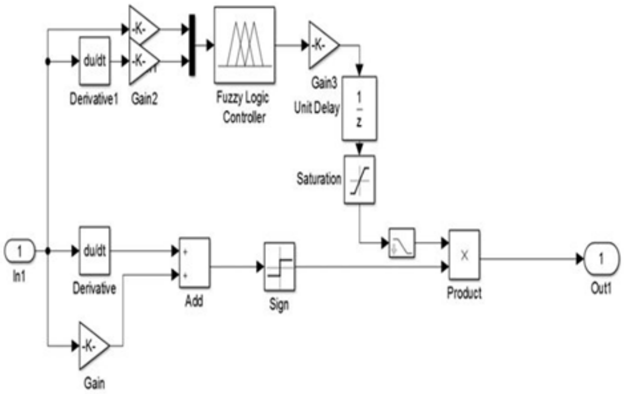


Fig. 8. Sub-System of FSMC Simulation

3.3 FSMC Architecture

To overcome the main drawback of sliding mode control chattering phenomena Fuzzy Sliding Mode Control (FSMC) scheme is used to improve system performance with speed compensation. This architecture combines SMC used to improve system robustness and fuzzy logic control to increase the learning ability by providing better damping and reduced chattering effect. Fig. 8.shows the block diagram representing the PMBLDCM controller's subsystem. In Table3. fuzzy rules used in the FSMC controller are described.

Table 3. The table describes fuzzy rules used in FSMC

e/e	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5	5	5	5	5	5	5	4	3	2	1	0
-4	5	5	5	5	5	4	3	2	1	0	-1
-3	5	5	5	5	4	3	2	1	0	-1	-2
-2	5	5	5	4	3	2	1	0	-1	-2	-3
-1	5	5	4	3	2	1	0	-1	-2	-3	-4
0	5	4	3	2	1	0	-1	-2	-3	-4	-5
1	4	3	2	1	0	-1	-2	-3	-4	-5	-5
2	3	2	1	0	-1	-2	-3	-4	-5	-5	-5
3	2	1	0	-1	-2	-3	-4	-5	-5	-5	-5
4	1	0	-1	-2	-3	-4	-5	-5	-5	-5	-5
5	0	-1	-2	-3	-4	-5	-5	-5	-5	-5	-5

3.4 AFSMC Architecture

Lack of design technique is the limitation of FSMC; for the same performance of system fuzzy rules varies and selecting suitable membership functions is also difficult. To overcome these limitations AFSMC is used. Fig. 9.shows the block diagram representing the AFSMC controller's subsystem. In Table4. fuzzy rules used in the AFSMC controller are described.

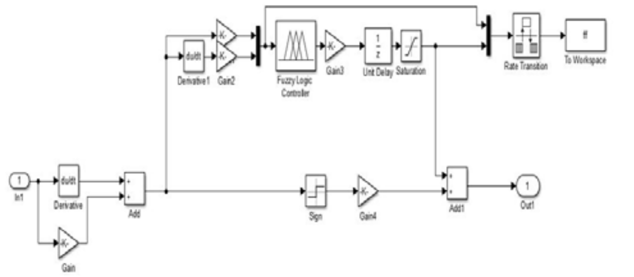


Fig. 9. Sub System of AFSMC Simulation

Table 4: The table describes fuzzy rules used in AFSMC

e/e'	NB	NS	Z	PS	PB
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PB	NS	Z	PS	PB	PB
PS	Z	PS	PB	PB	PB

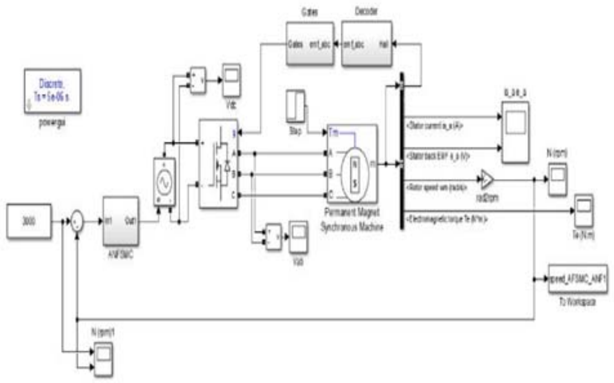


Fig. 10. ANF-SMC Control System Diagram

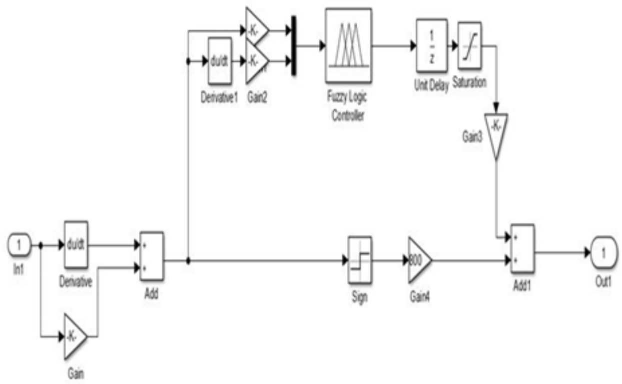


Fig. 11. ANF-SMC Control Subsystem Diagram

Table 5. ANF-SMC Fuzzy Rule for e/ė

e/e	-5	-4	-3	-2	-1	0	1	2	3	4	5
-5	5	5	5	5	5	5	4	3	2	1	0
-4	5	5	5	5	5	4	3	2	1	0	-1
-3	5	5	5	5	4	3	2	1	0	-1	-2
-2	5	5	5	4	3	2	1	0	-1	-2	-3
-1	5	5	4	3	2	1	0	-1	-2	-3	-4
0	5	4	3	2	1	0	-1	-2	-3	-4	-5
1	4	3	2	1	0	-1	-2	-3	-4	-5	-5
2	3	2	1	0	-1	-2	-3	-4	-5	-5	-5
3	2	1	0	-1	-2	-3	-4	-5	-5	-5	-5
4	1	0	-1	-2	-3	-4	-5	-5	-5	-5	-5
5	0	-1	-2	-3	-4	-5	-5	-5	-5	-5	-5

3.5 ANF-SMC Architecture

In the case of the AFSMC control scheme, it is difficult to state rules or to tune the rule-base parameters as it could arise to tune. To overcome all these limitations of existing controllers in our work we proposed a control scheme with ANMF with sliding mode control named ANF-SMC to PMBLDC motor and its sub-system. Simulink model and its subsystem of PMBLDC implemented with MATLAB/Simulink R2020b with Takagi Sugano fuzzy toolkit as shown in Fig. 10.and its subsystem inFig. 11. In Table 5. fuzzy rules of **e/ė** used in ANF-SMC controller is described.

4. Simulation Results

In Table6.**PMBLDCM Specifications** were described.

Table 6. PMBLDCM Specifications

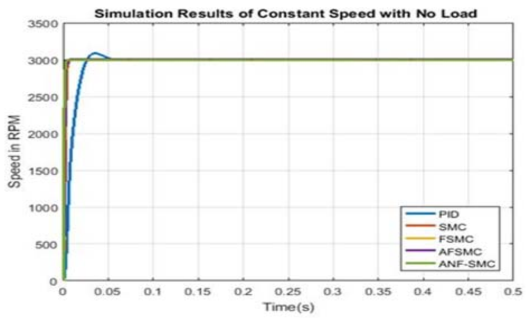
Parameters	Values
Stator Phase Resistnce Rs (Ohms)	2.8750
Stator Phase Resistnce Ls (H)	$8.5e^{-3}$
Back EMF Flat Area(degrees)	120
Inetia ($Kg.m^2$)	$0.08e^{-3}$
Viscous Damping (N.m.sec)	$1e^{-3}$
Poli Pairs	4
Flux Linkage established by magnets (V.s.)	0.175
Voltage Constant (V_peak L-L/krpm)	146,6077
Torque Constant (N.m/A_peak)	1.4

4.1 PMBLDC Motor Comparative Simulation Results of Speed, EMT, Stator Current, and BackEMF with Constant Speed and no load condition

4.1.1 Speed

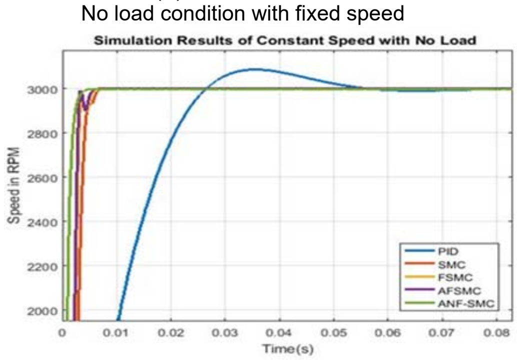
Comparative simulation results of the ANF-SMC controller with the other four controllers with a constant speed of 3000RPM under no load condition with a time of 0 to 0.5 seconds are shown in the following diagram. Simulation With these results we can infer that the proposed controller takes very less time when compared to other controllers which are shown in the zoomed diagram.

