

Comparison of PI, Fuzzy and Sliding Mode Control Techniques in Speed Control of BLDC Motor

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Abstract—Developments made in the fields of control system engineering is responsible for paradigm shift in technology and industries. The paper constitutes of BLDC motor load fed from Luo converter. A Luo converter is special DC-DC converter with a single switch. The negative output elementary Luo converter is employed for conversion of voltages. The input for BLDC motor load is fed from a three phase VSI with 120° conduction mode. In this paper speed control of BLDC motor is done by employing various controllers like PI, fuzzy logic and SMC controllers. The converter system used here is Luo converter for DC-DC conversion followed by three phase inverter circuit for DC-AC conversion to energise BLDC. The input DC power is generated by photovoltaic systems. For obtaining maximum power from PV system, MPPT algorithm also used. The circuit is simulated in MATLAB Simulink. The step responses of three controllers compared from the obtained results. The optimum speed control is seen in SMC controller when compared to fuzzy and PI.

Keywords—Proportional Integral (PI) controller, fuzzy logic controller, Sliding Mode controller, BLDC motor, PV system, MPPT, Luo converter, inverter, delay time, rise time, settling time, steady state error, Three phase VSI.

I. INTRODUCTION

The total installed capacity of India as on July 2019 is 360,456 MW which is 3.52% more than the last year. It clearly shows significance of energy needs in India. Energy can be utilized to fullest by following advanced technical approaches and methodologies. It's been quite common now a days to employ power electronic devices in both domestic and industrial field for proper control of electrical machines and equipment such that it gives rated output with minimal amount of energy. When the power electronic devices are further enhanced with the help of controllers the required output is achieved quickly meeting accuracy and efficiency.

Luo converter is a single end primary inductor converter, is basically a boost converter that boost up voltage levels. There are positive and negative converters, which may be elementary or self-lift types [2]. In this paper, a negative output elementary Luo converter is considered.

Adaptation of controllers in the system has become compulsory in various domains, as the advantages it provides is in large scale. The controllers like PI, fuzzy logic and SMC are mainly discussed in the paper [8-9]. Among above mentioned three, PI controller is one of the oldest and simple controllers. PI controller can be mainly used for linear systems whereas Fuzzy and SMC controller can be commissioned in nonlinear systems

also. SMC controllers have high stability and robustness. Faster dynamic responses are obtained when nonlinear controllers are placed in power electronic controlled systems. There are other nonlinear controllers like one-cycle control, current mode controller, sliding mode controller which are employed for DC-DC converters. Amongst all those mentioned, fuzzy logic control and SMC are advantageous as they are simple and model free techniques. Plant uncertainties and external disturbances are two major problems for systems, to make system free from those two issues, SMC is developed and is powerful technique which results in a very robust closed loop system. Thus, system now becomes independent of effects due to modelling uncertainties, parameter fluctuations and disturbances.

The power electronic designs been complicated and sophisticated day by day for more precise output. In this paper Luo converter and three phase inverter is used to operate BLDC motor. When compared with conventional motors like Induction motor or synchronous motor, BLDC motor have advantages like very large power to weight ratio, higher speeds, less maintenance and feasibility of electronic control [6]. Brushless DC motors find their applications in automobile industry, aircraft system models, computer peripherals like printers, disk drives, some of hand held power tools, pumping systems etc.

II. METHODOLOGY

In this paper, three controllers namely PI, Fuzzy and Sliding Mode controller, been used for the purpose of speed control of BLDC motor. The speed response of the three controllers are compared. The entire system here energized by solar PV system and DC voltage obtained from the PV panel manipulated by Luo converter which is also called "single end primary inductor converter" (SEPIC). BLDC motor is fed from Luo through VSI. The actual speed compared with reference speed and control signal obtained as output of controller, given as gate pulses to MOSFET of Luo converter. The design of Luo converter and other controllers made accordingly with the rating of BLDC motor [7]. The above model is simulated in MATLAB software and results been analyzed.

