

Implementation of speed control of sensorless brushless DC motor drive using H-infinity controller with optimized weight filters

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ABSTRACT

The hardware implementation of sensorless brushless direct current motor drive incorporating H-infinity control strategy with optimized weights by particle swarm optimization in the speed control is carried out in this work. The methodology involved in the design of brushless direct current (BLDC) motor control with sensorless position detection technique, the design of H-infinity speed controller, steps involved in particle swarm optimization for optimizing coefficients of its weights and the hardware implementation is discussed in detail in this paper. Texas Instruments microcontroller board C2000 Delfino Launchpad LAUNCHXL F28377S and driver BOOSTXL DRV8301 are used for realization of the speed controller. The code is developed using C2000 hardware support package in MATLAB/SIMULINK platform. A comprehensive performance analysis is accomplished during starting of the motor and during the fast application and removal of load. This strategy is found to be robust resulting in faster load disturbance rejection and better reference speed tracking. The experimental results of the proposed strategy are compared with that of conventional proportional-integral (PI) controller. The time domain parameters are also compared. It is found that the proposed strategy exhibits better performance characteristics during transients and sudden disturbances in load.

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1. INTRODUCTION

Sensorless control of brushless direct current (BLDC) motor drives find an important role in various applications including military, home appliances, and medical equipment because of their merits such as increased reliability, less maintenance, low noise and vibration, and exhibition of good performance such as increased torque at low speed. A lot of research work concentrating on various control techniques in order to further improve their performance under loaded conditions has been observed in the literature. The experimental validation of these control techniques for the motor is essential for proper analysis of its performance on load.

The control design of BLDC motor poses several non-linearity issues. This prompts the researchers all over the world to do experimentation of robust control techniques in the position and speed control of BLDC motor, some of which are discussed here. Assawinchaichote and Chayaopas [1] designed BLDC

motor speed controller on the basis of Takagi-Sugeno fuzzy model by linear matrix inequality approach to derive the conditions for achieving H-infinity performance in a BLDC motor with the purpose of avoiding the effects of non-linearity and disturbance. Soliman *et al.* [2] optimized the linear control component of a robust sliding mode controller for challenging system uncertainty when there are changes in load inertia. A study has been carried out comparing continuous with fractional order sliding mode controller and experimentally proved that fractional order sliding mode controller shows good trajectory tracking [3]. A linear quadratic sliding mode controller for effective position tracking of BLDC motor exhibits a better performance with friction as well as backlash [4]. The detection of load disturbance has been carried out using an linear-quadratic (LQ) controller with a load observer [5]. Ohishi *et al.* suggested a dual passive adaptive control loop to avoid state error caused by changes in parameters and forced disturbances [6]. Niapour *et al.* [7] A H-infinity de-convolution filter has been designed for the enhancement of robustness over a wide range of speed for sensorless BLDC motor drive. For optimal tuning of the parameter of proportional integral derivative (PID) controller, the optimization technique genetic algorithm (GA) has been used [8]. A hybrid controller based on sliding mode and fuzzy logic has been realized [9].

Experimental study of the mechanical characteristics of BLDC motor running in both forward and reverse directions has been carried out using an advanced RISC machine (ARM) 2148 microcontroller [10]. An imbalance corrector module has been combined with TMS320F240 in order to identify the non fed phase zero crossing of back electromotive force (EMF) [11]-[13]. PIC16F877A has been used to achieve the control of speed of BLDC motor [14]. A three phase fully controlled bridge whose firing pulses are generated by Spartan-3 is used in the speed control of BLDC motor [15]. The position information equivalent to hall effect sensor is generated from the neutral point voltage calculation using TMS320C242 digital signal processor (DSP) controller [16].

A simulation study has been carried out for analyzing the variation in speed torque characteristics, motor current and back EMF on no load as well as on load [17]. A fuzzy PID control has been compared with model reference adaptive control (MRAC) for studying reference tracking in the presence of disturbances in the load as well as variations in parameters [18]. Experimental validation of a proportional integral sliding mode control (PISMC) current control using national instruments data acquisition card 6229 has been conducted in MATLAB environment [19]. An experimental validation using ARM led to the analysis of speed torque characteristics of BLDC motor for different load torques when it is working in both forward and reverse directions [11]. A comparative study of PID with fuzzy PID has been done to reduce the jerky behavior of the BLDC motor when the load is suddenly applied and removed. Fuzzy PID shows a reduction in jerks when the load is gradually removed [20]. The problem of initial peak of control input in the proposed H-infinity controller has been identified and solved experimentally [21]. To regulate current and speed of BLDC motor, 2 DOF H-infinity control loop is proposed whose controller parameters are optimized by GA [22].

