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Speed Characteristics of Two-Fold Sliding Mode Control of BLDC Motor

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Abstract*: BLDC motors are generally implemented in copious industrial processes because of its high proficiency, large torque and minimum volume. The variation in load torque, causes the variation of speed in BLDC motor, which leads the complete system in unstable condition. In this paper a robust first-order SM controller scheme depends on twofold controlling algorithm for angular velocity and also current control in Brushless DC motor to attenuate the chattering problems. Two cascaded sliding mode controllers of first-order are used and first sliding mode controller generates stator currents based on speed error then the second SM controller generates voltage based on current-error in stator which runs the universal bridge by this controlled voltage source. In addition to the method suggested by Slotine, two feed forward loops are added to both speed and current errors to improve the response. The existing sliding-mode control is unresponsive to uncertainties and will cause undesirable chattering problems. To overcome this snag, a manual control law in conjunction with Sliding mode control is utilized that provides smooth and chattering free actual control signal. The overall system stability performance is implemented in MATLAB/SIMULINK and simulation results shows that proposed scheme is robust with respect to uncertainty in the system.

***Index Terms*: BLDC motor, current, speed, torque, sliding mode control.**

I. INTRODUCTION

Productivity and cost are the significant concerns in the improvement of small power motor drives focusing on household applications, for example, fans, water pumps, blowers, mixers and so forth [1]. There are two forms of dc motor drives utilized for most of the applications. The primary one is the ordinary direct current motor and its magnetic flux is formed by the current flowing through the coils of the fixed pole construction. The other one is Brushless DC (BLDC) motor that are electronically computed and its permanent magnet on rotor provides the required air gap magnetic-flux rather the wire wound filed poles [2]. The proportion of driving torque of direct motor measurements is high in the Brushless DC motors and its speed-torque bend is superior when compared to the brushed motors [3]. Owing to the Brushless DC motors ideal mechanical and electrical properties, those are broadly utilized as a part of servo applications, for example, automotive, aviation and actuators prerequisites [4].

Also, Brushless DC motor offers many important points including conservative form, high proficiency, easy of control, high flux density per unit volume, and minimum EMI (Electro-Magnetic Interference) and minimum maintenance prerequisite. A Brushless DC motor requires position sensor and inverter to commutate and the motor line current is in stage with the comparing back electromotive force (EMF)[5]. In this Brushless DC motor, connection between the commutators and mechanical brushes[6].The Brushless DC motor is employed broadly with a generally extensive variety of rotational speed, and this speed control needs that the line voltage of motor changes with respect to the speed [7].

The surface-mounted Brushless DC motor having trapezoidal back EMF bolstered by a 2-phase conduction scheme has maximum power/ torque/current proportions and this is more reasonable because of those concentrated windings which curtail the end coils [8].

The customary method to govern a Brushless DC motor is by means of voltage source-current controlled inverters. This inverter has to supply a rectangular shaped current waveform with a magnitude is relative to the shaft torque of motor [9]. In Brushless DC motor with distinct winding excitation, for variable-speed applications, the goal is to manipulate the field and armature voltage inputs in such a way that motor speed can be made to track a reference signal, requiring a quick recuperation from speed drop produced because of the influence of load [10]. They typically utilize at least three number of Hall sensors to get rotor angular velocity and position estimation. This is important to inverse the time contrast between two Hall sensor signals which are progressive, signs to acquire steady speed estimation [11]. The angular velocity regulator of Brushless DC motor is an imperative viewpoint in numerous industrial processes. Various control plans have been used for enhancing the angular velocity control execution of Brushless DC motor drives. Therefore, interests in rising canny control frameworks for Brushless DC motor drive has expanded altogether and various intelligent control plans for Brushless DC motor were composed according to linear and non-linear models [12]. Section II describes mathematical modelling of Brushless DC motor. Section III describes proposed controlling scheme, section IV describes simulation results and section V describes conclusion.