III. OPEN LOOP SYSTEM

The system is energized by solar PV array system, whose power is regulated by MPPT algorithm [4]. The self-lift negative Luo converter is chosen as it has advantages over positive Luo for BLDC motor load. The voltage is boosted

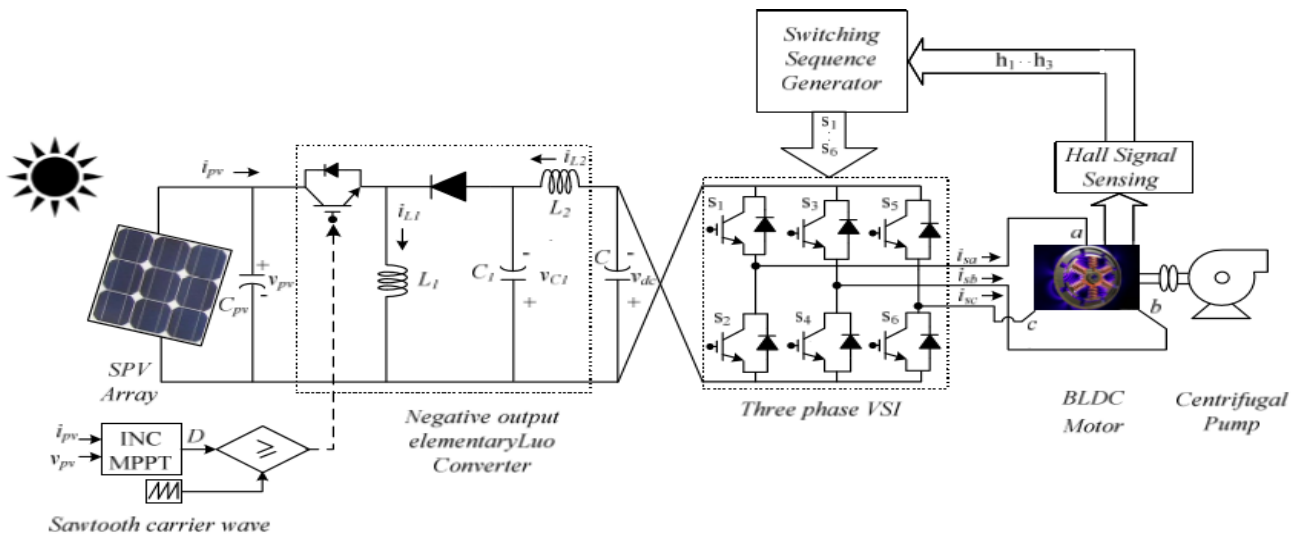


Fig. 1: Block diagram of open loop system

with help of negative Luo converter and its output is given to three phase voltage source inverter from where BLDC motor load is connected to system. The specifications of solar PV panel selected such that it is sufficient enough to power the BLDC. The rated power is achieved through series and parallel combination of solar panel that constitute to form an array. Appendix I shows the ratings of considered photovoltaic system. The design of Luo converter and modeling of BLDC motor is given in below section.

A. LUO CONVERTER

Among all DC-DC converter, Luo converter has its own importance [5]. In the design of Luo converter, it is necessary to estimate the rating of input inductor L_1 , intermediate capacitor C_1 , output inductor L_2 and output capacitor C . All the above elements are calculated with the duty ratio $D=0.5$. In this paper, Luo converter operates in continuous conduction mode. Switching frequency $f_{sw}=20$ kHz been considered as it gives less rated value of above elements. The output current of Luo converter I_{dc} is equal to I_{mpp} , which is input current of Luo converter. Here I_{mpp} is obtained as output current from PV system by employing MPPT algorithm. The DC link current of VSI is also the output current of Luo converter [1].

Input inductor L_1 is calculated as

$$L_1 = \frac{D \cdot V_{mpp}}{f_{sw} \cdot \Delta I_{L1}} = \frac{0.5 \cdot 310}{20000 \cdot (19.35 + 19.35) \cdot 0.04} = 5mH \quad (1)$$

where ΔI_{L1} is value of ripple allowed in the current flowing through L_1 , addition of input and output current of Luo converter.

Output inductor L_2 is calculated as

$$L_2 = \frac{(1-D) \cdot V_{mpp}}{f_{sw} \cdot \Delta I_{L1}} = \frac{0.5 \cdot 310}{20000 \cdot (19.35 + 19.35) \cdot 0.04} = 5mH \quad (2)$$

where ΔI_{L2} is amount of ripple permitted in the current flowing through L_2 , equal to the output current of Luo converter.