The authors observed that good tracking of speed and rejection of disturbances have been achieved in simulation with the coefficients of weights optimized using particle swarm optimization (PSO) algorithm for proposed controller [23]. A simulation has been carried out to study the four quadrant operation of the motor and also the proposed speed controller has been compared with PI controller and the performance parameters are analyzed [24], [25]. A study of the motor performance has also been carried out by the authors with the motor on no load condition and the results are discussed in detail [26].

This paper focuses on the comparative study of the performance characteristics of the BLDC motor experimentally, by the application and removal of load incorporating proposed optimized H infinity with PI speed controller. The hardware realization of BLDC motor speed control incorporating sensorless algorithm has been accomplished by TI C2000 Delfino Launchpad LAUNCHXL F28377S alongwith driver BOOSTXL DRV8301. Section 2 discusses about the methodology involved in the design of sensorless BLDC motor drive, PSO optimized coefficients of weights for H infinity speed controller. Section 3 elaborates about the implementation of hardware. The results are discussed in detail in section 4.

2. METHODOLOGY INVOLVED IN THE DESIGN OF PROPOSED CONTROLLER

2.1. Design of sensorless BLDC motor drive

The rotor position detection is an important factor for deciding the activation and commutation of proper phases in a BLDC motor. The information about the position of rotor at an instant decides the perfect sequence of commutation. Although in normal cases, hall sensors play a significant role in detecting present rotor position, sensorless techniques play a major development in detecting rotor position as they save money as well as space. Figure 1 shows the equivalent circuit diagram of BLDC motor. The information about precise commutation point in detecting rotor position is derived by obtaining the difference in terminal voltages as per (1)-(6) and the exact commutation points are shown in Figure 2 [27], [28].

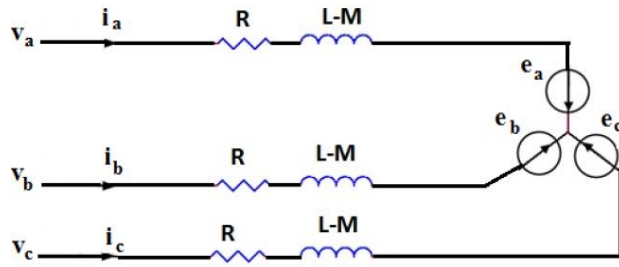


Figure 1. Equivalent circuit diagram

$$V_{ba} - V_{ac} = V_{baac} = R (i_b - 2i_a + i_c) + L \frac{d}{dt} (i_b - 2i_a + i_c) + e_b - 2e_a + e_c \tag{1}$$

$$V_{cb} - V_{ba} = V_{cbba} = R (i_c - 2i_b + i_a) + L \frac{d}{dt} (i_c - 2i_b + i_a) + e_c - 2e_b + e_a \tag{2}$$

$$V_{ac} - V_{cb} = V_{accb} = R (i_a - 2i_c + i_b) + L \frac{d}{dt} (i_a - 2i_c + i_b) + e_a - 2e_c + e_b \tag{3}$$

A BLDC motor has only two phases connected to the supply at an instant with the third one open. When A is connected to +ve and B is connected to -ve terminals, C is open. Therefore, it can be inferred that $i_a = -i_b$ and i_c is zero; also $e_a = -e_b$. By applying the above inference in (1)-(3), the terminal voltages can be obtained as.

