Research Article

Effect of Parameter Variations on Sensorless Control of BLDC Motor Using Disturbance Torque Estimation

Mitesh B. Astik[1], Praghnesh Bhatt[2]*, Bhavesh R. Bhalja[3]

[1]Department of Electrical Engineering, A. D. Patel Institute of Technology, New Vallabh Vidyanagar, India
[2]Department of Electrical Engineering, C. S. Patel Institute of Technology, CHARUSAT, Changa, India
[3]Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India

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Correspondence to:
*Praghnesh Bhatt:
pragneshbhatt.ee@charusat.ac.in

Abstract:

The performance of a Brushless DC (BLDC) motor drive can be affected by disturbance torque which acts on the shaft of the motor. Hence, the information of the disturbance torque is important and necessary. The disturbance torque is estimated using disturbance torque observer. This disturbance estimated torque is the sum of proportional and the time integral of the estimation error of current. The speed of BLDC motor is estimated from the knowledge of estimated disturbance torque. A new controller scheme based on Modified Hybrid Fuzzy PI (MHFPI) controller is proposed to control the speed of BLDC motor. Simulations have been carried out for different disturbances such as step changes in the reference speed and load torque of the motor. Transient and steady state accuracy are determined in nominal conditions and the effects of motor parameters variations are analyzed. Comparison of the proposed scheme with the existing schemes clearly depicts that the effect of disturbance on actual and estimated responses are very less.

Keywords: : BLDC Motor, Disturbance Torque Estimation, MHFPI Controller, Observer Design, Sensorless Control.

INTRODUCTION

In an actual system, some external factors always exist which affect the system behavior. Disturbance torque acting on the motor shaft is one of the external factor which affect the behavior of the BLDC motor drive. Hence, the knowledge of the disturbance torque is important and necessary. But the disturbance torque cannot easily measured and hence, estimation is required. The estimation of disturbance torque has been proposed for DC motor, BLDC motor, PMSM motor and servo motor drive (Buja et. al. (1995); Park et. al. (2003); Akrad et. al. (2010); Chen and Cheng (2012)) respectively. Park et. al. (2003) proposed the load torque observer in which q-axis current of BLDC motor has been considered as compensating current. Rodriguez and Emadi (2006) have suggested digital control technique for BLDC motor drive using the speed and torque observation from the state observer. Bernat and Stepien (2011) have proposed LQR and feedback linearization method to design the optimal current driver.

Ghassemi and Vaez-Zade (2005) proposed a method for Direct Torque Control (DTC) of PM motors. The rotor position estimation error decreases the starting torque; consequently, it increases the time needed for start-up, especially in the DTC of PM Motors. So it is important that the rotor position estimation error be minimized. Asaei and Rostami (2008) presented an estimation method based on the stator current variations due to the saturation of the stator core. The error in estimated rotor position is around 6° during starting. Stirban et. al. (2012) proposed position and speed observer for sensorless control of PM BLDC motor from the estimation of line-to-line values of PM flux linkage. In this method, the speed error is very high and estimated rotor position error is around 3-4 electrical degree. Terzic and Jadric (2001) proposed an estimation method based on extended kalman filter for estimation of speed and rotor position of a BLDC motor. This method has very large estimated rotor position error for below rated speed of the motor. Rostami and Asaei (2009) proposed a method for the estimation of initial rotor position for PM motors based on saturation effect. This method has the maximum estimated rotor position error is ±3.75°.

Nowadays, the Proportional Integral (PI) controller has been commonly used but they are not suitable for non-linear and particularly complex systems those have no exact mathematical models. Fuzzy logic is a controller which does not need a precise mathematical model of the system. Hence it can be used in place of PI controller. Shanmugasundram et. al. (2014) proposed design and implementation of the fuzzy controller to control the speed of BLDC motor in which the comparison between fuzzy and PID controller has been discussed. Arulmozhiyal (2012) proposed design and implementation of the fuzzy controller for BLDC motor using FPGA. In recent years, the hybrid fuzzy logic controller was proposed for induction motor, permanent magnet synchronous motor and BLDC Motor drive (Rubaai et. al. (2001); Zerikat and Chekroun (2007); Sant and Rajagopal (2009)) respectively.

In this paper, the disturbance torque is continuously estimated using classical observer. For accurate estimation of disturbance torque, two schemes are used in this paper i.e. disturbance torque as an unidentified input and as a state variable. The estimated disturbance torque is considered as the sum of proportional and time integral of the estimation error of current. This estimated disturbance torque is useful to estimate the speed of BLDC motor. The estimated rotor position is found from the estimated speed of the motor. Modified Hybrid Fuzzy PI (MHFPI) controller is used to control the speed of the motor. From the simulation results; the maximum estimated rotor position error observed in this paper is less than 1 electrical degree for nominal parameter and maximum 6 electrical degrees when 10% variations are applied to motor parameters.