To find out the value of DC link capacitor C , the fundamental output voltage frequencies of the VSI corresponding to the

rated speed of BLDC motor, ω_{rated} and the minimum speed of BLDC motor essentially required to pump the water ($N = 1100$ rpm), ω_{min} are taken into consideration which are calculated as

$$\omega_{rated} = 2 \cdot \pi \cdot f_{rated} = \frac{2 \cdot \pi \cdot N_{rated} \cdot p}{120} = \frac{2 \cdot \pi \cdot 3000 \cdot 6}{120} = 942 \text{ rad/sec} \quad (3)$$

$$\omega_{min} = 2 \cdot \pi \cdot f_{min} = \frac{2 \cdot \pi \cdot N_{min} \cdot p}{120}$$

$$= \frac{2 \cdot \pi \cdot 1100 \cdot 6}{120} = 347.57 \text{ rad/sec} \quad (4)$$

where f_{rated} and f_{min} are the frequencies corresponding to ω_{rated} and ω_{min} respectively, in Hz; N_{rated} is rated speed of BLDC motor; p is the number of poles in BLDC motor.

The 6th harmonic component of ac voltage is most dominant harmonic in DC link of VSI and it is flown into system from motor. Two values of C are calculated corresponding to ω_{rated} and ω_{min} as

$$C_{rated} = \frac{I_{dc}}{6 \cdot \omega_{rated} \cdot \Delta V_{dc}} = \frac{19.35}{6 \cdot 942 \cdot 310 \cdot 0.06} = 184 \mu F \quad (5)$$

$$C_{min} = \frac{I_{dc}}{6 \cdot \omega_{min} \cdot \Delta V_{dc}} = \frac{19.35}{6 \cdot 347.57 \cdot 310 \cdot 0.06} = 500 \mu F \quad (6)$$

where ΔV_{dc} is the value of allowed ripple in the voltage across C . Hence, $C = C_{min} = 500 \mu F$ is commissioned as DC link capacitor (larger one out of the two calculated values to make sure that there is satisfactory performance of modelled system irrespective of the operating conditions). The remaining capacitor C_1 taken as $500 \mu F$ to avoid the oscillations in the various parameters of Luo converter. Calculated values of elements of Luo converter are repeated in Appendix II.

B. BLDC MODELLING

In a BLDC motor considered, the commutation takes place with no brushes on the rotor and commutation done electronically at specific rotor positions. There are multiple ways available for configuration of windings of stator phase. One way is to insert windings in the slots of the stator and the other way is to wound as single coil on the magnetic pole. The back EMF of the BLDC is said to be in trapezoidal in behaviour, hence permanent magnets on the rotor are chosen in such a way that their magnetisation and displacement results in trapezoidal back EMF, that further results in a rectangular shaped three phase voltage system. The rotational field thus have low torque ripples. Constant torque is generated with square wave currents, which is a result of trapezoidal back EMF as mentioned earlier. Conventional BLDC motor is driven via a six switch three phase inverter, which is connected through stator windings. The three Hall effect position sensors provide commutation for BLDC and there are six commutation points for each electrical cycle [9].

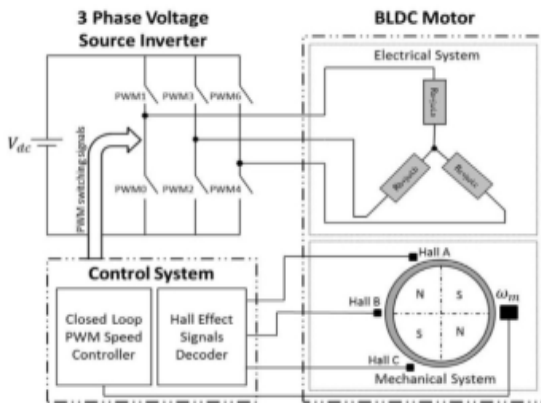


Fig. 2: Schematic view of BLDC motor

BLDC motor can be modelled as permanent magnet synchronous machine. A three-phase inverter which gives square wave or sinusoidal wave shape voltage is applied as input voltage, care is taken such that voltage is kept within maximum limits. In armature side equations are modelled as follows

$$V_a = I_a R_a + L_a \left(\frac{dI_a}{dt} \right) + E_a \quad (7)$$

$$V_b = I_b R_b + L_b \left(\frac{dI_b}{dt} \right) + E_b \quad (8)$$

$$V_c = I_c R_c + L_c \left(\frac{dI_c}{dt} \right) + E_c \quad (9)$$

where, \$V_a, V_b, V_c\$ are the phase voltages \$I_a, I_b, I_c\$, are the phase current \$E_a, E_b, E_c\$ are the back EMF's. The back EMFs can be expressed as,