Simulation Results



(a) Simulation Results

No load condition with fixed speed

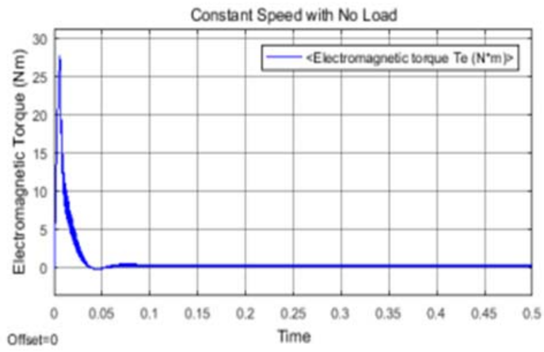


(b) Zoom Diagram

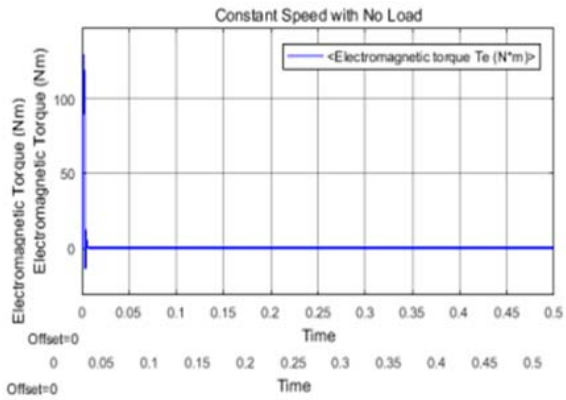
Fig. 12. Comparative results under no load with fixed speed Condition

4.1.2 EMT, Stator Current, and Back EMF

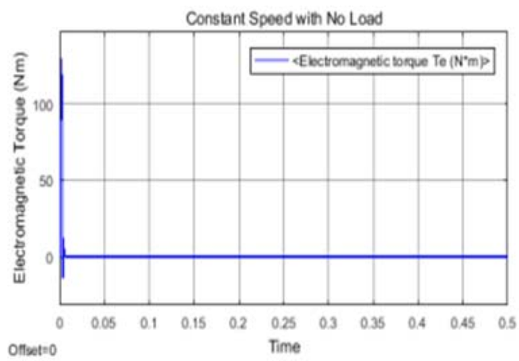
Comparative simulation results of ANF-SMC controller with other four controllers with a constant speed of 3000RPM under no load condition with time 0 to 0.5 seconds. With these simulation results, we can infer that the proposed controller takes a very Electro Magnetic Torque (EMT) value of 32Nm within less time when compared to other controllers shown in Fig. 13.



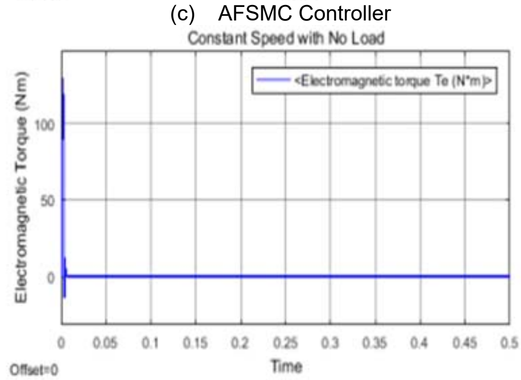
(a) PID Controller



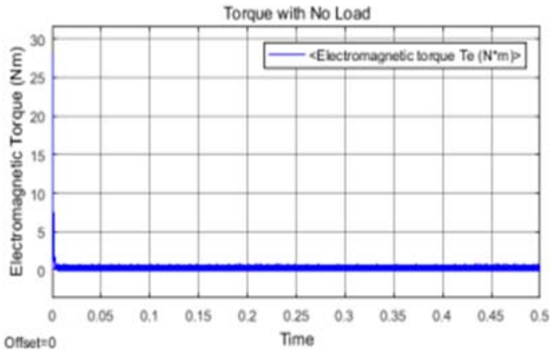
(b) SMC Controller



(c) AFSMC Controller



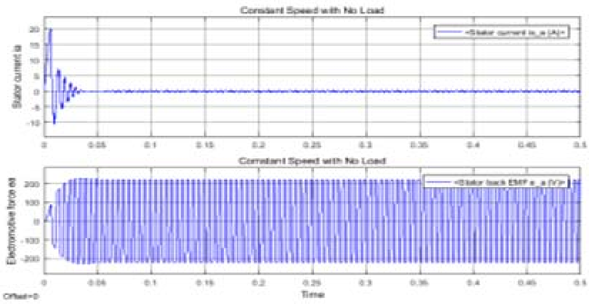
(d) ANF-SMC Controller



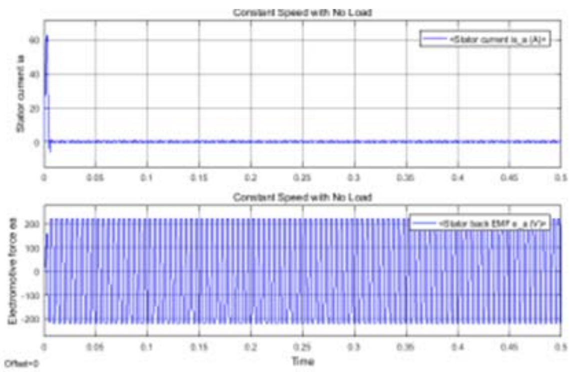
(e) ANF-SMC Controller

Fig. 13. Comparative Simulation results of five controllers EMT vales with no load, constant speed condition

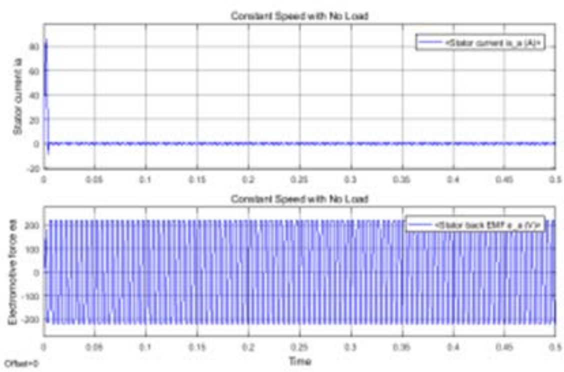
Comparative simulation results of ANF-SMC controller with other four controllers with a constant speed of 3000RPM under no load condition with time 0 to 0.5 seconds. With these simulation results, we can infer that the proposed controller takes very less stator current of 14A in very less time, constant back EMF irrespective of the time when compared to other controllers which are shown in Fig. 14.



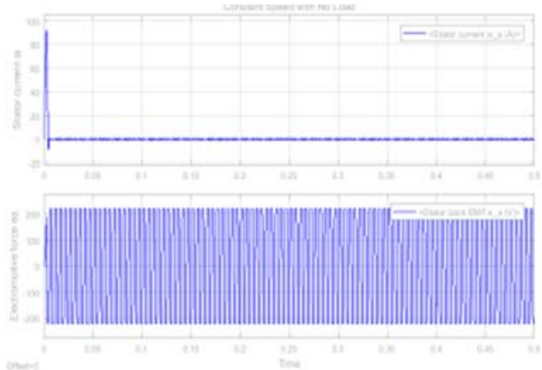
(a) PID Controller



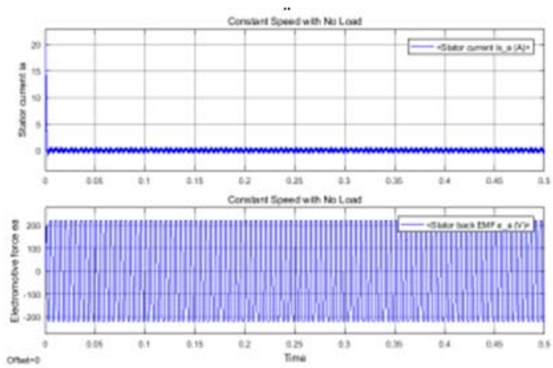
(b) SMC Controller



(c) FSMC Controller



(d) AFSMC Controller



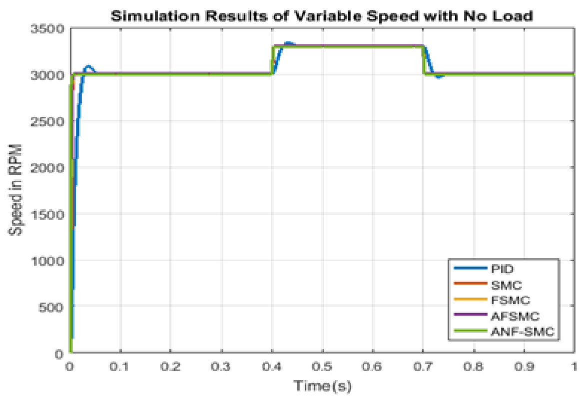
(e) ANF-SMC Controller

Fig. 14. Comparative Simulation results of five controllers stator current and back EMF vales with no load, constant speed condition