MODELING OF BLDC MOTOR

The equation of the three phase voltages of BLDC motor can be expressed as Eq. (1) (Lee and Ahn (2009); Xia (2012)).

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

Where, V_a, V_b and V_c are stator phase voltages, i_a, i_b and i_c are the stator phase currents, R and L are the stator resistance and inductance per phase respectively, e_a, e_b and e_c are the back EMFs of each phase.

The relationship between motor speed (ω) and back EMF (e) can be represented as shown in Eq. (2) (Park et. al. (2012).

$$\omega = \frac{e}{K_T} \tag{2}$$

Hence, Eq. (1) can be rewritten as shown in Eq. (3)

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + K_T \begin{bmatrix} \omega_a \\ \omega_b \\ \omega_c \end{bmatrix} \tag{3}$$

The Mechanical equation of BLDC motor can be represented as Eq. (4).

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{4}$$

Where, T_e is the electromagnetic torque, B and J are viscous friction coefficient and moment of inertia respectively and T_L is the load torque.

The relationship between torque and current is given by

$$T_e = K_T i \tag{5}$$

The line-to-line electrical and mechanical equations can be expressed by Eqs. (6) and (7) respectively

$$v_z = Ri_z + L\frac{di_z}{dt} + K_T\omega_z \tag{6}$$

$$K_T i_z = J\frac{d\omega_z}{dt} + B\omega_z + T_L \tag{7}$$

Where z is Line-to-line quantities of BLDC motor. The equations of brushless dc motor in terms of disturbance are given by

$$\dot{i}_z = -\frac{R}{L}i_z - \frac{K_T}{L}\omega_z + \frac{1}{L}v_z - \frac{1}{L}v_{dz} \tag{8}$$

Where,

$$v_{dz} = \Delta R i_z + \Delta L \dot{i}_z + \Delta K_T \omega_z \tag{10}$$

$$T_{dz} = T_L + \Delta J\dot{\omega}_z + \Delta B\omega_z - \Delta K_T i_z \tag{11}$$

Where, Δ is for the parameter variations, dzv and dzT are Line-to-line disturbance voltage and disturbance torque respectively. By rearranging the mechanical equation of the BLDC motor in Eq. (9), the disturbance torque can be written as

$$T_{dz} = K_T i_z - B\omega_z - J\dot{\omega}_z \tag{12}$$

This scheme requires a speed sensor which presents several disadvantages like an increase in machine size, reduction in reliability and more value of noise. In order to eliminate the speed sensor, the sensorless control method is proposed.

ESTIMATION OF SPEED AND DISTURBANCE TORQUE

In a sensorless BLDC motor drive, only currents and voltages can be measured. In this paper, the disturbance torque is estimated from the estimation error of current. For accurate estimation of disturbance torque, following two schemes are discussed in this section.

Disturbance Torque as an Unidentified input

The state variable model of the BLDC motor can be represented by

$$\begin{aligned} \dot{x} &= Ax + Bu + ET_{dz} \\ y &= cx \end{aligned} \tag{13}$$

Since the system expressed by Eq. (13) is completely observable; the full-order state observer can be designed by Eq. (14).

$$\dot{\hat{x}} = A\hat{x} + Bu + Kc(x - \hat{x}) \tag{14}$$

Where,

$$A = \begin{bmatrix} -\frac{R}{L} & -\frac{K_T}{L} \\ \frac{K_T}{J} & -\frac{B}{J} \end{bmatrix},\ B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix},\ c = \begin{bmatrix} 1 & 0 \end{bmatrix},\ E = \begin{bmatrix} 0 \\ -\frac{1}{J} \end{bmatrix} \tag{15}$$

$$u = v_z,\ K = \begin{bmatrix} k_1 \\ k_2 \end{bmatrix},\ (x - \hat{x}) = \begin{bmatrix} e_{iz} \\ e_{\omega z} \end{bmatrix} = \begin{bmatrix} i_z - \hat{i}_z \\ \omega_z - \hat{\omega}_z \end{bmatrix}$$

Where K is the observer gain matrix. e_{iz} and $e_{\omega z}$ are the Line-to-line estimation error of current and speed respectively. From Eqs. (13-15)

$$\begin{bmatrix} \dot{e}_{iz} \\ \dot{e}_{\omega z} \end{bmatrix} = \begin{bmatrix} \dot{i}_z - \dot{\hat{i}}_z \\ \dot{\omega}_z - \dot{\hat{\omega}}_z \end{bmatrix} = \begin{bmatrix} -\left(\frac{R}{L} + k_1\right) & -\frac{K_T}{L} \\ \left(\frac{K_T}{J} - k_2\right) & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_z - \hat{i}_z \\ \omega_z - \hat{\omega}_z \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{1}{J} \end{bmatrix} T_{dz} \tag{16}$$