$$E_a = K_e \omega_m F(\theta_e) \quad (10)$$

$$E_b = K_e \omega_m F \left(\theta_e - \frac{2\pi}{3} \right) \quad (11)$$

$$E_c = K_e \omega_m F \left(\theta_e + \frac{2\pi}{3} \right) \quad (12)$$

where, \$\omega_m\$ is Angular speed of rotor. \$\theta_m\$ is Mechanical angle of rotor. \$\theta_e\$ is Electrical angle of rotor. \$F(\theta_e)\$ is Back-EMF reference function of rotor position.

Generally, a three-phase system is used for modelling of BLDC, but for sliding mode controller its convenient to consider \$\alpha\$-\$\beta\$ coordinate frame and the field-oriented frame d-\$q\$ coordinate frame [10].

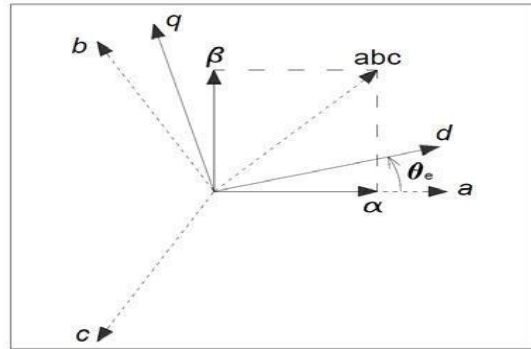


Fig. 3: Transformation of co-ordinate system

The differential equations governing the electrical subsystem of the non-salient pole BLDC motor in the \$d; q\$ coordinate frame can be written as,

$$\dot{I}_d = \frac{1}{L} [v_d - R_e i_d + L n_p \omega_m i_q] \quad (13)$$

$$\dot{I}_q = \frac{1}{L} [v_q - R_e i_q + L n_p \omega_m i_d - \Phi_m n_p \omega_m] \quad (14)$$

Where, \$I_d, I_q\$ are stator currents in d-q coordinates. \$v_d, v_q\$ are stator voltage in d-q coordinates. \$R, L\$ are stator resistance and inductance respectively. \$n_p\$ represents number of pole pairs. \$\Phi_m\$ is magnetic flux of rotor. The relationship between speed and torque of the BLDC motor, in the form of state space equation thus given as

$$\dot{\omega}_m = \frac{1}{J} \left[\frac{3}{2} \Phi_m n_p i_q - \omega_m B_m - \tau_l \right] \quad (15)$$

Where, \$J\$ is rotational inertia, \$B_m\$ is viscous fictional coefficient and \$\tau_l\$ is load torque.

IV. PI CONTROLLER

The simple and conventional controller for controlling all DC-DC converters is PI Controller. For linearised control systems the PI controller alone is self-sufficient controller, where as if system have non linearity in it, controllers like SMC, fuzzy logic controller, hysteresis current loop controller is required. The PI controller can also be used as band filter in some applications. The control signal, which is generated by PI controller for a DC-DC converter, here a negative Luo converter is used for continuous mode operation. The general equation known for PID controller is

$$u(t) = k_p e(t) + k_i \int e(t) dt \quad (16)$$

Here, $e(t)$ is a error in speed. Error in speed is difference of measured speed with the reference speed [8].

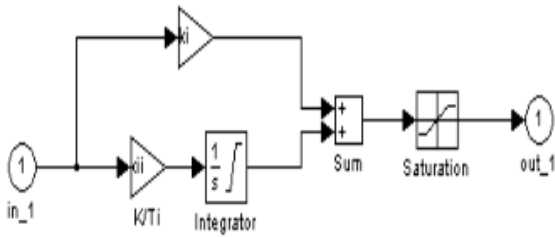


Fig. 4: Block Diagram of PI controller

V. FUZZY LOGIC CONTROLLER

Conventional controllers require complex mathematical modeling which involves complex mathematical equations. On the other hand, fuzzy logic controller doesn't involve any complex mathematical modelling and can be easily modeled for nonlinear systems. In fuzzy logic controller, operational laws are in terms of linguistic terms rather than simple mathematical equations. There exist many complex controllers where it be difficult to model them accurately. So, it is better to employ fuzzy logic for nonlinear controllers as they are easier and much more feasible. The Simulink model involves Luo converter three phase inverter and a BLDC motor. The fuzzy logic controller is used along with PI controller.