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II. MATHEMATICALMODEL OF THE BDCM

The BDCL motor drive has three identical windings in stator and a permanent-magnet on the rotor. The dynamic equations of stator windings can be obtained by applying KCL and KVL in stator circuit, currents induced in the rotor can be ignored and, so it's equivalent circuit equations of the three phase winding variables are [15]

$$\begin{pmatrix} V_a \\ V_b \\ Vc \end{pmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + p \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad \ldots(1)$$

$L_a = L_b = L_c = L$, Lab =Lbc =Lca = M but $i_a + i_b + i_c = 0$.

Therefore $M_{ib} + M_{ic} = -M_{ia}$ …(2)

Hence in state space form of motor we have that

$$p\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{bmatrix} 1/L-M & 0 & 0 \\ 0 & 1/L-M & 0 \\ 0 & 0 & 1/L-M \end{bmatrix} \begin{pmatrix} V_a \\ V_b \\ Vc \end{pmatrix} - \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} - \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad \ldots(3)$$

and

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\ \omega_r \quad \ldots(4)$$

Equations (1), (2), (3) & (4) describes mathematical model of BLDC motor

III. PROPOSED CONTROLLING SCHEME

The feeding electrical supply can be considered as a freely controllable voltage source. The time behaviour of a working cycle for various cases of the angular velocity can easily be analysed. At small speeds, the current can be switched on at the instant with smallest inductance and switched off at the aligned position. In order to switch-on and to switch-off the current as fast as possible, maximum and minimum voltages are applied. The current rise is as quicker as the decay, because the winding inductance in the aligned position is larger as at switch on. If rise of current and decay of current are finished within the intervals of nearly constant inductance.

At higher speed, the current rise takes more time due to the increased counter voltage. It must be considered that the angle is passed through faster at higher speed, also contributing to a flatter shape of the current vs. angle. The counter voltage, however, helps in the demagnetization phase. Switch-on and switch-off would be triggered when the small angular velocity in order to rise the torque as fast as possible and to bring it down before the winding inductance reduces again and would generate negative torque. Because of rounded shape of the current a cut back of the converted work and also of the torque has to be considered and compared to the idealized cycle.

At high speed, switch-on and switch-off angles have to be pulled ahead. The counter voltage is now so large that the current will no longer reach its previous peak value. The exploitation of work and torque reduces distinctly. As an approximation, the torque reduces inversely proportional to the angular velocity.

In case of a simple angular velocity control, the angular velocity controller acts directly on the armature voltage. However, a feed forward path which is used for compensation of EMF turns out as an advantageous detail. In doing so, the EMF action paths in the motor model and in the controller are mutually cancelled out. As a result, we will get an equivalent control system consisting only of a P-T1 delay element and an integrator. The attainable bandwidth of feedback control system can be varied in some range, however, in any case the bandwidth is below the corner frequency of the system transfer function. The important plant time constant is given here by the armature circuit time constant.

$$\tau_A = La/Ra \quad \ldots(5)$$

With small time constants or small requirements with respect to dynamical performance, such a design may suffice with higher dynamic demands which come up typically with motors of higher power rating where the armature circuit time constants are even large, this type of control is usually no longer applied. Another drawback of single-loop angular velocity control is the fact that there is no direct supervision of the armature-current. The armature current is a critical quantity as exceeding of the rated value may damage the devices due to heating-up. The motor thermal time constants are usually large, an excess of the rated current can be tolerated for a short span of time (usually some seconds). Even more critical are the feeding power electronic devices as their thermal time constants are very small, e.g. some fractions of a second. So, over currents are often not allowed at all. A control, which cannot guarantee that the current will retain within the allowed limits, is thus very critical.

However, it is possible to supervise the armature current, also the transient behaviour will be improved. The is construction of control in so-called cascaded manner. The objective of the inner control for current loop is to track the demand current value, that is provided from the outer controller for speed. Since the torque and armature current are proportional, the inner current control can be seen as torque control. Similar to the single-loop speed control, an EMF feedforward compensation is recommended also here.

The control design starts with design of the current control in armature circuit first. The plant time constant is given by the armature time constant. However, unlike as with the single-loop control above, here the transfer function does not include an integrator. If applicable, another small time constant could be included in the transfer function for considering the influences of data sampling or sensor time constants. According to the symbols used with the Magnitude Optimum design this small time constant would be τ_σ . The armature circuit time constant τ_A now plays the role of the large plant time constant τ_s. The achievable control bandwidth is now in the range of the small time constant τ_σ while the large armature circuit time constant is not important for the tracking behaviour. So, the achievable transient performance of current control turns out to be dimension better than the performance of the single-loop control.