The estimation error of current tends to constant and hence the time derivative of estimation error i.e. $\dot{e}_{iz} = 0$ for a nearly constant disturbance torque. Thus, estimation error of speed can be expressed in terms of estimation error of current and is given by Eq. (17).

$$e_{\omega z} = -\left(\frac{R + k_1 L}{K_T}\right) e_{iz} \tag{17}$$

To estimate the disturbance torque, consider the time derivative of speed error of Eq. (16) is to be zero and replace the value of speed error from Eq. (17) into Eq. (16). Thus the estimated disturbance torque can be represented by

$$\hat{T}_{dz} = \left[(K_T - k_2 J) + \left(\frac{B}{K_T}\right)(R + k_1 L)\right] e_{iz} \tag{18}$$

Assuming the viscous friction coefficient (B) is very less. Hence, Eq. (18) becomes

$$\hat{T}_{dz} = (K_T - k_2 J) e_{iz} \tag{19}$$

Disturbance Torque as a state variable

The state variable model of BLDC motor with disturbance torque as a state variable can be represented in Eq. (20).

$$\dot{x}_a = A_a x_a + B_a u \tag{20}$$

$$y_a = c_a x_a \tag{21}$$

As the pair A_a and c_a is observable, the motor states can be estimated by

$$\dot{\hat{x}}_a = A_a \hat{x}_a + B_a u + K_a c_a (x_a - \hat{x}_a) \tag{22}$$

where,

$$K_a = \begin{vmatrix} k_1 \\ k_2 \\ k_3 \end{vmatrix} \tag{23}$$

From Eqs. (22) and (23), the state of the motor can be estimated in the simplified form and can be written as

$$\begin{bmatrix} \dot{\hat{i}}_z \\ \dot{\hat{\omega}}_z \\ \dot{\hat{T}}_{dz} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{K_T}{L} & 0 \\ \frac{K_T}{J} & -\frac{B}{J} & -\frac{1}{J} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_z \\ \hat{\omega}_z \\ \hat{T}_{dz} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix} v_z + \begin{vmatrix} k_1 \\ k_2 \\ k_3 \end{vmatrix} \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_z - \hat{i}_z \\ \omega_z - \hat{\omega}_z \\ T_{dz} - \hat{T}_{dz} \end{bmatrix} \tag{24}$$

From Eq. (24), the estimated disturbance torque can be represented by

$$\hat{T}_{dz} = k_3 \int e_{iz} dt \tag{25}$$

From Eqs. (19) and (25), the total estimated disturbance torque can be expressed as

$$\hat{T}_{dz} = (K_T - k_2 J) e_{iz} + k_3 \int e_{iz} dt \tag{26}$$

From Eq. (26), the disturbance estimated torque is the sum of proportional and the time integral of the estimation error of current.

The resultant disturbance estimated torque is given by

$$\hat{T}_d = \frac{\hat{T}_{d\,ab} + \hat{T}_{d\,bc} + \hat{T}_{d\,ca}}{3} \tag{27}$$

Fig. 1 shows the block diagram of disturbance torque and speed estimation of BLDC motor.

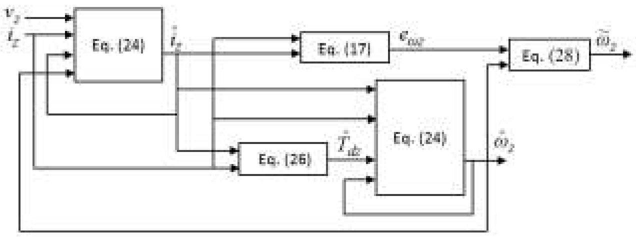

Fig. 1 Block diagram of speed and disturbance torque estimation

Actual speed of the motor ($\tilde{\omega}_z$) is found out by addition of speed delivered by the observer ($\hat{\omega}_z$) and estimation error of speed ($e_{\omega z}$) and can be represented as Eq. (28)

$$\tilde{\omega}_z = \hat{\omega}_z + e_{\omega z} \tag{28}$$

The final estimated speed of BLDC motor ($\hat{\omega}_m$) is found by considering the absolute and maximum value of all the three line-to-line actual speed of the motor as shown in Fig. 2.