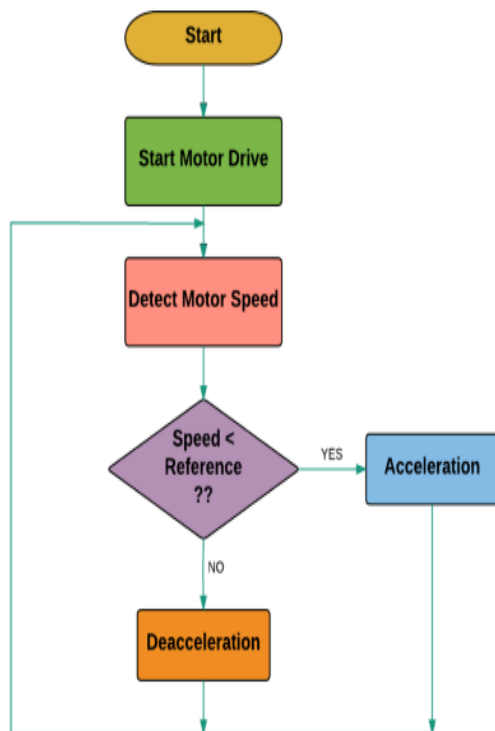


Fig. 5: Basic flow chart of Fuzzy speed

The modelling of fuzzy logic controller involves:

1. Input and output both have seven fuzzy sets.
2. Fuzzification of inputs using continuous universe of discourse.
3. Connotation using Mamdani's 'min' operator.

4. 'Centroid' method used for defuzzication.

Triangular membership function is based on equation of straight line which for the ease of computation is used to design fuzzy sets. This triangular curve can be represented as

$$\mu_A(x) = \max\left(\min\left(\frac{x-a}{c-a}, \frac{c-x}{c-b}\right), 0\right) \quad (17)$$

Here 'e' indicates error and 'ce' indicates change in error and are two inputs of fuzzy system. The output of fuzzy is an active component of current. The fuzzy rule table with seven input and output fuzzy set is given [9].

Table 1: Rule base matrix for output

e/ce	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Both 'e' and 'ce' i.e. speed error and change in speed error respectively are measured continuously and given as input to the fuzzy block in Simulink model. When compared to the trapezoidal membership functions, the triangular membership functions have advantage of simplicity in construction. Hence triangular membership function is used in this paper. The seven membership functions are represented as 'NB'-Negative Big, 'NM'-Negative Medium, 'NS'-Negative Small, 'ZE'-Zero, 'PS'-Positive Small, 'PM'-Positive Medium, 'PB'-Positive Big. On the basis of different range of values for 'e' and 'ce', the discrimination of membership functions are done. The input triangular membership functions 'e' and 'ce' are shown below.

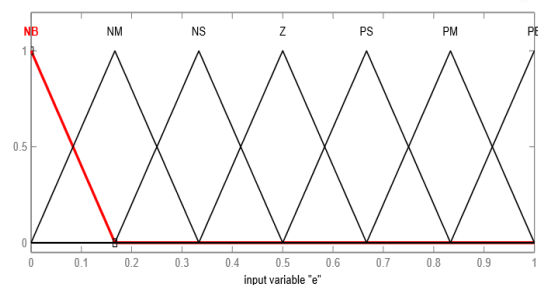


Fig. 6: Triangular waveform of Fuzzy input variable "e"

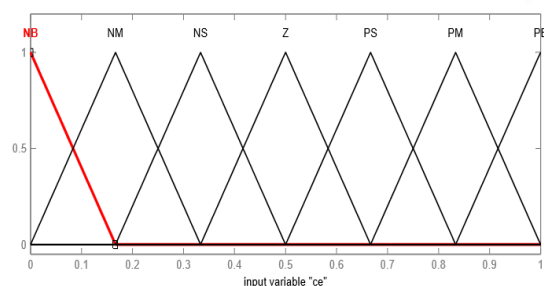


Fig. 7: Triangular waveform of Fuzzy input variable "ce"

VI. SLIDING MODE CONTROLLER:

Sliding mode controller is one among those nonlinear controllers, that adjusts the system performance characteristics by controlling the variables, simultaneously by knowing the current status of the system considered. Changing the controlled variable causes the system to choose a better trajectory over a well predefined sliding surface. The figure represents two mode system's state trajectory and its sliding surface.