Now, also the angular velocity controller benefits from the good transient behaviour of current control. The angular velocity controller can be designed much faster as with the single-loop approach.

In order to do so, the feedback current control is being approximated by a delay component with a small time constant.

The design of the angular velocity controller can be again done with the Symmetrical Optimum approach, however, now resulting in a much better performance.

The supervision of the current allowed current rating, as discussed above, can now be realized easily by a simple limitation of the current reference value. In fact, there may occur deviations between demanded and actual current values. If the current controller is well tuned, theses deviations will usually be only small so that the actual current will really retain within the allowed limitation, where a small safety margin should be taken into account.

The advantage of the projected controller was that it minimizes the overshoots of the control voltage at the startup of the converter in terms of magnitude variation of loads. Arun Prasad *et al.* [13] have proposed fuzzy SM controller (FSMC). A powerful and reliable system controlling method is necessary in the Brushless DC motor control system to minimize the motor's nonlinear characteristics and uncertain delay in the system. Hence, in this paper SM control method is utilized along with the manual tuning of sliding surface parameters, to improve dynamic behavior, and the disturbance rejection ability, a new sliding mode control with manual tuning controller parameters will be developed.

Slotine suggested an equation to identify the sliding surface [14] represented in the following form

$$S = \left(\alpha + \frac{d}{dt}\right)^{n-1} e \qquad \text{.... (6)}$$

Where, e is the error, n is order of the system, and α is a constant.

For controlling of two loops i.e. current loop and speed loop consider

$$S_1 = e_1 = i_{ref} - i \qquad \text{.... (7)}$$

$$S_2 = e_2 = \omega_{ref} - \omega \qquad \text{.... (8)}$$

Where, i_{ref} and ω_{ref} are reference current and reference speed value. By employing reaching law approach for the inner current sliding mode controller is S_1

$$\overset{*}{S}_1 = -\alpha\,\mathrm{sgn}(S_1) - \beta S_1 = \frac{de_1}{dt} \qquad \text{.... (9)}$$

By using equation (7)

$$\frac{de_1}{dt} = \frac{d(i_{ref} - i)}{dt} = -\alpha\,\mathrm{sgn}(S_1) - \beta S_1 \qquad \text{.... (10)}$$

By using (9)

$$\frac{di_{ref}}{dt} - \frac{di}{dt} = \frac{V - iR - E}{L} = -\alpha\,\mathrm{sgn}(S_1) - \beta S_1 \qquad \text{.... (11)}$$

Now using equation (11) and (14)

$$V = L\left(\alpha\,\mathrm{sgn}(S_1) + \beta S_1 + \frac{di_{ref}}{dt}\right) + E + (i_{ref} - i)R \qquad \text{.... (12)}$$

The outer loop speed controller

$$\overset{*}{S}_2 = -\gamma\,\mathrm{sgn}(S_2) - \zeta S_2 \qquad \text{... (13)}$$

$$\frac{de_2}{dt} = \frac{d(\omega_{ref} - \omega)}{dt} = -\gamma\,\mathrm{sgn}(S_2) - \zeta S_2 \qquad \text{....(14)}$$

$$\frac{d\omega_{ref}}{dt} + \frac{(B\omega - T + T_L)}{J} = -\gamma\,\mathrm{sgn}(S_2) - \zeta S_2 \qquad \text{....(15)}$$

Now using equation (13) and (7)

$$T = J\left(\gamma\,\mathrm{sgn}(S_2) + \zeta S_2 + \frac{d\omega_{ref}}{dt}\right) + T_L + (\omega_{ref} - \omega)B \qquad \text{... (16)}$$

In addition to the method suggested by Slotine, two feed forward loops are added to both speed and current errors to improve the response. The block representation of the sliding mode controller is demonstrated in Fig. 1