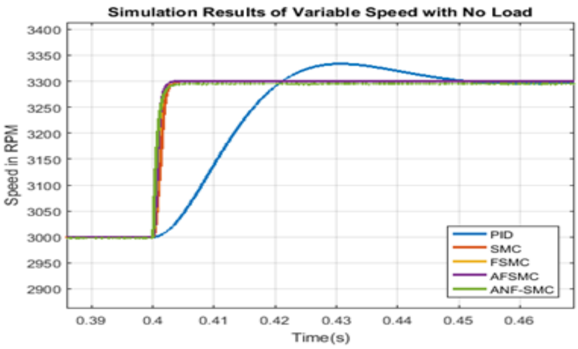
4.2 PMBLDC Motor Comparative Simulation Results of Speed, EMT, Stator Current, and BackEMF with variable speed and no load condition

4.2.1 Speed

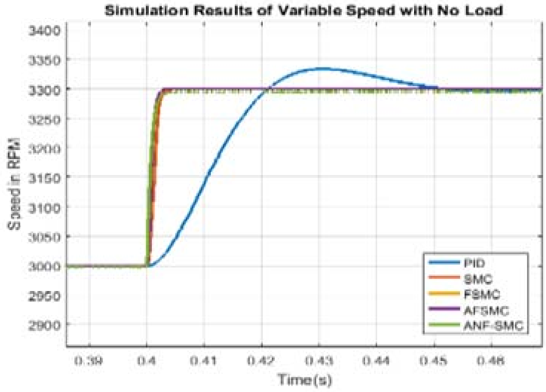
Comparative results of the proposed ANF-SMCwith other four controllers with variable speeds of 3000RPM to 3300RPM under no load condition with time 0 to 1.0 seconds shown in the following Fig. 15. From these results infer that the proposed controller takes very less time when compared to other controllers in both the cases which were shown from zoom1 to zoom3 diagrams.



(a) No load condition with variable speed



(b) Zoom1 Diagram



(c) Zoom2 Diagram

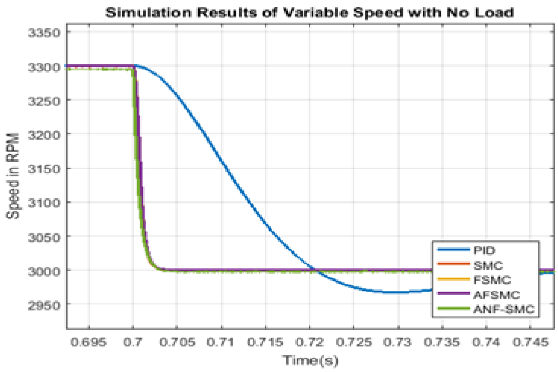
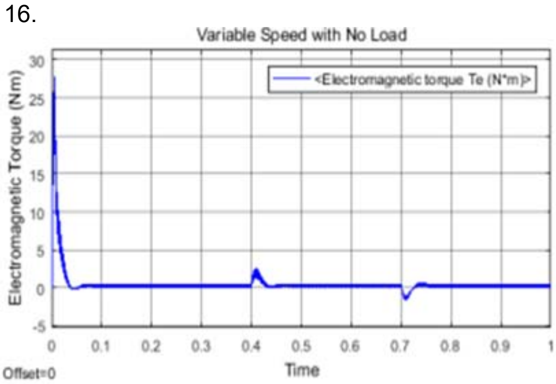


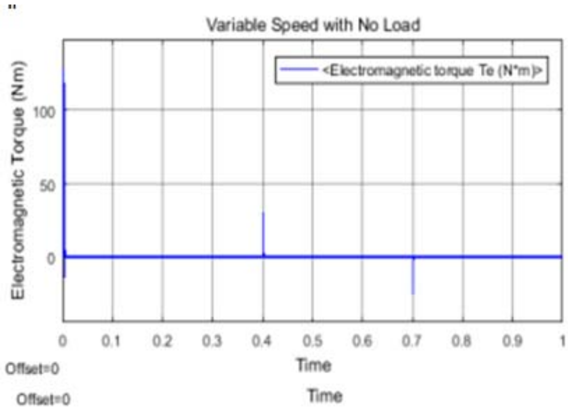
Fig. 15. Comparative Simulation results of Variable Speed with No Load Condition

4.2.2 EMT and Stator Current and Back EMF

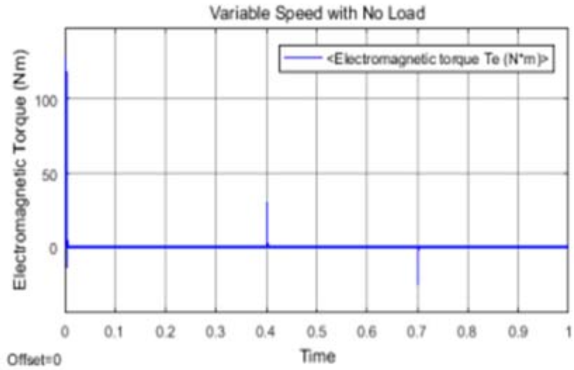
Comparative simulation results of ANF-SMC controller with other four controllers with variable speed under no load condition with time 0 to 1.0 seconds. With these simulation results, we can infer that the proposed controller takes a very less Electro Magnetic Torque (EMT) value of 32Nm with less time when compared to other controllers shown in Fig. 16.



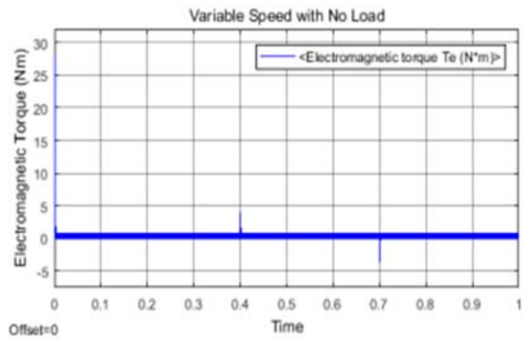
(a) PID Controller



(b) SMC Controller



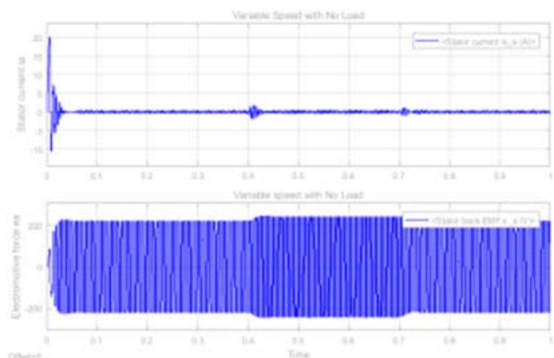
(c) AFSMC Controller



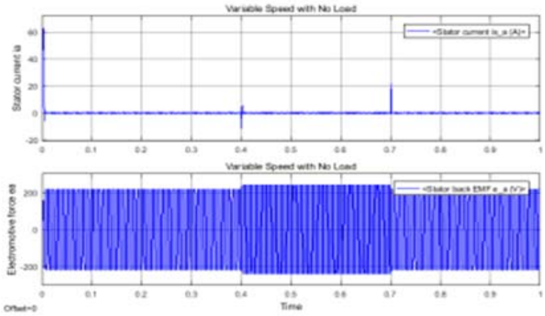
(d) ANF-SMC Controller

Fig. 16. Comparative Simulation results of five controllers EMT vales with no load, variable speed condition