The disturbance current which is obtained from the disturbance torque estimation can be expressed by Eq. (29)

$$i_d = \frac{\hat{T}_d}{K_T} \tag{29}$$

The reference current i_s^* for the hysteresis current controller can be expressed as Eq. (30) which is the addition of the current i_c from the MHFPI controller and disturbance current i_d.

$$i_s^* = i_c + i_d \tag{30}$$

Fig. 2 shows the overall block diagram of the proposed sensorless BLDC motor drive. The line-to-line voltage is calculated using DC-link voltage and commutation signals. The speed and disturbance torque are estimated from the observer as mentioned in this section. The estimated position of the rotor is found from the estimated speed of the motor. The estimated speed is fed to the error detector which finds the difference between the estimated and desired value of the speed. The output of the error detector is fed to the modified hybrid fuzzy PI speed controller which decides the current set value depending upon the gain values of the controller. The torque reference divided by the torque constant K_T would give current I_c. The reference current I_s^* for the hysteresis current controller is expressed from Eq. (30). The gate signals for inverter are generated using commutation signals and comparing the actual and reference current using the hysteresis current controller. These gate signals decide exact voltage to be applied across the BLDC motor. The gain of the hysteresis band controller using in this paper is 0.01 for better current control. For a better disturbance torque and speed estimation, the values of the observer gains k_1, k_2 and k_3 set in this paper are 5076, -192757 and 1688669 respectively. Ackerman's method is used to calculate the observer gains which is mentioned in Mandal (2006).

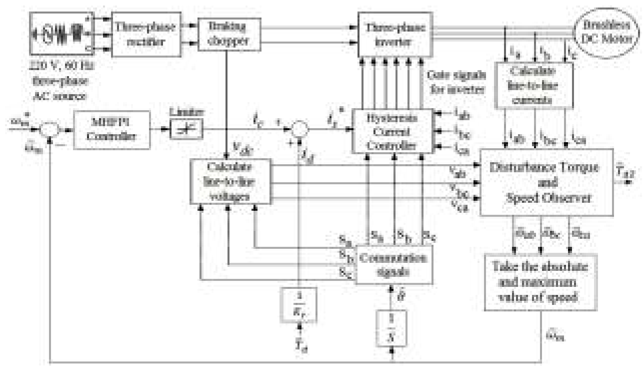

Fig. 2 Overall block Diagram of the proposed sensorless BLDC motor drive

MODIFIED HYBRID FUZZY PI CONTROLLER

The fuzzy logic controller has two inputs i.e. the error and change of error which are defined by

$$\omega_e(n) = \omega_m^*(n) - \hat{\omega}_m(n) \tag{31}$$

$$\Delta\omega_e(n) = \omega_e(n) - \omega_e(n-1) \tag{32}$$

Where, $\omega_m(n)^*$ and $\omega_m(n)$ are the reference speed and estimated speed of the motor respectively. $\omega_e(n)$ & $\Delta\omega_e(n)$ are the error and change of error in speed respectively. Indexes n and (n-1) indicate the present and the previous state respectively. $\Delta u(n)$ is output f fuzzy controller. Membership function of the FLC input $\omega_e(n)$ is normalized between [-15, 15], $\Delta\omega_e(n)$ is normalized between [-1e^6, 1e^6] and the output $\Delta u(n)$ is normalized between [-25, 25]. The linguistic labels used to describe the fuzzy sets were "Negative Big" (NB), "Negative Medium" (NM), "Negative Small" (NS), "Zero" (Z), "Positive Small" (PS), "Positive Medium" (PM) and "Positive Big" (PB). The rule base structure used in this paper is Mamdani type. The set of decision rules used in this paper is shown in Table 1.

Table 1.Table of fuzzy rules

$\Delta\omega_e(n)$ / $\omega_e(n)$	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

Parallel Fuzzy PI (PFPI) controller is the addition of PI and fuzzy controller. The combination of PI and PFPI controller are used as an MHFPI controller. The objective of this controller is to produce the better response than the conventional controllers. Two switching functions for the MHFPI controller have been considered. An approach for the switching control of this controller is such that for most of the time PI controller is activated and use of the PFPI controller only when the system behavior is oscillatory or tends to overshoot. The selection between the PI and PFPI controller is based on the following condition:

If the error signal $\omega_e(n)$ is strictly greater than zero and its previous value $\omega_e(n\text{-}1)$ was strictly less than or equal to zero, the PI controller will work. If the previous value of error signal is strictly greater than zero, PFPI controller will work.

$$U_{MHFPI} = \begin{cases} U_{PI},\ for\ \omega_e(n-1) \le 0 \ \&\ \omega_e(n) > 0 \\ U_{PFPI},\ for\ \omega_e(n-1) > 0 \ \&\ \text{all}\ \omega_e(n) \end{cases} \tag{33}$$

SIMULATION RESULTS AND DISCUSSIONS

The parameters of BLDC motor used in MATLAB/Simulink environment are given in Table 2.

Various simulations have been performed on BLDC motor to validate the effect of MHFPI controller and disturbance torque observer on its dynamic performance. The effect of variations in rotor reference speed and load torque along with the parameter variations have been evaluated in the proposed work.