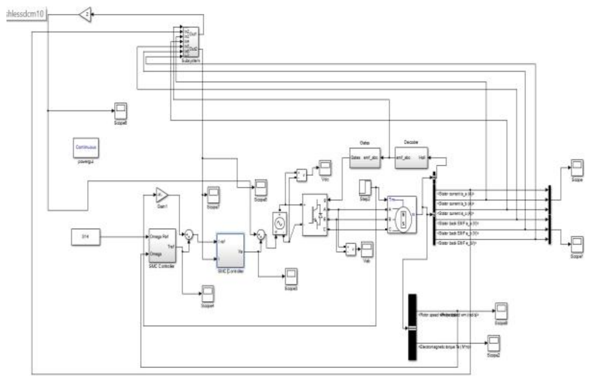

Fig. 1. SMC block diagram for BLDC

IV. SIMULATION RESULTS

To authorize the control methods as considered, simulation and mathematical modeling were approved out on a BLDC motor drive scheme by using simulation. The parameters and their values used in the modelling of BLDC motor is listed in table 1.

I. PARAMETERS OF THE BLDC MOTOR

Symbol	Quantity	Value of the parameter
J	Moment of inertia	0.0008 Kg m^2
B	Friction-coefficient,	0.001kg / msec
K_b	Back emf-constant	146.6 volts / rad / sec
K_t	Torque-constant	1.4 Nmt / amp
L	Inductance	0.0085 henries
P	Pole pairs	4
R	Resistance	2.875 ohm

The speed characteristics of open loop BLDC motor is shown in figure 2.

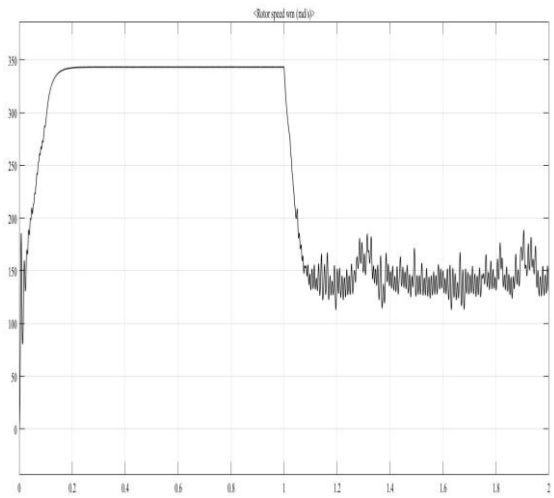

Fig. 2. Variation of speed without controller (load at T=1sec)

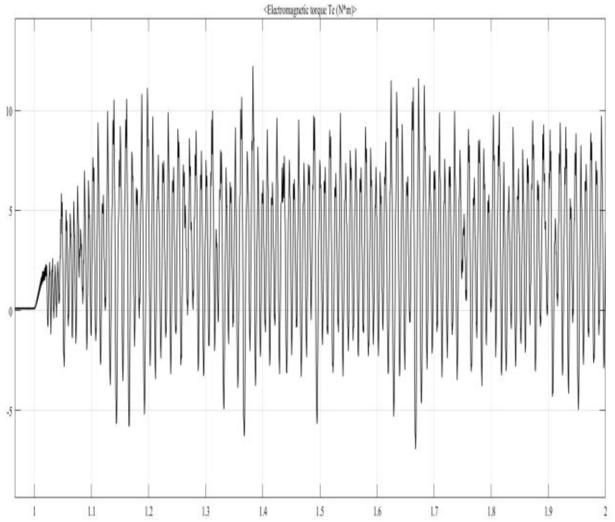

Fig. 3. Variation of torque without controller (load at T=1sec)

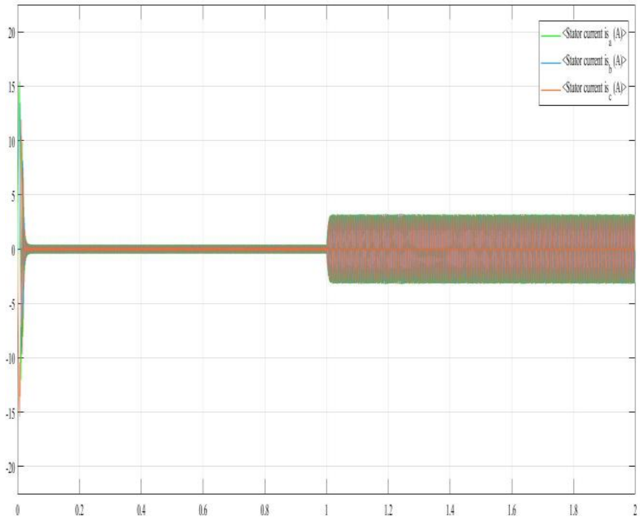

Fig. 6 stator currents with PI controller (load at T=1sec)