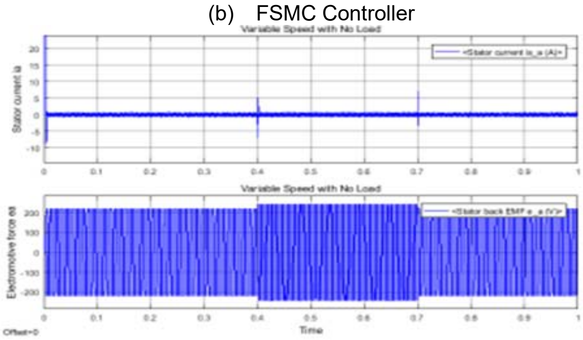
Comparative simulation results of ANF-SMC controller with other four controllers with variable speed under no load condition with time 0 to 1.0 seconds. With these simulation results, we can infer that the proposed controller takes very less stator current of 20 in very less time, constant back EMF irrespective of the time when compared to other controllers which are shown in Fig. 17



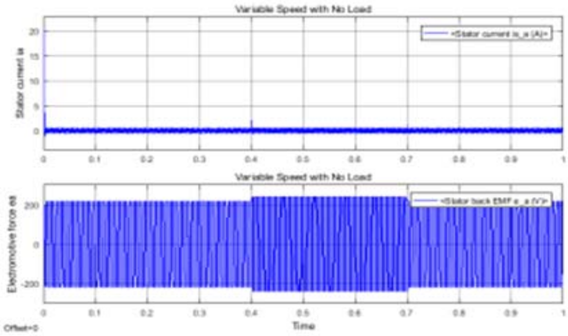
(a) PID Controller



(b) FSMC Controller



(c) AFSMC Controller



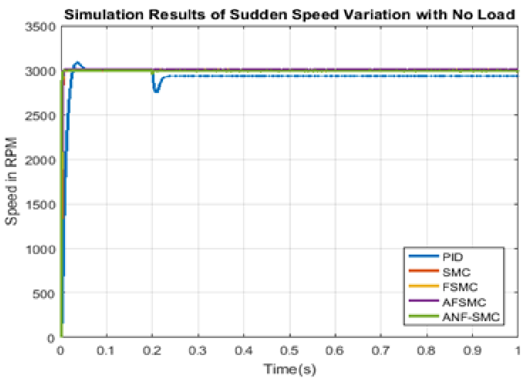
(d) ANF-SMC Controller

Fig. 17. Comparative Simulation results of five controllers stator current and back EMF vales with no load, variable speed condition

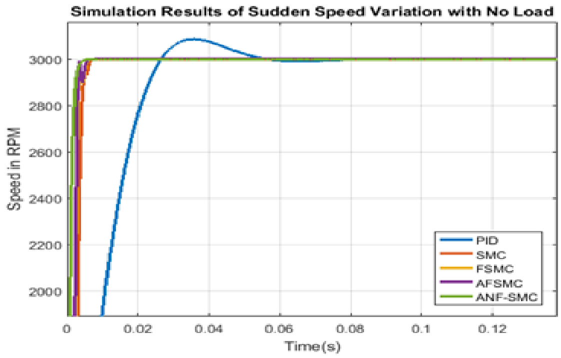
4.3 PMBLDC Motor Comparative Simulation Results of Speed, EMT, Stator Current, and BackEMF sudden disturbance in speed and no load condition

4.3.1 Speed

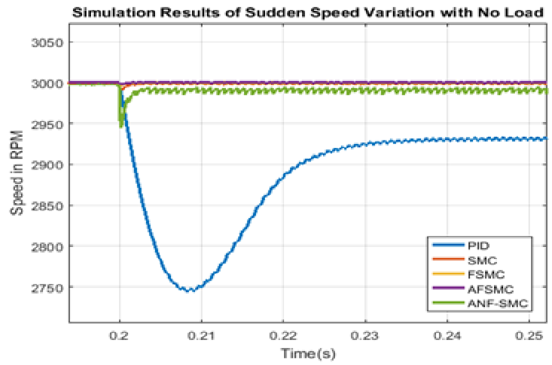
Comparative simulation results of proposed ANF-SMCwith other four controllers with sudden speed variation after 0.2 seconds under no load condition with time 0 to 1.0 seconds shown in the following Fig. 18. From these results infer that the proposed controller takes very less time when compared to other controllers in both the cases shown in zoom1 and zoom2 diagrams.



(a) Sudden Disturbance in Speed with No Load



(b) Zoom1 Diagram

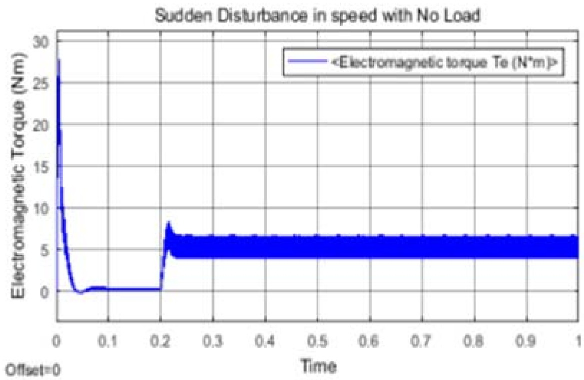


(c) Zoom2 Diagram

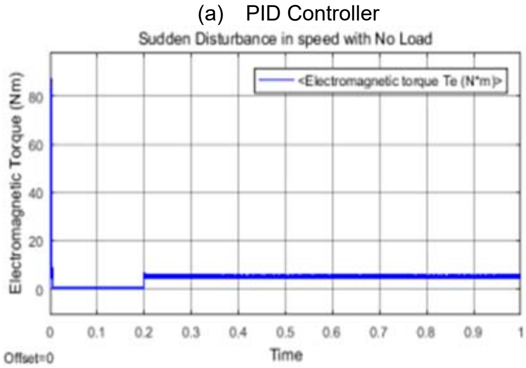
Fig. 18. Comparative Simulation results of Sudden Disturbance in speed with no load condition

4.3.2 EMT and Stator Current and Back EMF

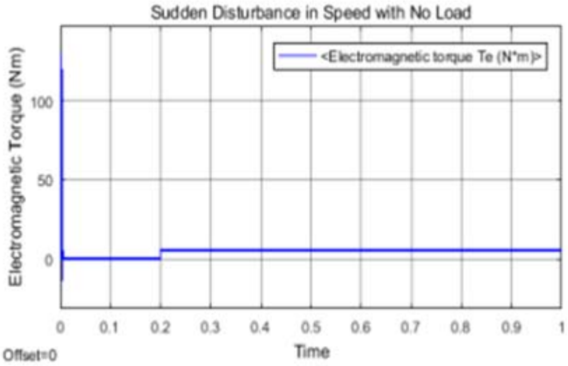
Comparative simulation results of ANF-SMC controller with other four controllers with variable speed under no load condition with time 0 to 1.0 seconds. With these simulation results, we can infer that the proposed controller takes a very Electro Magnetic Torque (EMT)value of 1Nm to 5Nm in 0 to 0.2 sec time when compared to other controllers shown in the following diagram.