$$V_{baac} = -2e_a \tag{4}$$

$$V_{cbba} = -2e_b \tag{5}$$

$$V_{accb} = -2e_c \tag{6}$$

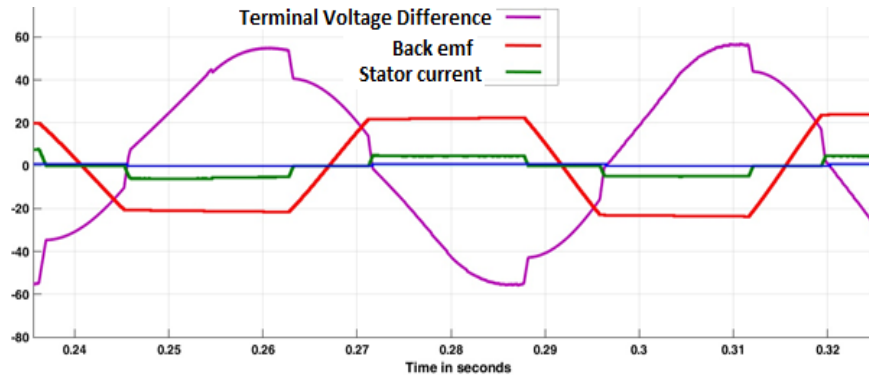


Figure 2. Commutation instant estimation

The relation between rotor speed and position is given by:

$$\frac{d\theta}{dt} = \frac{P}{2} \omega_m$$

Figure 3 shows the block diagram representation of sensorless BLDC motor drive control circuit [18]. The design of a speed controller circuit plays a crucial phase for realizing preferred steady state and transient behavior of the motor. Here the incorporation of H infinity speed controller whose weight coefficients are optimised by PSO with PI current controller has been done.

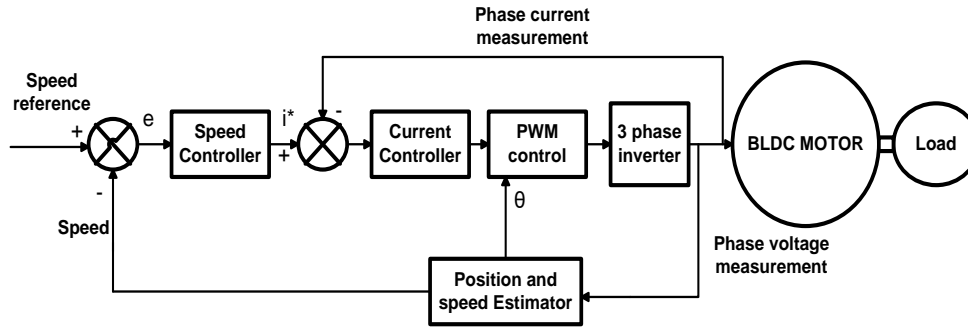


Figure 3. Block diagram for the control of sensorless BLDC motor drive

2.2. Design of hinfinity controller

The main objective is the design of hinfinity speed controller K which attains stabilization of closed loop system with guaranteed performance. Maximum amplification of a sinusoidal signal of ω when it is passed through the plant is achieved by H-infinity controller. The infinity norm of the system $G(s)$ exists if and only if $G(s)$ is proper with no poles on the imaginary axis. Let a linear time invariant (LTI) system be represented by P, controller by K, control input by u and measured output by y. Reference commands, load disturbances, and sensor noise are represented by w, and tracking errors, performance variables, and actuator signals are represented by z [29]. Figure 4 shows the H-infinity control problem which indicates that the controller should be able to achieve a robust output in the presence of disturbances.

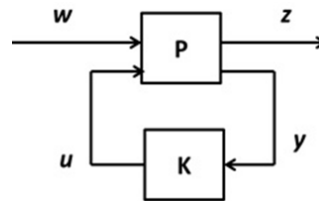


Figure 4. Block diagram showing H-infinity control problem

If P is partitioned as

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \tag{7}$$

From Figure 4, it can be written as

$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} \\ P_{21} & P_{22} \end{bmatrix} \begin{bmatrix} w \\ u \end{bmatrix} \tag{8}$$