Table 2. BLDC motor parameters

Parameters	Ratings
Stator resistance (R)	0.2 (Ω)
Stator inductance (L)	8.5 (mH)
Rotor inertia (J)	0.089 (kg-m^2)
Friction (B)	0.005 (Nm-s)
Number of poles (P)	4
Rated speed (ω_s)	300 (rpm)
Torque Constant (k_T)	1.4 (Nm/A_peak)
Flux linkage established by magnets (λ_p)	0.175 (volt-s)
Motor Output Power	3 HP

The following cases are considered for the validation of the proposed method.

Step Changes in Reference Speed Keeping Load Torque Zero

The variations in current, speed, torque, speed difference between actual and estimated speed, rotor position and difference in rotor position are shown in Fig. 3 for the step changes in speed from 0 rpm to 50 rpm at t=0 s, 50 rpm to 300 rpm at t= 0.15 s and 300 rpm to 50 rpm at t=0.5 s. From Fig. 3(a), it is observed that only two winding currents are conducted at any time and third winding current is zero. The variations in actual and estimated speed can be observed in Fig. 3(b), which indicate that the actual and estimated speed always keep tracking for every step changes in rotor reference speed. From Fig. 3(c), it can be seen that the actual torque successfully tracks the reference torque at all instants even during the step changes in the rotor reference speed. The maximum speed difference between actual and estimated speed is observed from Fig. 3(d) is 5 rpm during starting and 1 rpm during steady state. From Fig. 3(e) and 3(f), it is observed that the actual rotor position successfully tracks the estimated rotor position and the maximum difference between the two rotor positions is around 0.07 electrical degree.

The variations in moment of inertia and stator resistance are applied in BLDC motor along with the step changes in reference speed. The effect of these variations are observed in terms of speed difference

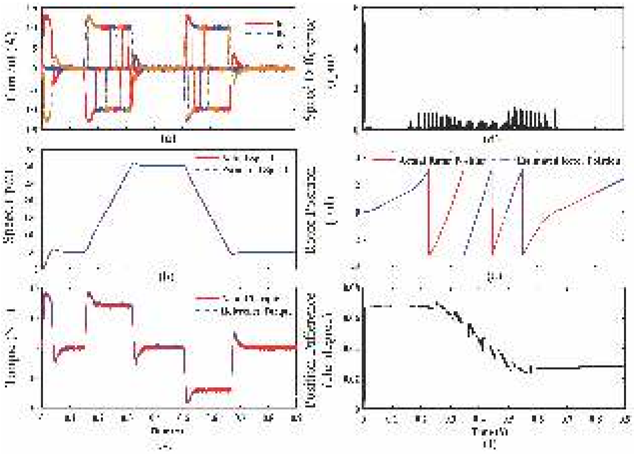

Fig. 3 Dynamic responses of stator current, speed, torque, speed difference, rotor position and position difference for the step changes in reference speed keeping load torque (T_L) = 0 Nm

and rotor position difference as shown in Fig. 4 and 5 respectively. It can be seen from Fig. 4(a) and 5(a) that the effect of variation in J on speed difference and position difference are almost same as they were obtained in Fig. 3(d) and 3(f) respectively. From Fig. 4(b), it can be observed that the maximum speed difference during starting is 5 rpm and transient and steady state speed difference are around 3 rpm and 1

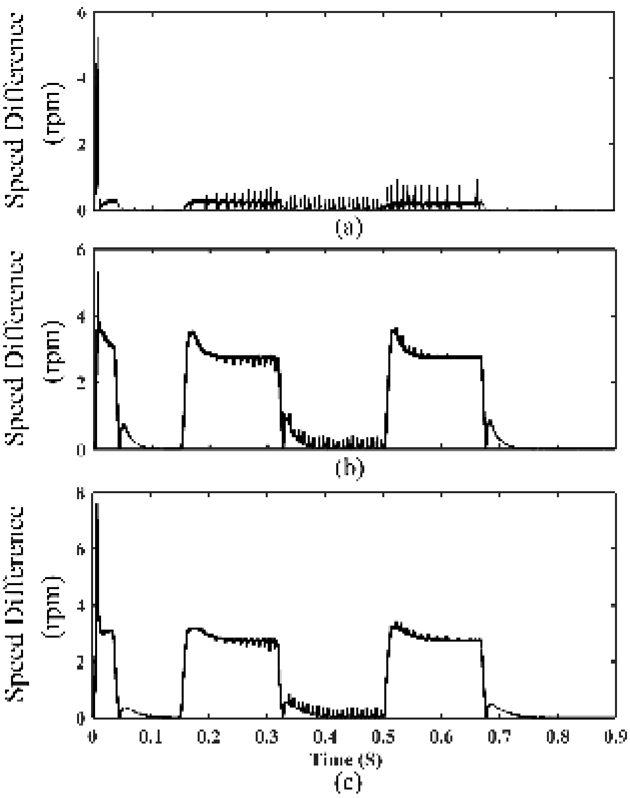

Fig. 4 Speed difference for the variations in (a) J= +10% (b) R= +10% and (c) R= +10% and J= +10% for the step changes in reference speed