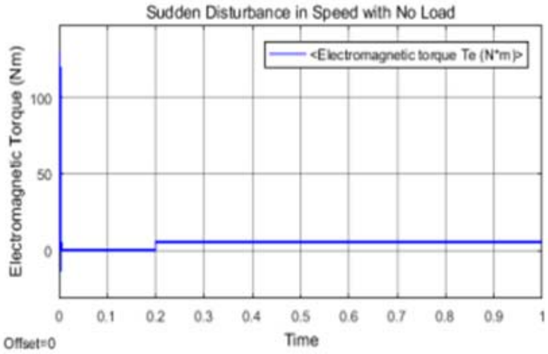
(a) PID Controller



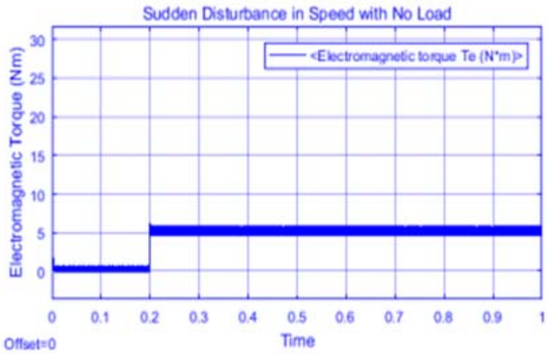
(b) SMC Controller



(c) FSMC Controller



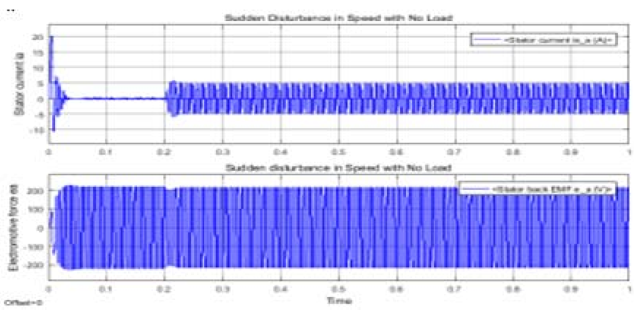
(d) AFSMC Controller



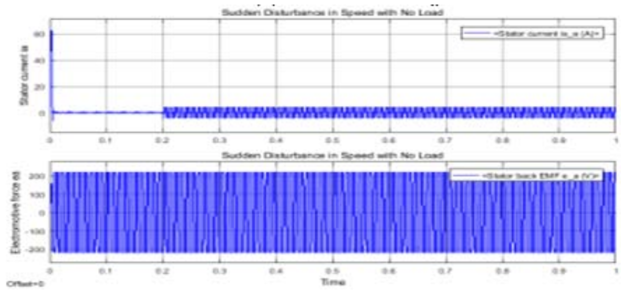
(e) ANF-SMC Controller

Fig. 19. Comparative Simulation results of five controllers EMT vales with no load, sudden disturbances in speed condition

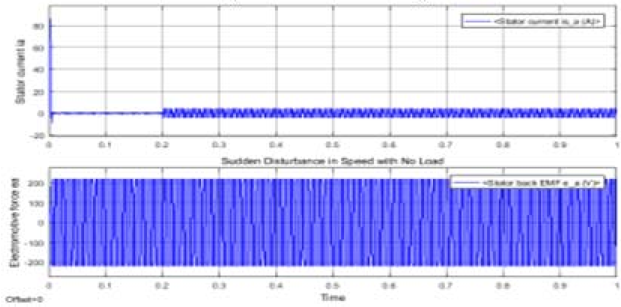
Comparative simulation results of ANF-SMC controller with other four controllers with variable speed under no load condition with time 0 to 1.0 seconds. With these simulation results, we can infer that the proposed controller takes very less stator current of 4 in very less time, constant back EMF irrespective of the time when compared to other controllers which are shown in the following diagram.



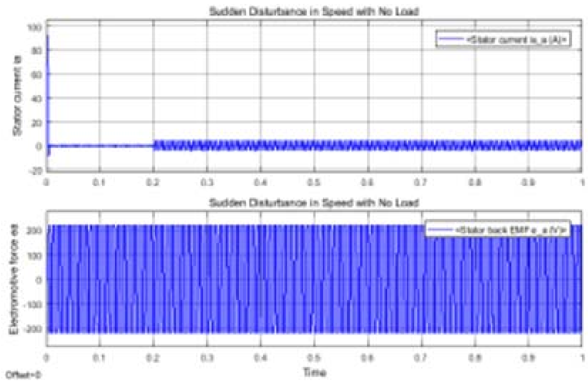
(a) PID Controller



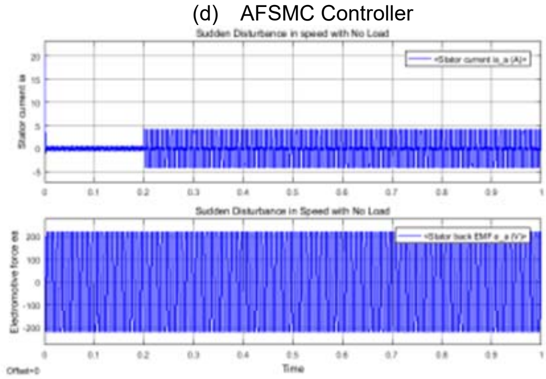
(b) SMC Controller



(c) FSMC Controller



(d) AFSMC Controller



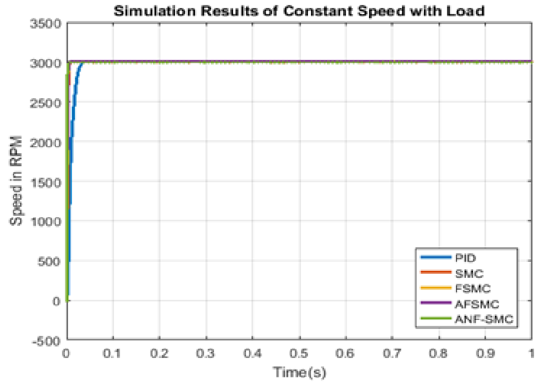
(e) ANF-SMC Controller

Fig. 20. Comparative Simulation results of five controllers stator current and back EMF vales with no load, sudden disturbances in speed condition

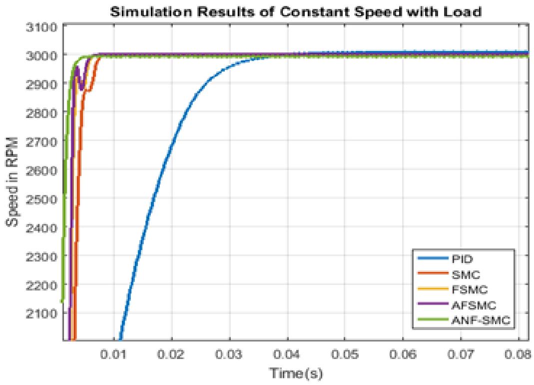
4.4 PMBLDC Motor Comparative Simulation Results of Speed, EMT, Stator Current, and BackEMF fixed speed and loaded condition

4.4.1 Speed

Comparative simulation results of the ANF-SMC controller with other four controllers with a constant speed of 3000RPM under load conditions with time 0 to 1.0 seconds shown in the following Fig. 21. From these results infer that the proposed controller takes very less time when compared to other controllers even under the loaded condition which is shown in the zoomed diagram.



(a) Fully loaded with fixed speed condition

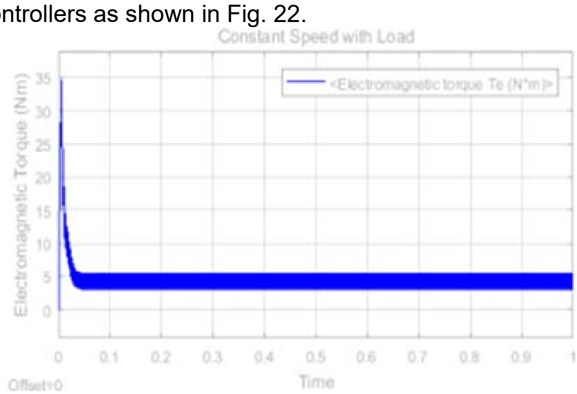


(b) Joom Diagram

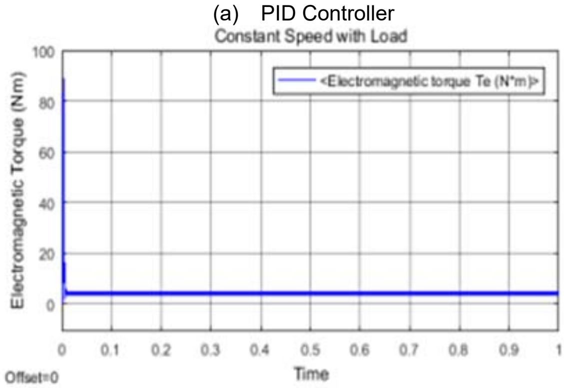
Fig. 21. Comparative simulation results of fixed speed with load condition

4.4.2 EMT and Stator Current and Back EMF

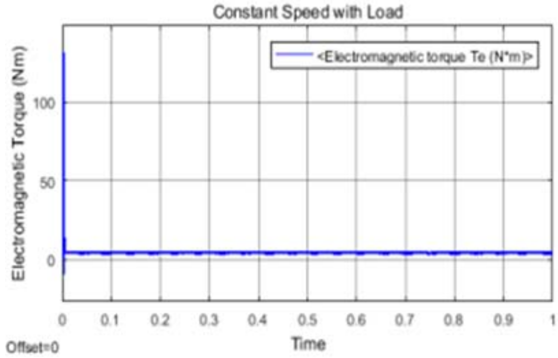
Comparative simulation results of ANF-SMC controller with other four controllers with fixed speed of 3000RPM under no load condition with time 0 to 1.0 seconds. With these simulation results, we can infer that the proposed controller takes a very Electro Magnetic Torque (EMT) value of 5Nmin very very less time when compared to other controllers as shown in Fig. 22.