and

$$u = Ky \tag{9}$$

Then,

$$z = P_{11}w + P_{12}u \tag{10}$$

$$y = P_{21}w + P_{22}u \tag{11}$$

Substituting for u in (11), we get

$$y = P_{21}w(1 - P_{22}K)^{-1} \tag{12}$$

From (9)-(12), we get

$$z = w[P_{11} + P_{12}K(1 - P_{22}K)^{-1}P_{21}] \tag{13}$$

$$z = wF_l(P, K) \tag{14}$$

The aim of control design is to achieve a robust controller K by the minimization of H-infinity norm of $F_l(P, K)$ over all realizable controllers $K(s)$ that stabilize the closed-loop system. Here the minimization of H-infinity norm is attained by using the MATLAB robust control toolbox wherein the solution of Ricatti equations is used [30]. The required robustness and performance is achieved by shaping the signals with the help of MATLAB script ‘hinfscyn’ that synthesizes a controller. Frequency domain loop shaping is attained by proper weights selection. By selecting proper weights $W1$ for error signal e , $W2$ for control signal u and $W3$ for output signal y the solution of H infinity control problem can be achieved. Figure 5 shows the augmented state space representation of plant G with weights.

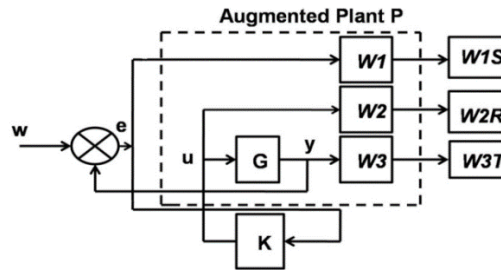


Figure 5. Augmented plant with weighting functions

The synthesis of controller is done by using the MATLAB command ‘hinfscyn’ and the transfer function KT is obtained (15)-(16).

$$K = \text{hinfscyn}(P) \tag{15}$$

$$KT = \text{tf}(K) \tag{16}$$

2.3. Selection of weight filters

A proper design of controller involves the suitable choice of weight filters. A simple low pass filter has been selected for W_l . The low frequency gain of the low pass filter has been chosen for limiting overshoot.

$$W_1 = \frac{1}{M_s} \frac{\tau_p s + 1}{\tau_p s + A/M_s} \tag{17}$$

Where $\tau_p = 1/M_s \omega_b$

M_s , A , ω_b represent the maximum sensitivity function, maximum steady state offset allowed and bandwidth of the system respectively [31]. As recommended by Christiansson and Lennartson [32] the other weights have been chosen as constants so that the order of the controller is made low. The choice of weights depends on the the coefficients of W_1 , W_2 , and W_3 . The literature suggests some thumb rules for the selection of coefficients such as a , b , c , and d of W_1 , g of W_2 and h of W_3 [33]. The selection of coefficients is considered as an optimization problem and PSO has been used for this purpose.

$$W_1 = \frac{a(s+b)}{cs+d} \tag{18}$$

2.4. Steps involved in particle swarm optimization of weight coefficients

PSO is an optimization algorithm in which best solution is searched in every iteration thereby converges at a faster rate when compared with other optimization techniques. The progression of algorithm is discussed in the following steps [34].

- The parameters of PSO such as particle number, total number of evaluations, the learning factors $C1$ and $C2$, inertia ω , random numbers $r1$, $r2$, and limits of search space are initialised.
- Random position of particle within search space is initialised.
- The weights obtained from particle position are used for synthesizing H infinity controller.
- The model is simulated with H infinity controller and the fitness value is updated.
- The personal best and global best for the entire problem is updated.

- The velocity and position are updated using (19), (20)

$$v_{ij}(t+1) = \omega v_{ij}(t) + r_1 C_1 ((p_{ij}(t) - x_{ij}(t)) + r_2 C_2 ((g_j(t) - x_{ij}(t))) \tag{19}$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \tag{20}$$

- The steps 3 to 7 are repeated until all the evaluations are completed.
- The optimal weights of Hinfinity controller are obtained form global best solution.

3. HARDWARE IMPLEMENTATION

The main hardware components used are power supply, C2000 Delfino Launchpad LAUNCHXL F28377S interfaced with PC and BLDC motor. Figure 6 shows the basic block diagram of the hardware setup. The functional block diagram of the experimental setup for the motor performance analysis on load is depicted in Figure 7. The implementation of sensorless algorithm, based on which the actual speed is estimated and selection of switching sequence is carried out by coding with embedded support package for C2000 Delfino Launchpad LAUNCHXL F28377S in SIMULINK platform. The phase voltages are sensed and the corresponding line voltages and the difference between them are calculated. The hall sensor signals are emulated from the zero crossing instants of back emf. Apart from this, the outer speed controller implemented with PSO optimized H infinity control and inner current controller implemented with PI control are also coded in SIMULINK. Figure 8 shows the convergence plot of PSO.

