Engineering and Technology Journal
Journal homepage: engtechjournal.org

Direct Current Deadbeat Predictive Controller for BLDC Motor Using Single DC-Link Current Sensor

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Submitted: 18/07/2019 Accepted: 31/08/2019 Published: 25/08/2020

K E Y W O R D S

BLDC motor, Deadbeat Predictive Controller, Single DC-Link Current Sensor

A B S T R A C T

BLDC motors are characterized by electronic commutation, which is performed by using an electric three-phase inverter. The direct control system of the BLDC motor consists of double loops; including the inner-loop for current regulating and outer-loop for speed control. The operation of the current controller requires feedback of motor currents; the conventional current controller uses two current sensors on the ac side of the inverter to measure the currents of two phases, while the third current would be accordingly calculated. These two sensors should have the same characteristics, to achieve balanced current measurements. It should be noted that the sensitivity of these sensors changes with time. In the case of one sensor fails, both of them must be replaced. To overcome this problem, it is preferable to use one sensor instead of two. The proposed control system is based on a deadbeat predictive controller, which is used to regulate the DC current of the BLDC motor. Such a controller can be considered as digital controller mode, which has fast response, high precision and can be easily implemented with microprocessor. The proposed control system has been simulated using Matlab software, and the system is tested at a different operating condition such as low speed and high speed.

How to cite this article: Q. M.Ali and M. M. Ezzaldean, "Direct Current Deadbeat Predictive Controller for BLDC Motor Using Single DC-Link Current Sensor," Engineering and Technology Journal, Vol. 38, Part A, No. 08, pp. 1187-1199, 2020.
DOI: https://doi.org/10.30684/etj.v38i8A.471

1. INTRODUCTION

In recent years, BLDC motors get more popularity and become more adopted in; household appliances, electric vehicles, and industrial fields because they have high power density, high torque/inertia ratio, high precision control ability, low maintenance and compact construction [1]. The BLDC motor has many advantages compared to other machines. DC machine needs more maintenance and it has higher electrical noise due to the presence of brushes, lower power density, and a lower range of speed control. The induction motor has higher rotor inertia enables lower dynamic response, the speed-torque characteristic is not flat in nature as a BLDC motor, higher starting current, and lower power density [2]. Moreover, the BLDC motor is more efficient because it has permanent magnets, which result in significantly lower rotor loss. On the other hand, the major disadvantages of the BLDC motor are their higher cost and relatively greater degree complexity introduced by the power electronic converter which used to drive it.

BLDC motor drives come with a feedback current loop, which regulates the load current at the desired position by controlling the constant DC-link voltage across the motor windings. The feedback current loop is included by a direct measurement device. It is a current sensor, each phase of the BLDC motor must be usually included by a current sensor. However, the current sensors and their contactors increase system cost, size, and make it more complex and reduce system reliability. Therefore, the reduction of sensors is desirable. The conventional method of the current control in the BLDC motor drive is to compare the reference (demand) currents with measured (actual) phase currents that are obtained from the current sensors [3]. This method of current measurement depends on the regularity of the current sensors. The problem of current sensor imbalance can raise the torque ripple at low speeds. On the other hand, the dc-link current is inherently balanced, therefore the kindliest current measurement and easiest method for BLDC motor are using a single dc-link current sensor [4]. Most of BLDC motors used the indirect control system (single-loop speed control system). It is usually a PI controller and PWM modulator; whereas a current limiter is followed in the speed loop and the PWM modulator can be concerned as a second saturation limiter. This method works on controlling the input dc-link voltage amplitude (speed) [5]. The Early BLDC motor drive was the voltage source inverter (VSI). It used the indirect current (torque) control system, this method works on controlling the input current indirectly through inverter's input voltage amplitude. The advantage of this method is no need for current sensors because it uses only single-loop for speed. However, the disadvantages of this method have not current limiter and have a slow dynamic response. After that, the direct current (torque) control system (dual-loop control system) is offered to be used with the BLDC motor. It uses the current sensors; the advantages of this control system are high and fast dynamic response, and the current limiter used. BLDC motor adopts most of the direct current control strategies: fixed and variable switching frequency PWM control, hysteresis current PWM control, and deadbeat predictive current control, etc. PWM current control with a fixed switching frequency is simple, easily implemented, and low switching frequency, but in the case of low speed (low switching frequency), the current dynamic response is slow and the current dynamic variables change with the current rate-change consequently. The hysteresis controller has a high current dynamic response, but the switching frequency is not fixed and high. Deadbeat predictive control has faster response, higher precision, and small distortion rate, etc. [6].

The current control method for the BLDC motor is either indirect current control or direct current control. The indirect control has less torque ripple and lower switching loss, the torque is indirectly controlled. The direct control gives higher switching losses, and lower speed range, the torque is directly controlled and the currents commutation ripple can be reduced. We will review some previous studies for direct dc-link current control methods as follow.