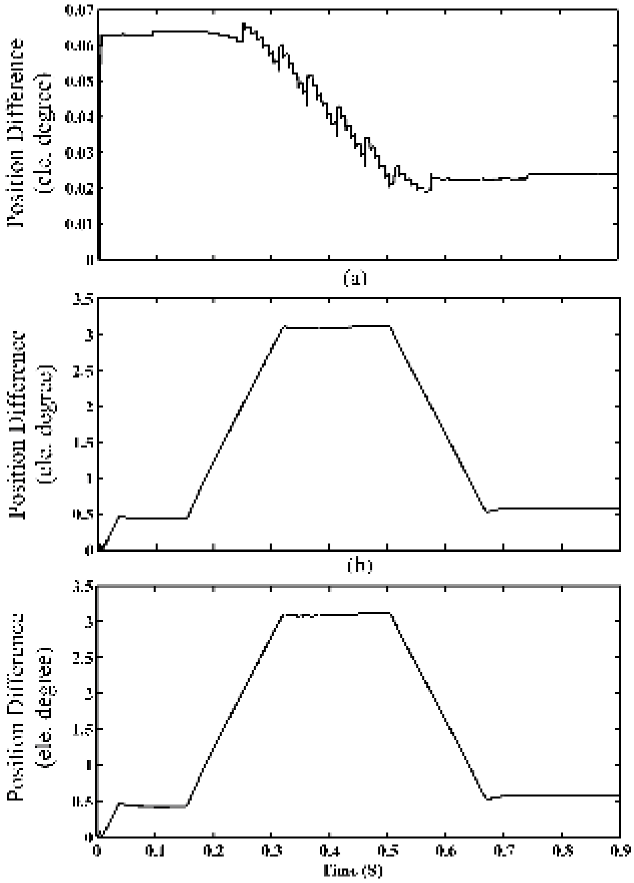

Fig. 5 Position Difference for the variations in (a) J= +10% (b) R= +10% and (c) R= +10% and J= +10% for the step changes in reference speed

rpm respectively when +10% variation is applied in stator resistance. It can be seen from Fig. 4(c) that the starting speed difference is increased when the variations are applied in R and J by +10% each. The steady state response is almost same as it was obtained in Fig. 4(b). From Fig. 5 (b), it can be observed that the maximum position difference is around 3 electrical degrees for +10% variation is applied in resistance. The same response is observed in Fig. 5(c) when the variation applied in R and J by +10% each.

Step Changes in Load Torque at Reference Speed

The variations in current, speed, torque, speed difference between actual and estimated speed, rotor position and difference in rotor position are shown in Fig. 6 for the step changes in load torque at constant reference speed. As shown in Fig. 6, the BLDC motor starts at 0 s and gradually attains 300 rpm within 0.2 s and remains 300 rpm up to 0.3 s. With the change in load torque from steady state torque to 10 Nm at 0.3 s, an increase in stator currents is observed as shown in Fig. 6(a). At 0.5 s, the load torque is set to -10 Nm with the associated changes in stator currents. The similar responses are found for the further change in load

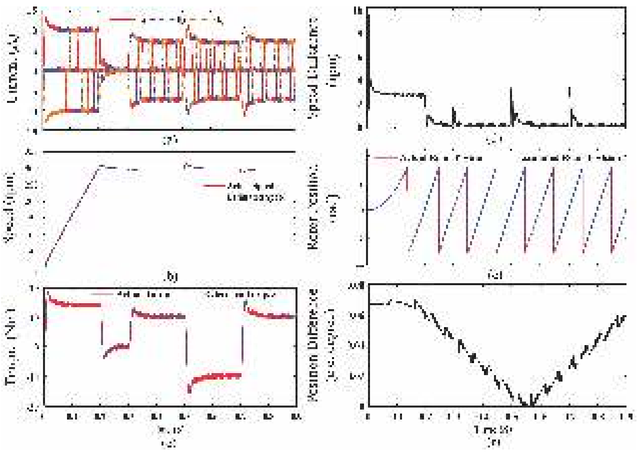

Fig. 6 Dynamic responses of current, speed, torque, speed difference, rotor position and position difference for the step changes in load torque (TL) keeping reference speed at 300 rpm

torque at 0.7 s. The momentary change in rotor speed can be seen from the Fig. 6(b) with the change in load torque. The actual torque successfully tracks the reference torque at all instants even during the step changes in the load torque which can be observed from Fig. 6(c). It can be seen from Fig. 6(d) that starting speed difference is around 9 rpm. Maximum steady state speed difference can be observed around 4 rpm when