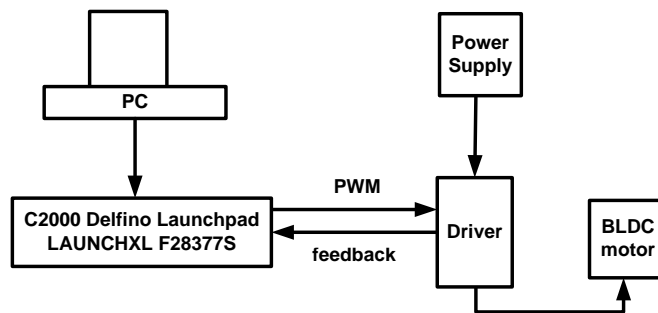


Figure 6. Basic block diagram

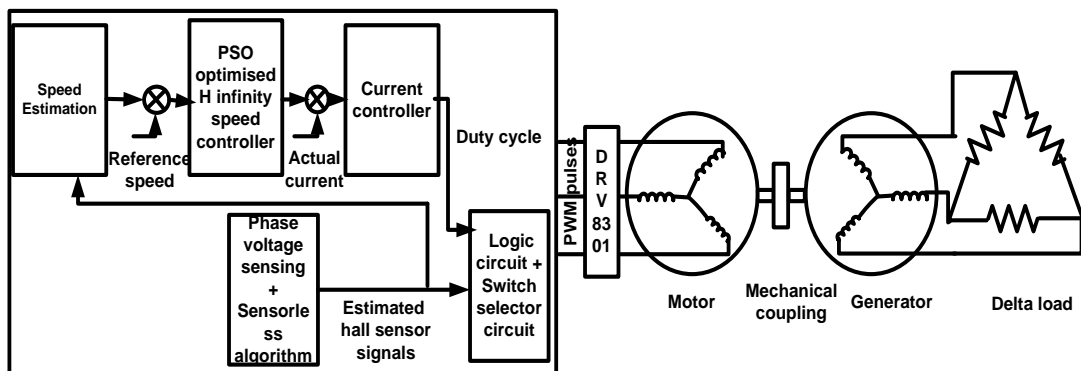


Figure 7. Functional block diagram

The transfer function of synthesized controller is given by (21).

$$KT = \frac{3206s^2 + 4.499e04s + 4.45e08}{s^3 + 2133s^2 + 2.097e06s + 1.112e08} \tag{21}$$

The optimized weight W_1 is given by (22) and W_2 and W_3 are 0.16 and 0.02 respectively.

$$W_1 = \frac{0.0796s+39.8}{0.1s+27.36} \tag{22}$$

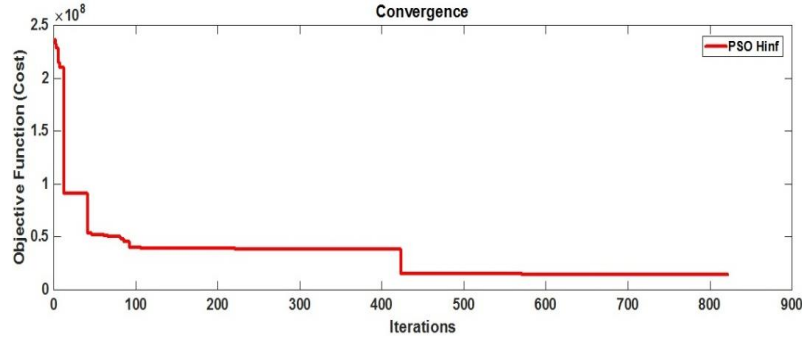


Figure 8. Convergence plot of PSO

Figure 9 shows the bode plot of controller. The gain margin is 32.8 dB and phase margin is from -139 to 132 degrees. The BLDC motor performance under loaded condition has been analyzed experimentally by a motor generator setup. A snapshot of the hardware set up with two 42BL61 BLDC motors coupled is shown in Figure 10. The motor which acts as generator is loaded by delta connected resistors of 47 ohms, 10 W in each arm. The performance of the motor has been studied while starting, by suddenly applying the load with a DPST for duration of 10 seconds and removing the load after 10 seconds.