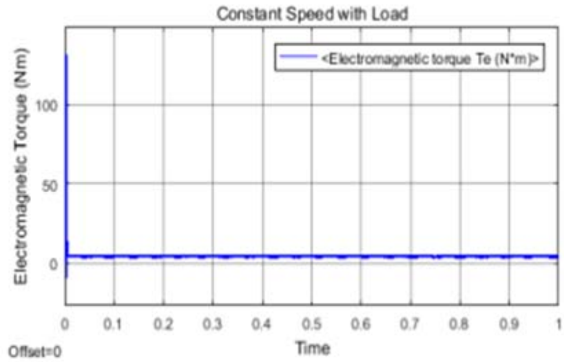
(a) PID Controller



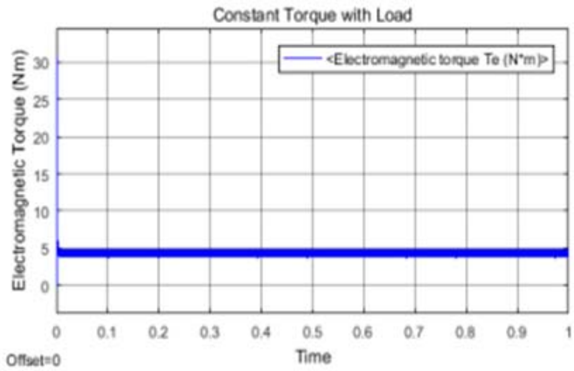
(b) SMC Controller



(c) FSMC Controller



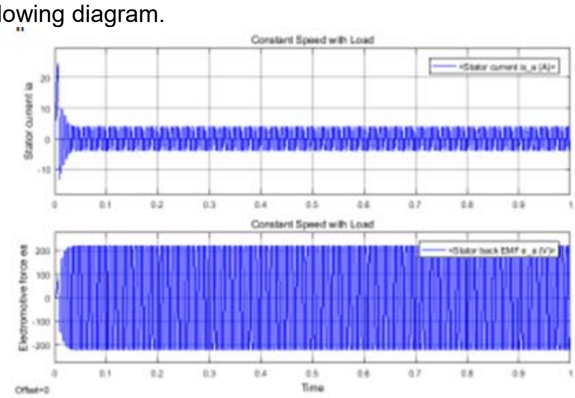
(d) AFSMC Controller



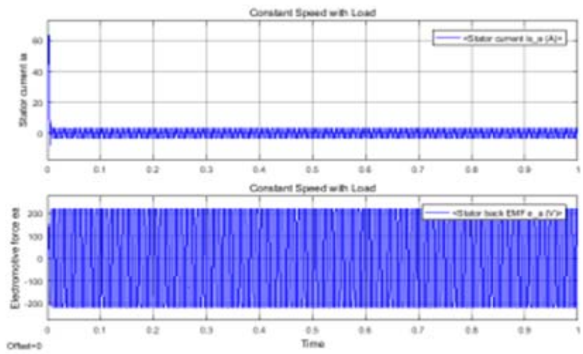
(e) ANF-SMC Controller

Fig. 22. Comparative Simulation results of five controllers EMT vales with loaded, fixed speed condition

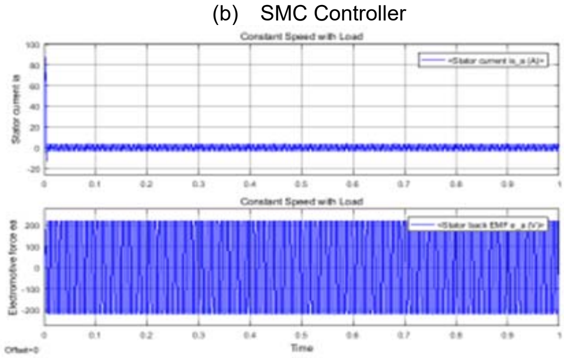
Comparative simulation results of ANF-SMC controller with other four controllers with a constant speed of 3000RPM under no load condition with time 0 to 1.0 seconds. With these simulation results, we can infer that the proposed controller takes very less stator current of 6 in very less time, constant back EMF irrespective of the time when compared to other controllers which are shown in the following diagram.



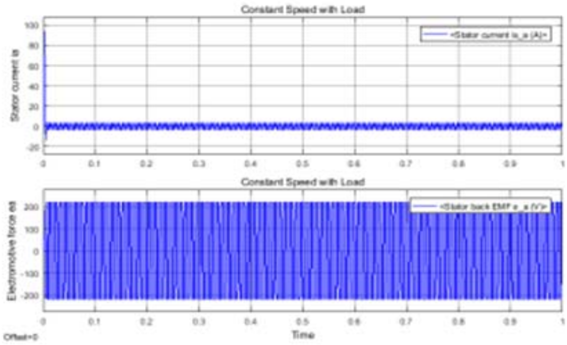
(a) PID Controller



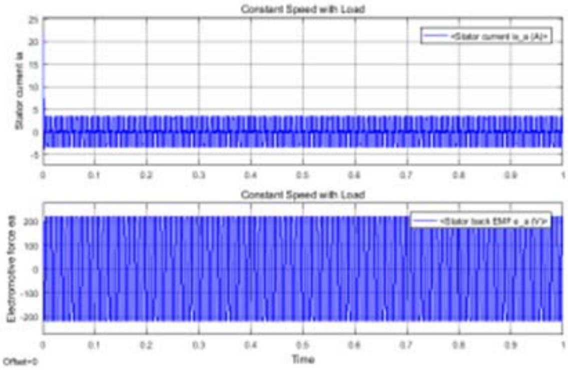
(b) SMC Controller



(c) FSMC Controller



(d) AFSMC Controller

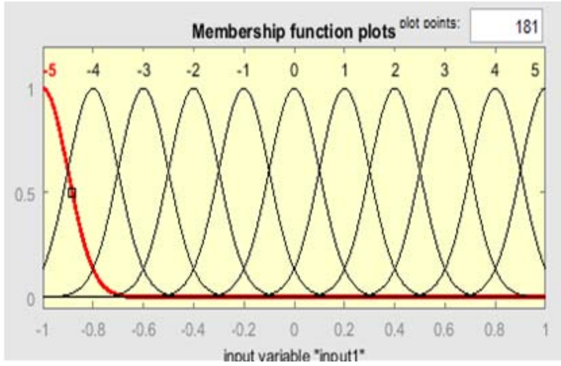


(e) ANF-SMC Controller

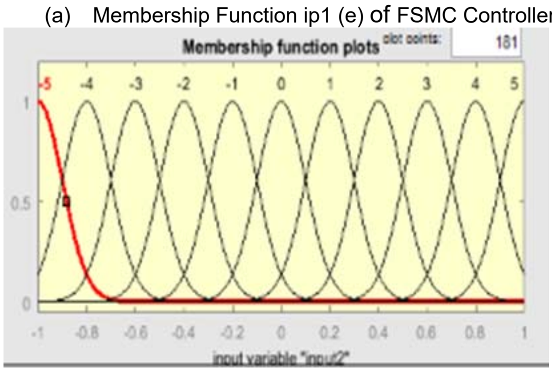
Fig. 23. Comparative Simulation results of five controllers stator current and back EMF vales with loaded, fixed speed condition

4.5Comparative Simulation Results of Membership Function and Surface View with Five Controllers

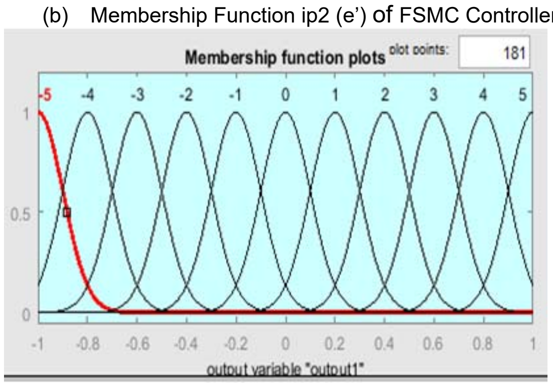
Comparative simulation results of ANF-SMC controller with FSMC and AFSMC controllers with sample input and output membership functions as an error (input1) and delta error (input2), got output membership functions and the surface view was shown for these three controllers. These results infer that the proposed controller shows better results when compared to other controllers which are shown in Fig. 24.