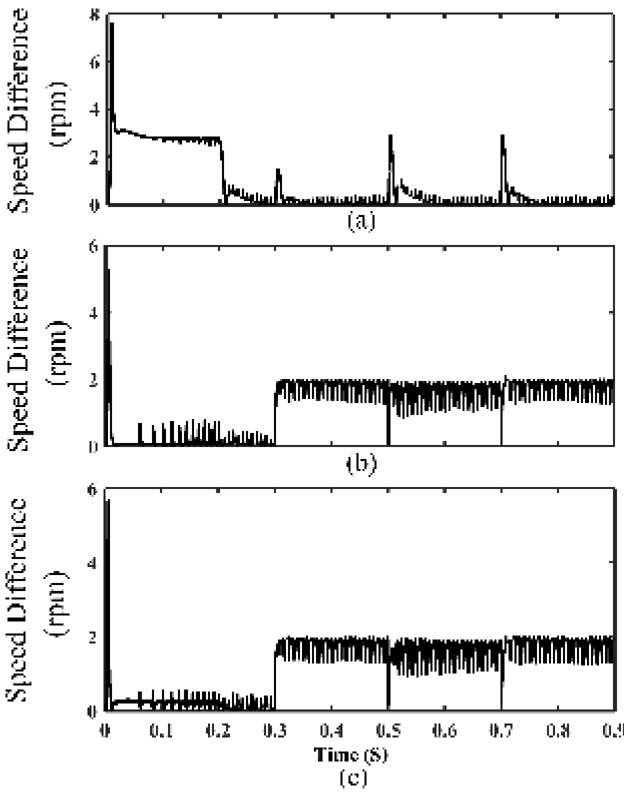

Fig. 7 Speed difference for the variations in (a) J= +10% (b) R= +10% and (c) R= +10% and J= +10% for the step changes in load torque

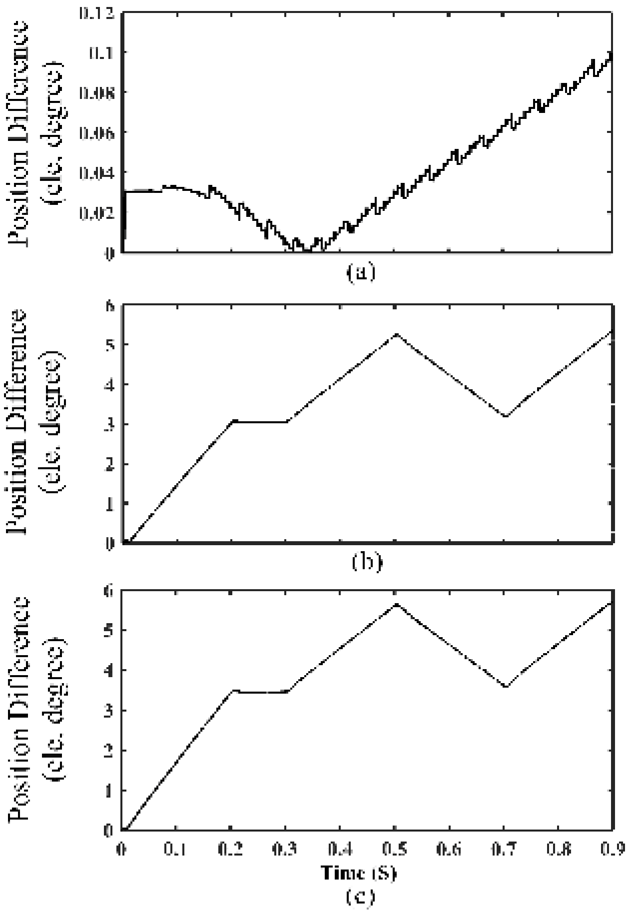

Fig. 8 Position Difference for the variations in (a) J= +10% (b) R= +10% and (c) R= +10% and J= +10% for the step changes in load torque

the step changes is applied to load and this difference is reduced below 1 rpm in steady state. From Fig. 6(e) and 6(f), it is observed that the actual rotor position successfully tracks the estimated rotor position and the maximum difference between the two rotor positions is around 0.07 electrical degree.

The variations in moment of inertia and stator resistance are applied in BLDC motor along with the step changes in load torque. The effect of these variations are observed in terms of speed difference and rotor position difference as shown in Fig. 7 and 8 respectively.

It can be seen from Fig. 7(a) and 8(a) that the effect of variation in J on speed difference and position difference are almost same as they were obtained in Fig. 6(d) and 6(f) respectively. From Fig. 7(b) and 7(c), it can be seen that the speed difference is around 6 rpm during starting and oscillations are increased but the speed difference is only 2 rpm during running conditions. From Fig. 8(b) and 8(c), it can be observed that the maximum position difference is 6 electrical degrees even variations are applied in R and J by +10% each.