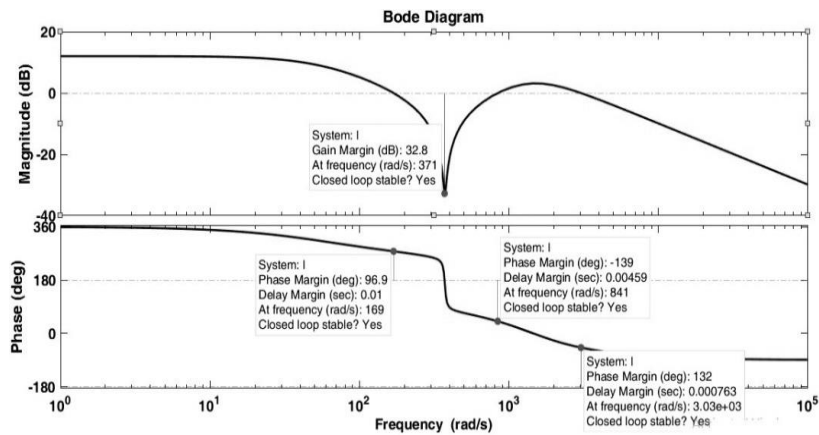


Figure 9. Bode plot



Figure 10. Hardware implementation

4. RESULTS AND DISCUSSION

The waveform of the tracking of reference speed by BLDC motor during starting as well as on load is depicted in Figure 11 and Figure 12. Figure 11 shows the reference tracking with PI controller and Figure 12 shows that of proposed controller. From these two figures it is clear that proposed controller shows better reference tracking than PI controller. The controller parameters such as percentage overshoot, steady state error and settling time are compared and tabulated in Table 1.

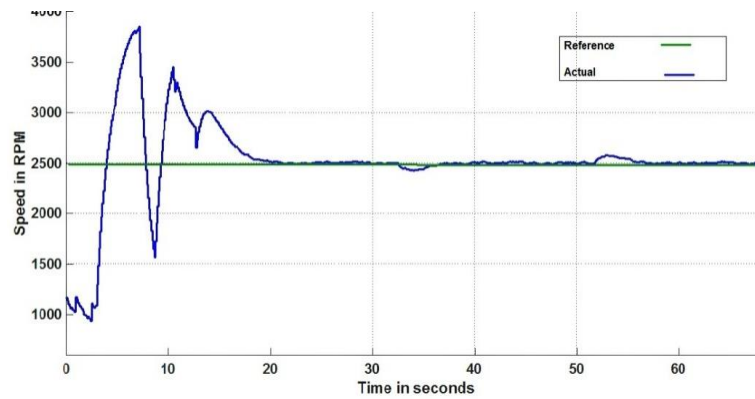


Figure 11. Reference tracking waveform with PI

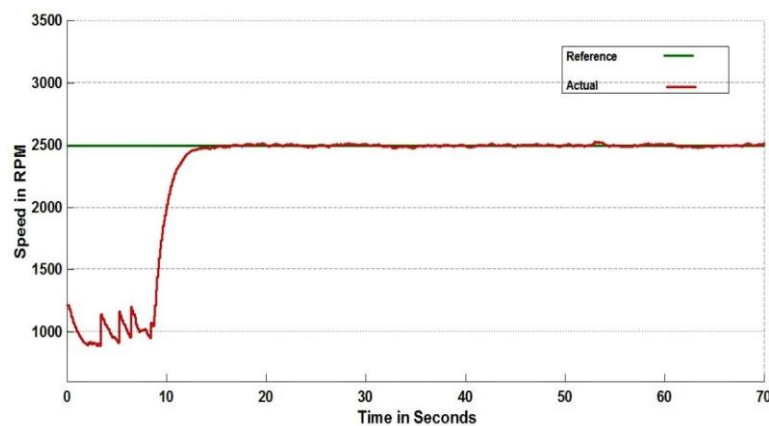


Figure 12. Reference tracking waveform with H-infinity

Table 1 Comparison of PI and proposed controller during starting

Controller	Peak Time (s)	% Overshoot	Settling Time (s)	Steady state error
PI	4.7	53.8	19.7	0.76%
H Infinity	8.3	0.24	8.7	0.6%