(a) Membership Function ip1 (e) of FSMC Controller

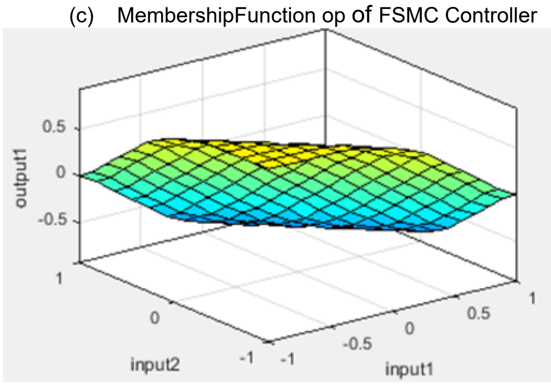


(b) Membership Function ip2 (e') of FSMC Controller

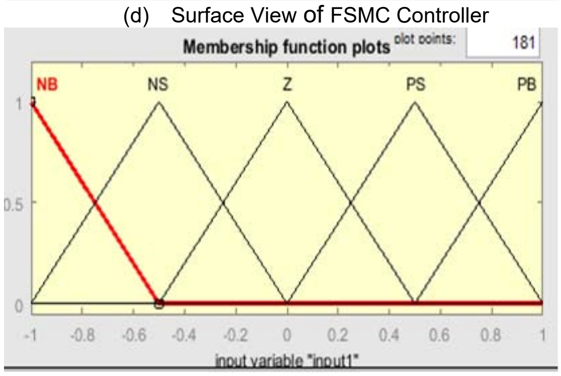


<

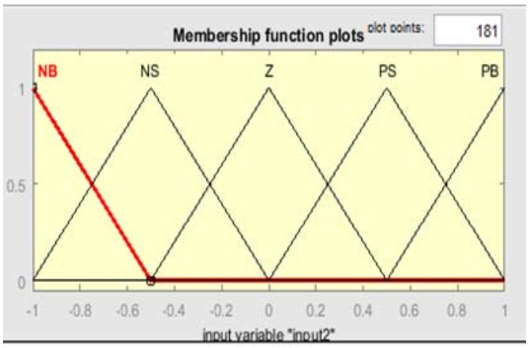
(c) MembershipFunction op of FSMC Controller



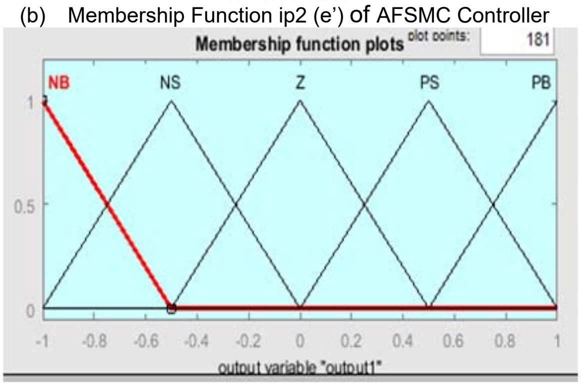
(d) Surface View of FSMC Controller



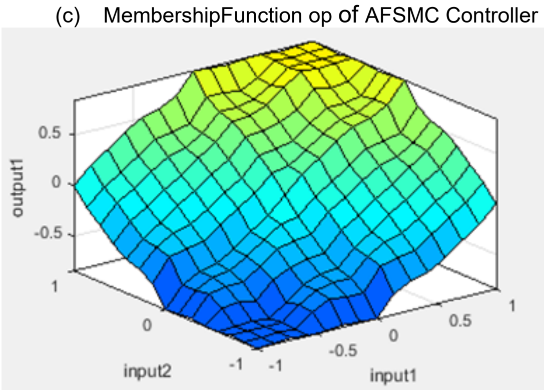
(a) Membership Function ip1 (e) of AFSMC Controller



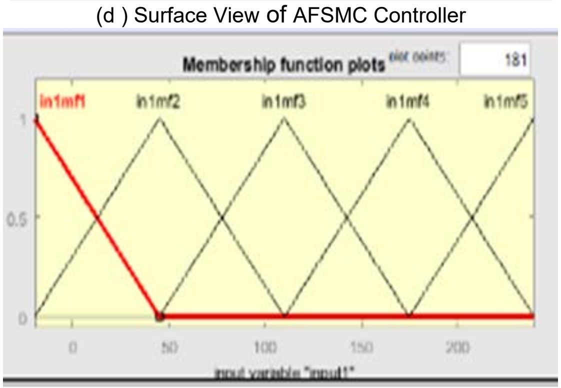
(b) Membership Function ip2 (e') of AFSMC Controller



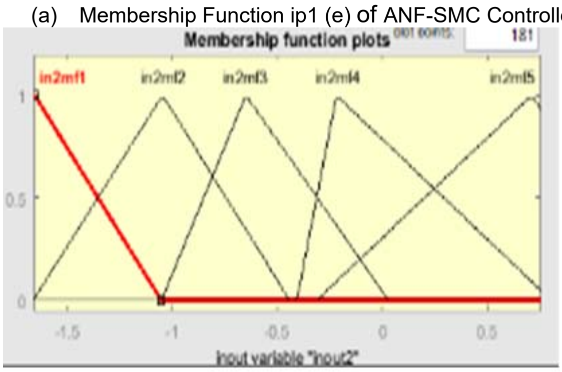
(c) MembershipFunction op of AFSMC Controller



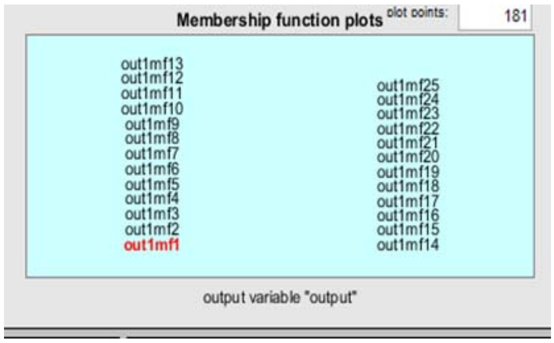
(d) Surface View of AFSMC Controller



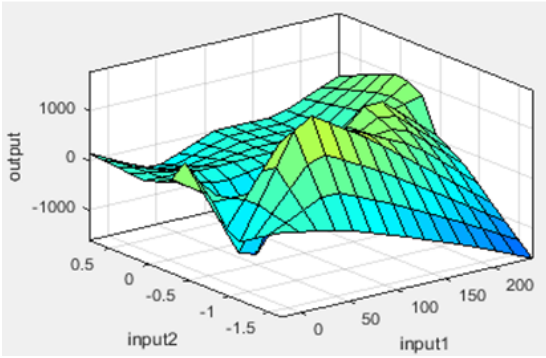
(a) Membership Function ip1 (e) of ANF-SMC Controller



(b) Membership Function ip2 (e') of ANF-SMC Controller



(c) Membership Function op of ANF-SMC Controller

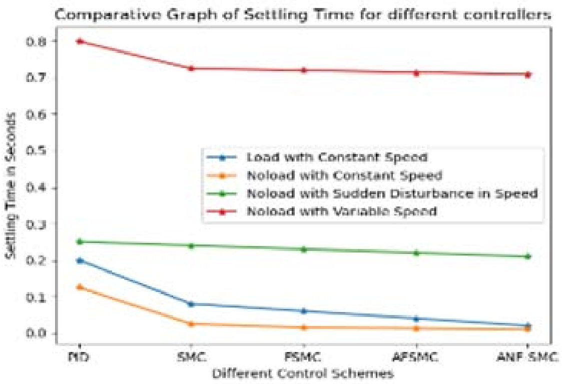


(d) Surface View of ANF-SMC Controller

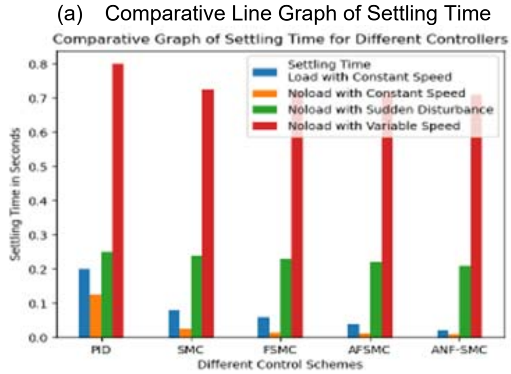
Fig. 24. Sample Input / Output Membership functions as an error (input1) and delta error (input2) and Surface View Comparative Simulation Results of PMBLDC Motor

4.6 Comparative Simulation Results of Measurement Parameters with Five Controllers

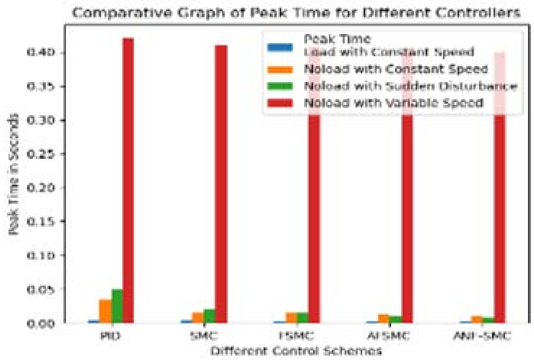
Measurement parameters comparative simulation results of ANF-SMC controller with other four controllers for settling time, peak time, and rise time in seconds were shown as line and bar graphs were shown in Fig. 25. From these results infer that the proposed controller takes very less time when compared to other controllers.