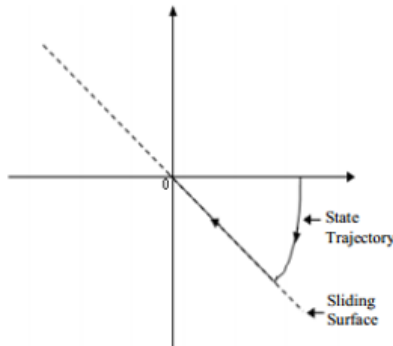


Fig. 8: Phase portrait of sliding motion

State space equations employed in the sliding mode equations are formulated in such a way that its feasible to choose sliding surface with an ease. Firstly, the state trajectory of the system need not be towards the sliding surface. But when the control actions start, the trajectory shifts its position in a such a way that it slowly approaches sliding mode surface within certain amount of time. This entire process is called as reaching, hitting or non- sliding phase. Here the system is sensitive to parameter changes and disturbance rejection, in this part of phase trajectory [8]. The next part is called as sliding phase, in which the system state trajectory approaches to the origin along the sliding surface and care is to be taken such that system never leaves the sliding surface.

During this process, the system is formulated by equation of the sliding surface and thus making it independent of the parameters of the system and disturbances that occur externally. Therefore, sliding mode design involves two major tasks:

1. Choosing a stable and well-defined sliding surface in state space on which the state trajectory should always lie on.
2. Designing and developing a unique control law, such that making the state trajectory approach to the sliding surface without much trouble in a certain time.

The sliding mode control, for the speed control for BLDC motor is also derived from theory of control structure which is variable in nature. This is discrete control process that involves control system in real time parametric variations. Sliding mode control now a days been frequently implemented in power converters due to its peculiar operational characteristics like robustness, speed and stable performance under wide load variations.

As already mentioned, the main principle in sliding mode control is the defining the surface, which is called as sliding surface. By mentioning the desired speed, the system control

law should be defined in such a way that state trajectory should always try to approach the sliding surfaces. Here both reference torque and desired speed is to be mentioned as shown in below figure.

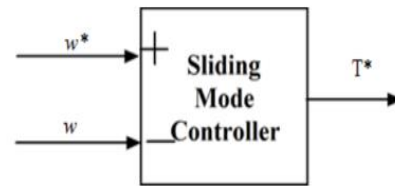


Fig. 9: Speed regulation using sliding motion

Here, the optimal performance means maintaining the speed of BLDC motor at rated speed, which is done by speed regulator built inherent in sliding mode controller. It is also important to maintain rated torque along with speed. The error in speed is calculated as a difference of rated speed and speed measured. ω^* is referred as rated speed and ω as measured speed [10].

Let,

$$e(n) = \omega^* - \omega = x_1 \quad (18)$$

The change error or derivative of error is given as,

$$x_2 = \dot{x}_1 = \frac{1}{T}[e(n) + e(n - 1)] \quad (19)$$

Here, T is the time interval and x_1, x_2 are state variables. The switching functions equations are defined as given below.

$$y_1 = \text{sgn}(zx_1) \quad (20)$$

$$y_2 = \text{sgn}(zx_2) \quad (21)$$

Where, z is given as following equation

$$z = c_1x_1 + c_2x_2 \quad (22)$$

The output equation of sliding mode controller be $u(n)$ and it is now considered as reference torque, T^* which is given as

$$u(n) = c_1x_1y_1 + c_2x_2y_2 \quad (23)$$

VII. RESULTS

The designed system been simulated in MATLAB and results are obtained. The performance characteristics of motor is also observed for all three controllers. The speed response of BLDC motor been carefully examined and response parameters are tabulated. It is seen that speed response of sliding mode controller has better response when compared to fuzzy and PI. The distortions in torques are seen in all three

cases. When the sliding mode controller is been considered, the torque response has more ripples, when compared with fuzzy and PI. The figures show performance characteristics of three controllers that contains the gate signals given to VSI, the inverter output voltage, the stator current, rotor speed and the electromagnetic torque of the BLDC motor.