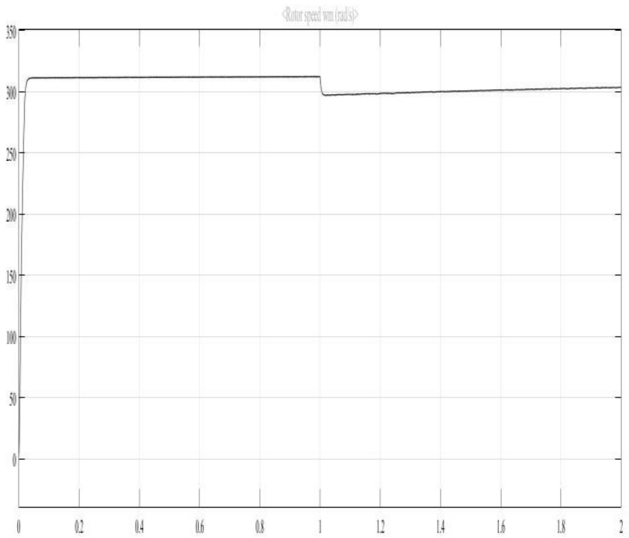

Fig. 4. Variation of speed with PI controller (load at T=1sec)

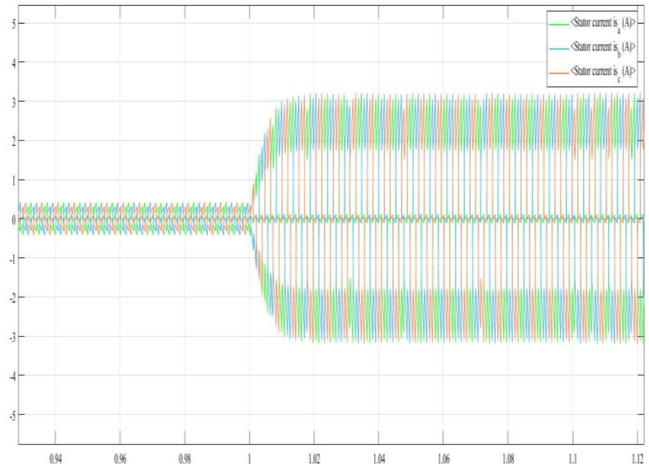

Fig. 7 Stator currents with PI controller in detail (load at T=1sec)

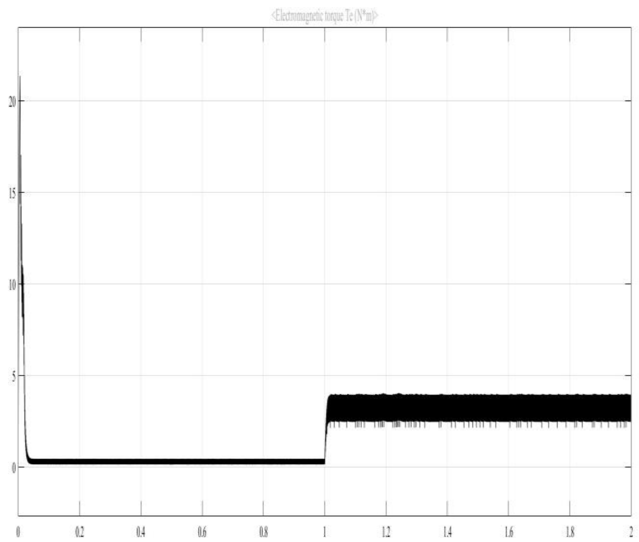

Fig. 5 Variation of torque with PI controller (load at T=1sec)