Comparative evaluation of the proposed scheme with the existing schemes

Comparative evaluation of the proposed scheme has been carried out with the existing schemes (Terzic and Jadric (2001); Asaei and Rostami (2008); Stirban et. al. (2012) and Rostami and Asaei (2009)) in terms of estimated rotor position error.

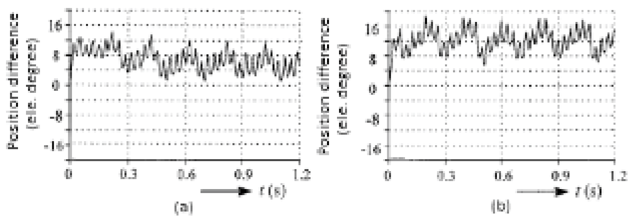

Fig. 9 Position Difference of the existing scheme (Terzic and Jadric) when motor runs at 100 rpm with load torque (a) 0.8 Nm and (b) 4 Nm

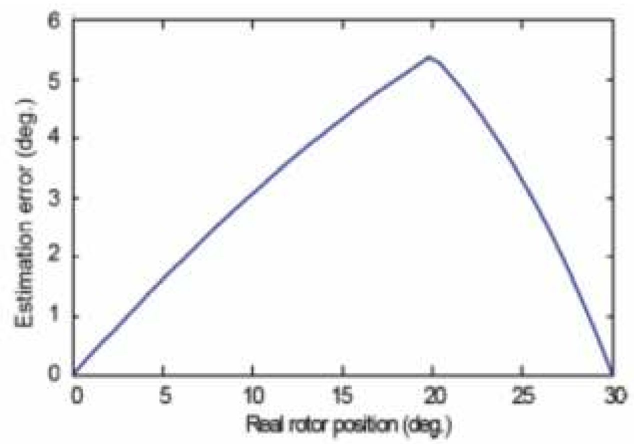

Fig. 10 The estimation error versus real rotor position of the existing scheme (Asaei & Rostami)

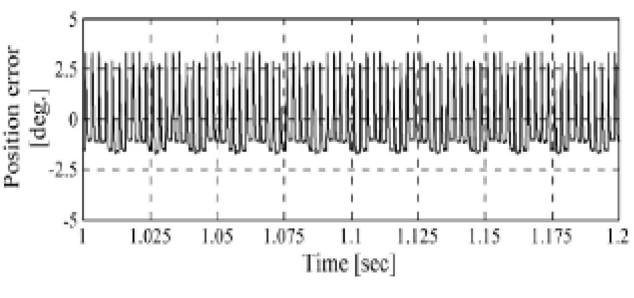

Fig. 11 Position error of the existing scheme (Stirban et. al.)

Table 3. Actual and estimated rotor position w.r.t. current space vector of the proposed scheme (Rostami and Asaei)

If	The rotor position	Estimated rotor position (°)
$i_s(30°) > i_s(45°)$	$30° < \theta_r < 37.5°$	33.75
$i_s(45°) > i_s(30°)$ and $i_s(30°) > i_s(60°)$	$37° < \theta_r < 45°$	41.25
$i_s(45°) > i_s(60°)$ and $i_s(60°) > i_s(30°)$	$45° < \theta_r < 52.5°$	48.75
$i_s(60°) > i_s(45°)$	$52.5° < \theta_r < 60°$	56.25

It has been observed from Fig. 9 to 11 and Table 3 that the maximum estimated rotor position error is 12-16, 5.5, 3-4 & ±4.25 electrical degree, respectively. These errors may be increased if the parameter variations are applied. Conversely, the error given by proposed scheme is less than 1 electrical degree for nominal parameters and around 6 electrical degrees for +10% variation applied in resistance and moment of inertia during transient as well as steady-state conditions for speed variations even with no-load/full load situation. This shows the effectiveness of the controller and observer design.

CONCLUSION

This paper presents an approach for sensorless control of BLDC motor using disturbance torque estimation. The estimated disturbance torque is the sum of proportional and integral of estimation error of current. The speed of the motor is estimated with the help of disturbance torque estimation without any additional hardware. The speed of BLDC motor is controlled using a new controller scheme based on Modified Hybrid Fuzzy PI (MHFPI) controller. From simulation results, it can be seen that maximum starting and steady-state speed difference between actual and estimated speed are around 3% and 1% respectively even for variation in parameters of BLDC motor. The difference between actual and estimated rotor position is less than 1 electrical degree for nominal parameters and around 6 electrical degrees for +10% variation in resistance and moment of inertia each in transient as well as in steady state conditions. Obtained results have been validated for below rated and rated speed of BLDC motor under different loading conditions.

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