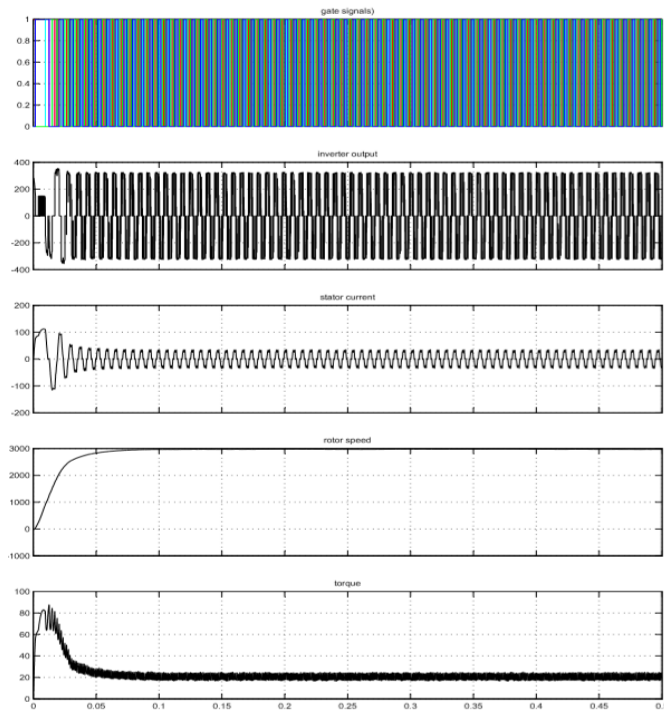


Fig. 10: Performance characteristics of BLDC motor with PI controller

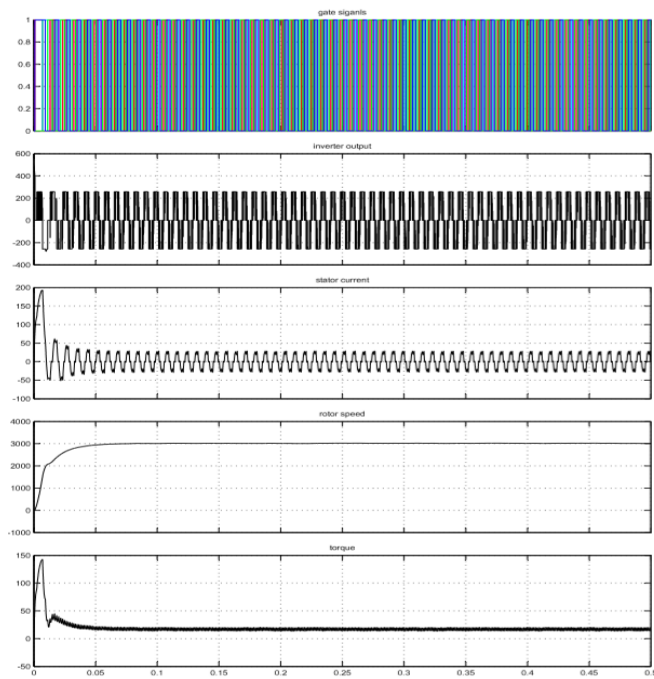


Fig. 11: Performance characteristics of BLDC motor with Fuzzy controller

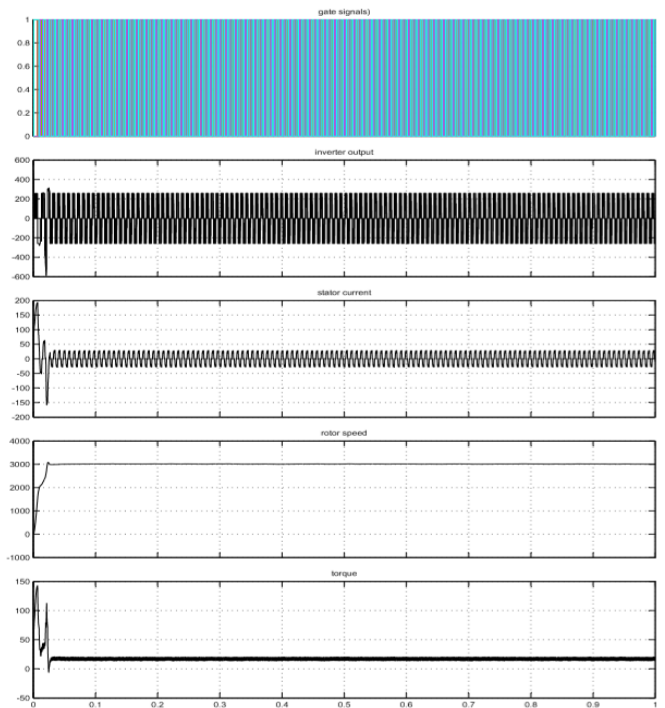


Fig. 12: Performance characteristics of BLDC motor with SMC controller

The speed of response of three controllers are compared and results are obtained as shown in the figure. The graph shows speed in rpm versus time in seconds.