H. Tan and S. Ho (1999) [7] three types of PWM were used to regulate the phase currents of BLDC motor including; double-sided basic PWM, single-sided PWM, and double-sided complementary PWM were introduced in this study; in which theses currents were measured using a single current sensor. It should be noted that double-sided basic PWM type increases the switching losses; the single-sided PWM and double-sided complementary have the lower switching losses. The experimental results show that the single-sided PWM is the adopted type for BLDC motor. In this study, the Phase currents could be calculated from the dc-link current. This paper introduced the three types of PWM methods, but it was not including the speed controller and the current controller.

A. Halvaei and A. Vahedi (2007) [8] designed and implemented a current controller for the BLDC motor drive. The torque was regulated via a hysteresis control strategy with the single dc-link sensor. The advantages of this method are reliability and cost reduction of the overall system. The implementation of the assembly language programming of a digital signal processor (DSP) resulted in reducing the hardware and fast response of the controller.

P. Wipasuramonton (2009) [9] introduced the current control PWM technique for the BLDC motor, which was implemented with a single shunt dc-link current sensor (resistor). Unipolar PWM was used. The torque was regulated with a predictive current control algorithm that has a fast response and can be simply implemented. The proposed technique led to a toque ripple reduction, due to the commutation between the three phases. This technique has high-performance control and it was implemented on a low-cost digital signal controller. The experimental results showed that the proposed technique reduced the commutation current ripple. The torque ripple was not illustrated in the simulation results. However, the reduction of commutation current ripple is too meaning the torque ripple was reduced.

M. Ebadpour et.al (2012) [4] proposed a cost-effective and simple position sensorless control for BLDC motor drive depending on a single DC-link current sensor. The motor drive was based on the generation of three-phase quasi-square currents. The hysteresis current controller was used to regulate phase currents. The proposed system has advantages; simple control scheme, no need the triangular PWM, and balanced phase currents. The simulation results explained that the proposed method has advantages over the two conventional methods; PWM control and dc-link voltage control. The current ripple due to the commutation between currents reduced but the switching frequency increased and it is uncontrolled, and the torque ripple increased. The proposed control system is suitable for cost-sensitive products such as air purifiers, air blowers, cooling fans, and related home applications.

Based on the dc-link current sensor, many current control methods had been used in the published works. PI controller is simple and its parameters are easily tunable, but the BLDC motor is a nonlinear system, so the integrator of PI controller may enter saturation state at high speeds, and that increases the torque ripple and raise the settling time of the speed response [5]. Hysteresis controller causes high switching ripple and hysteresis controller with dc-link current control requires regenerating phase currents. The deadbeat predictive current controller is simple, fast response, easily implemented and can be used with a dc-link current controller. In this paper, the deadbeat predictive controller is designed to control the current (torque) of the BLDC motor based on the dc-link current sensor. The proposed deadbeat predictive current controller uses triangular PWM; both of bipolar PWM and unipolar PWM approaches are involved. The proposed control system reduced the number of current sensors by using the single dc-link current sensor and also used a single current controller instead of using three current controllers, which were used to regulate three-phase currents.

The description of the BLDC motor and the mathematical model is presented in Sections 2. Section 3 introduces the proposed deadbeat predictive current controller for a BLDC motor. Section 4 shows the used Simulink and the obtained results. Finally, the conclusions are given in Section 5.

2. Mathematical Model of the BLDC Motor

In the conventional DC motors, the commutation is performed mechanically using mechanical commutator and brushes, while the BLDC motor is characterized by electronic commutation which is performed by using an electric inverter and hall-effect sensors. The windings of the BLDC motor are on the stator and the rotor is constructed from permanent magnets connected on steel core or maybe the rotor is constructed from only permanent magnets materials. Figure 1 shows the configuration of the BLDC motor drive. Hall-effect sensors determine the rotor position as the commutating signals. As the permanent magnet replaces the armature windings in the BLDC motor, the need for brushes is eliminated. The back-EMFs of the three-phase BLDC motor are trapezoidal and the phase currents are square-waves with 120° conduction mode as shown in figure 2.

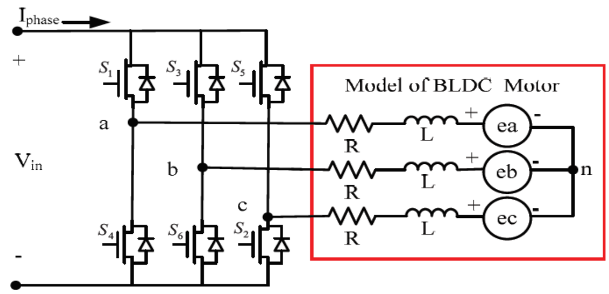

Figure 1: Construction of BLDC motor drive [10]

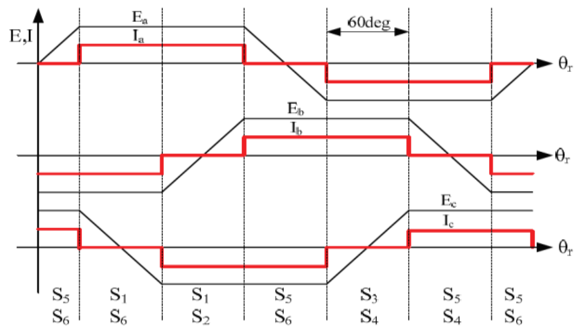

Figure 2: Back-emf and current waveforms [10]