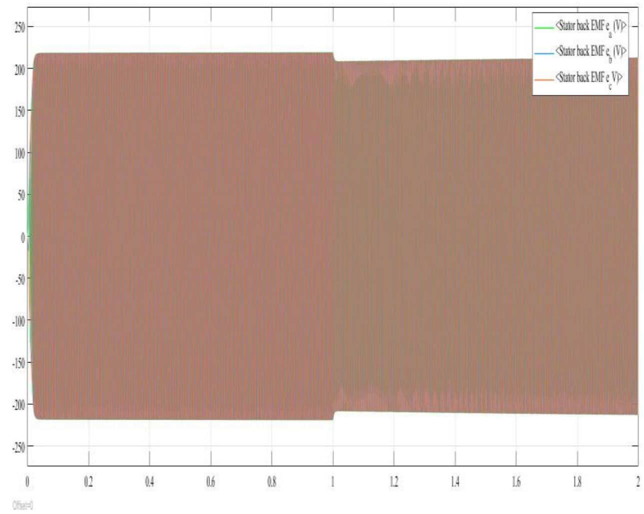

Fig. 8 back emf with PI controller (load at T=1sec)

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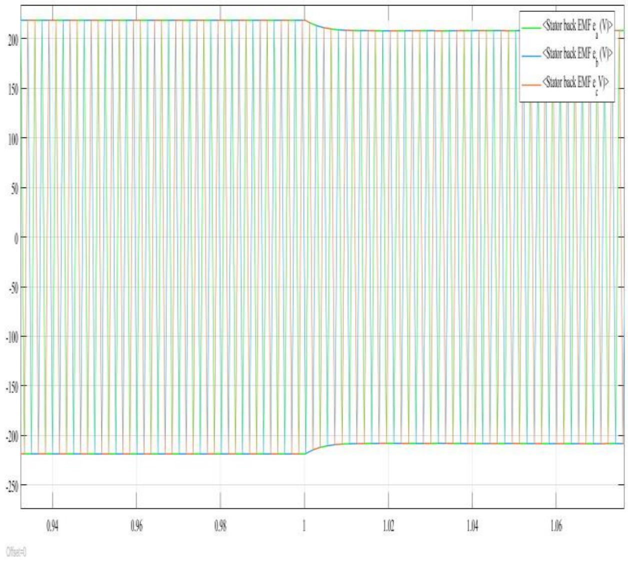

Fig. 9 Back emf using PI controller (load at T=1sec)

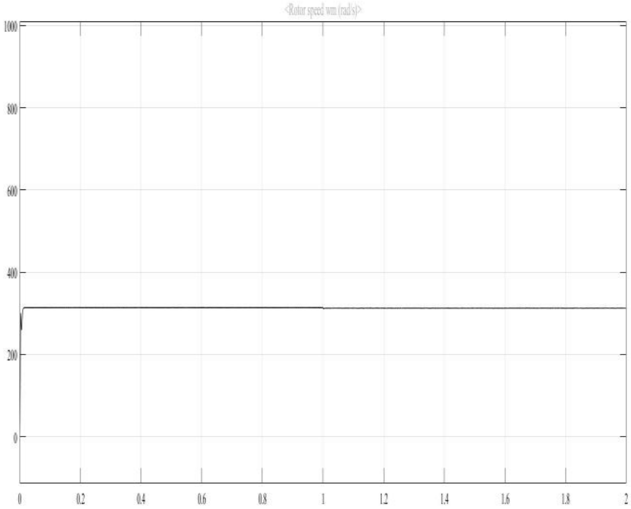

Fig. 10 Speed with SMC (load at T=1sec)

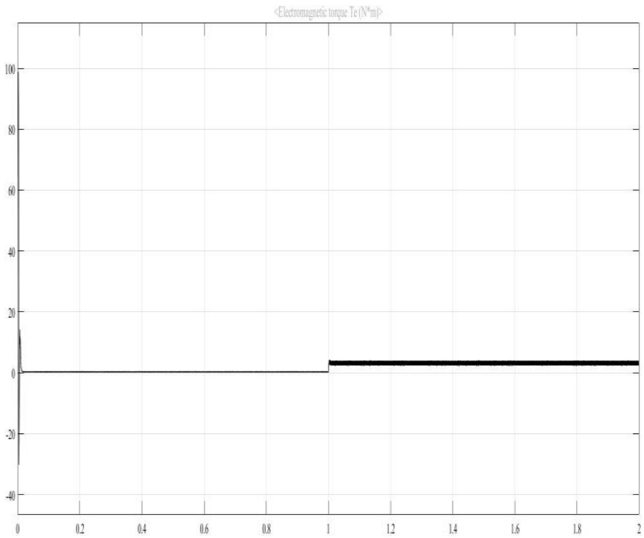

Fig. 11 Variation of torque with SMC (load at T=1sec)