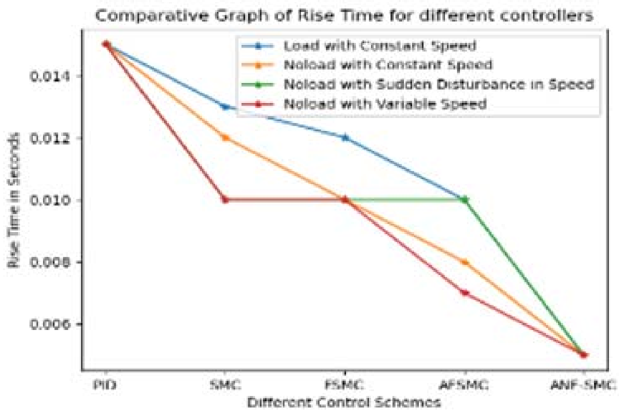
(a) Comparative Line Graph of Settling Time



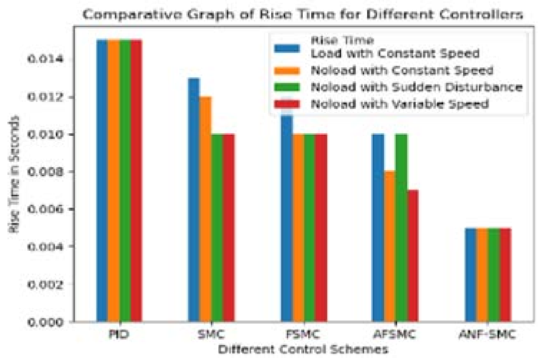
(b) Comparative Line Graph of Peak Time



(c) Comparative Bar Graph of Peak Time Controller wise



(d) Comparative Line Graph of Rise Time



(e) Comparative Bar Graph of Rise Time Controller wise

Fig. 25. Comparative Results of Measurement Parameters for Five Controllers

In Table7.comparative results of five controllers under constant speed with load and no load, and Table 8. comparative results of five controllers under sudden disturbance in speed with load and variable speed with no load were described.

Table 7. Comparative Results of Five Controllers under Constant Speed with load and no load

Parameter	Constant Speed with Load				
	PID	SMC	FSMC	AFSMC	ANF-SMC
SettlingTime	0.200	0.008	0.006	0.0040	0.0200
Peak Time	0.004	0.0035	0.003	0.0031	0.0030
Rise Time	0.0015	0.0013	0.001	0.0010	0.0005
Peak Speed	3000	3000	3000	3000	3000
Overshoot%	0.333	0.035	0	0	0
Parameter	Constant Speed with No Load				
	PID	SMC	FSMC	AFSMC	ANF-SMC
SettlingTime	0.125	0.0250	0.015	0.013	0.0100
Peak Time	0.035	0.0150	0.014	0.012	0.0100
Rise Time	0.015	0.0120	0.010	0.008	0.0050
Peak Speed	3000	3000	3000	3000	3000
Overshoot%	0	0	0	0	0

Table 8. Comparative Results of Five Controllers under Sudden Disturbance in Speed and Variable Speed under no load conditions

Parameter	Sudden Disturbance in Speed with No Load				
	PID	SMC	FSMC	AFSMC	ANF-SMC
Settling Time	0.25	0.24	0.230	0.220	0.2100
Peak Time	0.05	0.02	0.015	0.01	0.0080
Rise Time	0.02	0.01	0.010	0.01	0.0050
Peak Speed	3100	3000	3000	3000	3000
Set M Speed	2750	2995	2995	2995	2990
Overshoot%	3.333	0	0	0	0
Parameter	Variable Speed with No Load				
	PID	SMC	FSMC	AFSMC	ANF-SMC
Settling Time	0.800	0.7250	0.7200	0.7150	0.7100
Peak Time	0.420	0.4100	0.4080	0.4050	0.4000
Rise Time	0.015	0.0100	0.0100	0.0070	0.0050
Peak Speed	3300	3300	3300	3300	3300
Set M Speed	2990	3000	3000	3000	3000
Overshoot%	10.00	0	0	0	0

5. Conclusion part of ANF-SMC

The proposed ANF-SMC controller is used to overcome nonlinear and uncertainty problems because of dynamic loads with the usage of PMBLDC motors in the electric propulsion subsystem of EVs with absence, presence, and variable speed conditions. Simulation of proposed controller done with MATLAB/Simulink R2020b with Fuzzy tool kit, comparative study of the proposed controller with existing four controllers done for different speed and load conditions, with different measurement parameters. Simulation results infer that the proposed ANF-SMC controller (18%, 0.1%, 0.1%) less settling, peak and rise times respectively, (45%, 44%) less electro magnetic torque and stator current respectively than PID, (1.2%, 0.1%, 0.1%) less settling, peak and rise times respectively, (65%, 12%) less electro magnetic torque and stator current respectively than SMC, (0.02%, 0.01%) less peak and rise times respectively, (50%, 10%) less electro magnetic torque and stator current respectively than FSMC, (0.01%, 0.05%) less peak and rise times respectively, (60%, 10%) less electro magnetic torque and stator current respectively than AFSMC under constant speed with no load condition, (11.5%, 2.5%, 1.0%) less settling, peak and rise times respectively, (50%, 25%) less electro magnetic torque and stator current respectively than PID, (0.5%, 0.4%, 0.5%) less peak and rise times respectively, (25%, 25%) less electro magnetic torque and stator current respectively than SMC, (0.25%, 0.2%, 0.3%) less settling, peak and rise time(70%, 15%) less electro magnetic torque and stator current respectively than FSMC respectively, (0.25%, 0.2%, 0.3%) less settling, peak and rise time respectively (25%, 25%) less electro magnetic torque and stator current respectively than AFSMC under variable speed with no load condition, (4.5%, 4.2%, 2.0%) less settling, peak and rise times respectively, (14%, 1.0%) less electro magnetic torque and stator current respectively than PID, (3.0%, 1.2%, 1.0%) less settling, peak and rise times respectively, (10%, 1.2%) less electro magnetic torque and stator current respectively than SMC, (2.0%, 0.7%, 0.8%) less settling, peak and rise times respectively, (10%, 1.2%) less electro magnetic torque and stator current respectively than FSMC, (1.0%, 0.2%, 0.5%) less settling, peak and rise times respectively, (5%, 0.5%) less electro magnetic torque and stator current respectively than AFSMC under sudden disturbance in sudden disturbance in speed with no load condition, (9.0%, 1.0%, 0.01%) less settling, peak and rise times respectively, (25%, 1.5%) less electro magnetic torque and stator current respectively than PID, (1.5%, 0.5%, 0.5%) less settling, peak and rise times respectively, (28%, 1.8%) less electro magnetic torque and stator current respectively than SMC, (1.0%, 0.5%, 0.5%) less settling, peak and rise times respectively, (20%, 1.5%) less electro magnetic torque and stator current respectively than FSMC, (0.5%, 0.5%, 0.2%) less settling, peak and rise times respectively, (20%, 1.5%) less electro magnetic torque and stator current respectively than AFSMC under costant speed with loaded condition. With 0% overshoot and a peak speed of 3000RPM and constant back EMF irrespective of the time when compared to other controllers under different types of load conditions.

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