Figure 13 shows the enlarged image of reference tracking by applying the load during 30-40 seconds and removing the load during 50-60 seconds. A comparison has been made with PI and proposed controller strategy and the results are tabulated in Table 2 and Table 3. From the results it can be inferred that H infinity controller with its weights optimized by PSO shows a reduction of 1.84% in percentage overshoot. Also there is a reduction of settling time by 0.6 seconds and 0.68% of settling error when compared with PI controller during application of load. Thus the proposed controller strategy exhibits a better performance during disturbances in load. The current waveforms during the application and removal of load are shown in Figure 14. The ripples in current waveform with the proposed control strategy are found to be less when compared with PI controller. This results in less torque ripples thereby resulting in smoother operation of motor.

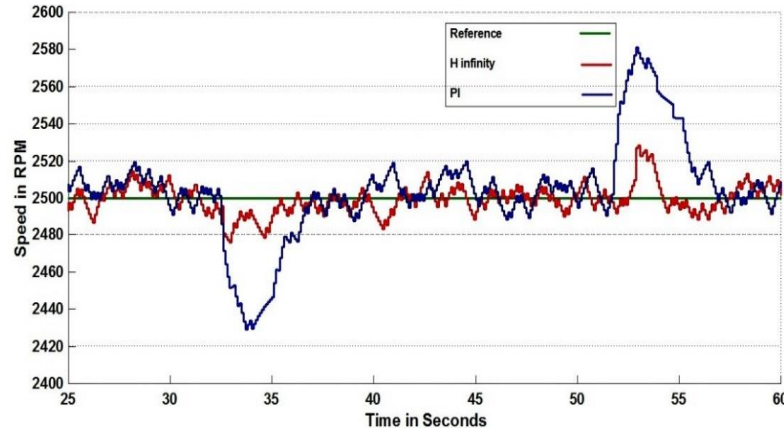


Figure 13. Enlarged image at the time of application and removal of load

Table 2 Comparison of PI and proposed controller during application of load

Controller	Peak Time (s)	% Overshoot	Settling Time (s)	Steady state error
PI	1.5	2.8	4.6	0.8%
H Infinity	0.4	0.96	4.0	0.12%

Table 3 Comparison of PI and proposed controller during removal of load

Controller	Peak Time (s)	% Overshoot	Settling Time (s)	Steady state error
PI	1.2	3.24	4.6	0.36%
H Infinity	0.5	1.12	1.7	0.12%

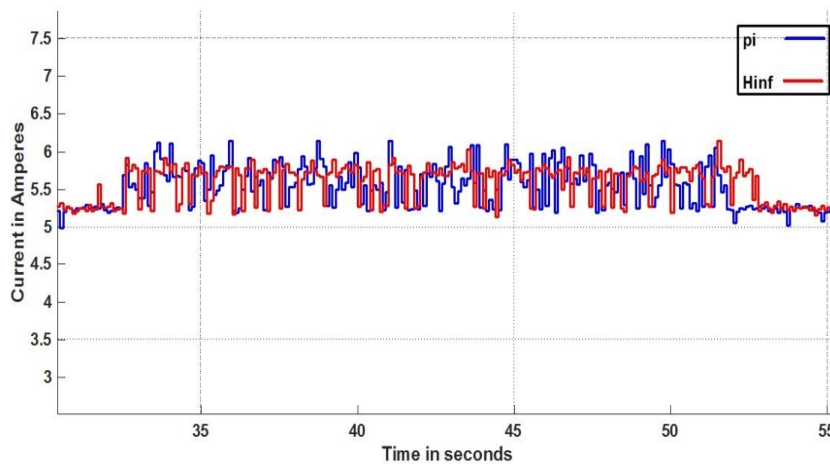


Figure 14 Current waveforms

5. CONCLUSION

An experimental study is conducted for studying the performance of sensorless BLDC motor drive with H-infinity speed controller whose weights are optimized by PSO by applying and removing load suddenly. The motor is loaded by coupling another BLDC motor which acts as a generator. A comparative study of the proposed and PI controller is conducted and results are tabulated. The performance parameters such as peak time, settling time, percentage overshoot and steady state error of both the controllers are studied. The results show that the proposed controller strategy exhibits a robust performance in the presence of load disturbances.

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