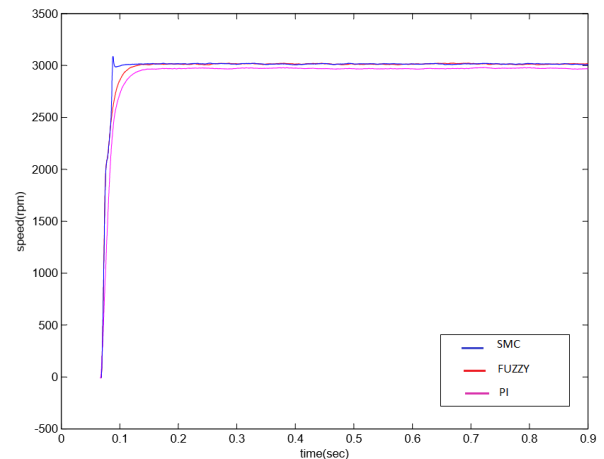


Fig. 13: Comparison of speed response using PI, Fuzzy and Sliding mode controllers

As seen in the above figure, the speed response of sliding mode control is better than the other two controllers. The table shows the speed response parameters of three controllers. The parameters like delay time, rise time, settling time and steady state error has been calculated and tabulated as shown in below table.

Table 2: Comparison of speed response with PI, Fuzzy and SMC controllers

S.No.	Parameters	PI	FUZZY	SMC
1	Delay time	0.014	0.007	0.006
2	Rise time	0.034	0.027	0.0035
3	Settling time	0.203	0.082	0.042
4	Steady state error	1.067%	0.53%	0.33%

VIII CONCLUSION

A Luo converter based BLDC motor has been proposed and designed along with the three controllers for optimum speed control using MATLAB along with the Simulink and sim power system toolboxes. The three controllers PI, fuzzy and sliding mode controllers are designed in accordance with Luo and BLDC and been simulated by considering with load torque constant. The rated speed has been obtained with PI control and fuzzy controllers also, but the parameters calculated shows that response was slow and sluggish. Simulated results show that sliding mode control is far better than conventional and linear controllers like PI and fuzzy controllers. The sliding mode control is to be designed carefully and constants are to be selected precisely.

APPENDIX I

Parameters of solar PV array: Open circuit voltage, $V_{oc} = 375.7$ V; Short circuit current, $I_{sc} = 20.65$ A; Maximum power, $P_{mpp} = 6$ kW; Voltage at MPP, $V_{mpp} = 310$ V; Current at MPP, $I_{mpp} = 19.35$ A; Numbers of cells connected in series in a module, $N_{ss} = 36$; Numbers of modules connected in series, $N_s = 17$; Numbers of modules connected in parallel, $N_p = 7$.

APPENDIX II

Parameters for Luo converter: Switching frequency, $f_{sw} = 20$ kHz; Input inductor, $L_1 =$ Output inductor, $L_2 = 5$ mH; Intermediate capacitor, $C_1 =$ DC link Capacitor, $C = 500$ μ F.

APPENDIX III

Parameters for BLDC Motor-Pump: Stator phase/phase resistance, $R_s = 0.41$ Ω ; Stator phase/phase inductance, $L_s = 2.13$ mH; Torque constant, $K_t = 0.74$ Nm/Apeak; Voltage constant, $K_e = 78$ VpeakL-L/krpm; Rated current, $I_{rated} = 22.15$ A; Rated torque, $T_{rated} = 16.5$ Nm; Rated speed, $N_{rated} = 3000$ rpm @ 310 V DC; Rated power, $P_{rated} = 5.18$ kW; No. of poles, $P = 6$; Moment of inertia, $J = 45.9$ kg.cm²; Proportionality constant, $K = 1.67 \times 10^4$.

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