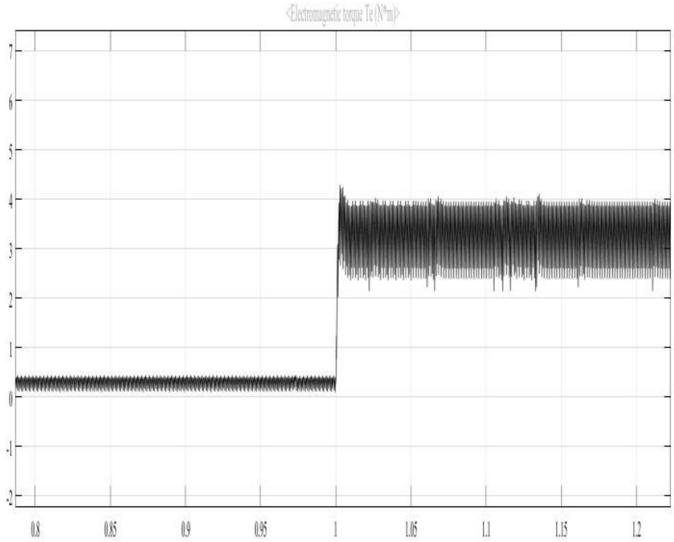

Fig. 12 Torque using SMC (load at T=1sec)

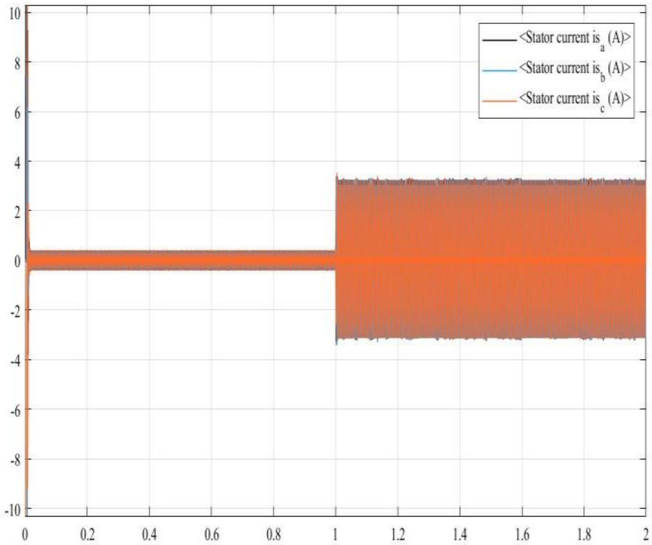

Fig. 13 Variation of stator currents with SMC (load at T=1sec)

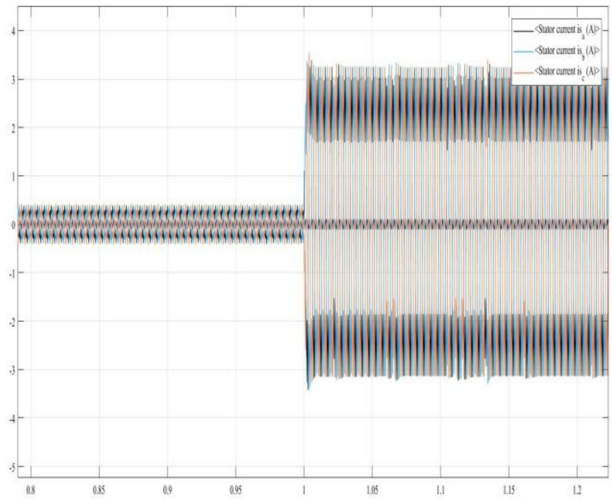

Fig. 14 Variation of stator currents with SMC (load at T=1sec)

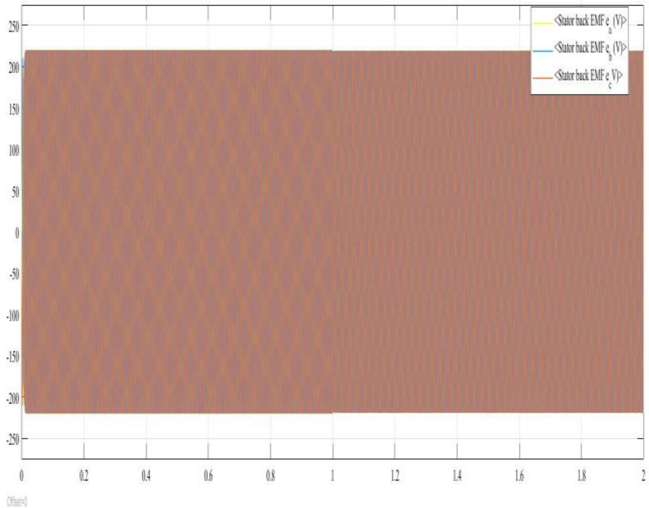

Fig. 15 Variation of back emf with SMC (load at T=1sec)

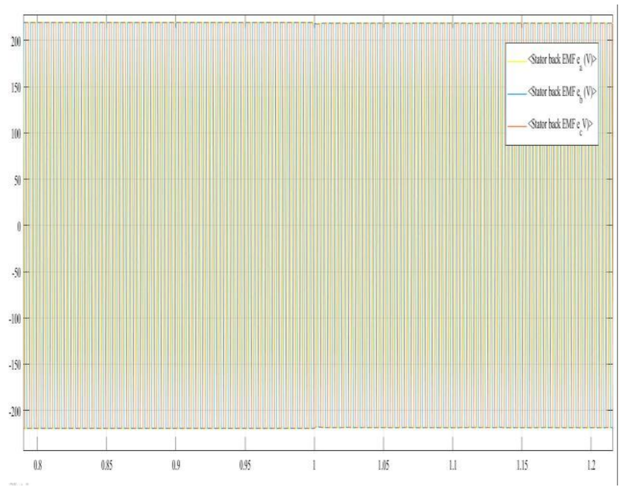

Fig. 16 Variation of back emf with SMC

To show the efficiency of our proposed SM controller we relate our simulation results with the results of PI controller with the response of the angular velocity of the Brushless DC motor which is shown in figures. From the figures, we can understand that our proposed controller affords better results compared with PI controller. The time taken for the motor to reach the steady state for the proposed controller is low compared with PI controller. The settling time T_s for the controllers are given in table II.

II. SIMULATION RESULTS

S. no	Methods	Settling Time, *Ts*	Speed error
1	Proposed method	5ms	0
2	PI	40ms	14rad/sec

In open loop control there is nearly 200rad/sec error in speed response and large variations in torque. Speed error depends only on the voltage given to the controller circuit, but this voltage is fixed in brushless DC motor without controller and this error can be reduced by using a controller.

From the simulation we can observe that the settling time for our proposed SM controller is fewer than the settling time taken for PI controlled BLDC motor, and also the change in speed when load of 3 Nm is applied at T=1sec is zero in our proposed method, whereas this speed change is nearly 15 rad/sec in PI controller, so we can conclude that SM controllers with feed forward loops giving better performance than PI controller. Torque variations under load conditions is minimum in SM controller when compared to PI controller

V. CONCLUSION

The SM Controller structure is proposed for the BLDC motor drive for tracing rapid angular velocity variations around the effective conditions. The results are analyzed for both our proposed and PI controllers, which shows the efficiency of the system. Results from simulation shows that the proposed improved two-fold SM controller provided faster convergence that enables less speed recovery time, chattering reduction and robust for quick speed changes. From the results, it's far clean that the proposed SM controller can able to eliminate the uncertainty trouble going on because of load variations and set speed variations, so that it is ideal for application in method industries. Future work may be focused on multiple sensors (currents, angular velocity and voltage) fault-tolerant control by means of designing appropriate additional controllers.

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