The differential equations of the BLDC motor are represented in matrix form as the following:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L_a - M & 0 & 0 \\ 0 & L_b - M & 0 \\ 0 & 0 & L_c - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where v_a, v_b, v_c are motor three-phase voltages, i_a, i_b, i_c are motor three-phase currents, e_a, e_b, e_c are motor three-phase back-emf waveforms, R is motor phase resistance, L_a, L_b, L_c are the self-inductance of each phase and M is the mutual inductance between any two phases, $L_a - M = L_b - M = L_c - M = L$ [5]. The electromagnetic torque can be illustrated as:

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_r \quad (2)$$

Where: T_e is the electromagnetic torque and ω_r is the mechanical speed. The motion equation of the BLDC motor is:

$$\frac{d}{dt}\omega_r = (T_e - T_L - B\omega_r)/J \quad (3)$$

T_L is the load on the motor shaft, B is the friction constant, and J is the moment of inertia of the drive plus load. The electrical frequency in terms of the mechanical speed for the motor rotor with p numbers of poles is: [10]

$$\omega_e = \frac{P}{2}\omega_r \quad (4)$$

3. THE PROPOSED CURRENT CONTROL SYSTEM FOR BLDC MOTOR

The control system of the BLDC motor should be designed according to the application of motor drive; taking into account the cost, precision, and efficiency. The proposed control system is based on the direct current control strategy using the deadbeat predictive current controller. The deadbeat control method was introduced by the famous control theory of skilled Kalman. Deadbeat control is a type of digital system. The development of digital control technology made the numerical calculations used, it realized easily full digital control mode. The deadbeat predictive current controller (DPCC) has a faster dynamic response than the other digital controller and can greatly improve the dynamic performance of the drive system [6]. A conventional deadbeat control system is a form of the pole placement control method. These pole(s) must be placed at the origin of the discrete z-plane. If the plant system is controllable, all pole(s) can be placed at the origin, and hence it will cause a near-perfect response [11].

The operation mode of the inverter depends on the three hall-effect signals which detect the rotor position. These signals are decoded into six switching signals to drive the full-bridge voltage source inverter VSI depending on the rotor position. Table I shows the six switching signals of the decoder [12]. Deadbeat predictive current controller with fixed switching frequency PWM operates with the six drive signals to drive the VSI. During any state of operation, only two-phases winding are energized and the third one is floating. The voltage across these two operating phases is the dc-link voltage source [13]. Figure 3 shows the energized two phases b and c.

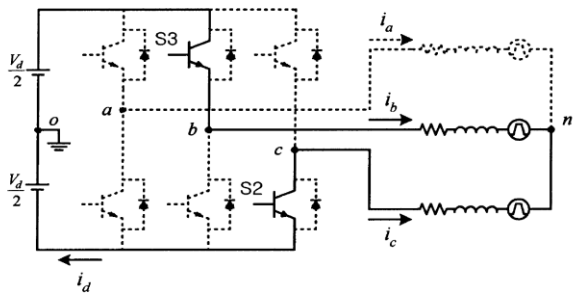

Figure 3: Operation mode with phase b and c energized [10]

TABLE I: six switching signals of decoder and hall-effect signals

Sequence	H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
1	1	0	1	1	0	0	0	0	1
2	1	0	0	1	1	0	0	0	0
3	1	1	0	0	1	1	0	0	0
4	0	1	0	0	0	1	1	0	0
5	0	1	1	0	0	0	1	1	0
6	0	0	1	0	0	0	0	1	1

From equation (1) the differential equation of voltage phase b and c are:

$$v_b = Ri_b + L\frac{d}{dt}i_b + e_b \tag{5}$$

$$v_c = Ri_c + L\frac{d}{dt}i_c + e_c \tag{6}$$

By combining equations (5) and (6):

$$v_{bc} = 2Ri_{bc} + 2L\frac{d}{dt}i_{bc} + e_{bc} \tag{7}$$

General subscripts are used for voltage and current as v_{xy} and i_{xy} where:$x, y \in a, b, c$ and $x \neq y$

$e_{bc} = 2E, E$ represents the magnitude of the back-EMF. $E = k_b\omega_r$, where $k_b$is the back-EMF constant.

$$v_{xy} = 2Ri_{xy} + 2L\frac{d}{dt}i_{xy} + e_{xy} \tag{8}$$

Figure (3) indicates that $v_{dc} = v_{xy}$ and $i_{dc} = i_{xy}$, the equation is reformed with dc-link side as:

$$v_{dc} = 2Ri_{dc} + 2L\frac{d}{dt}i_{dc} + 2E \quad (9)$$

The deadbeat predictive control principle is based on discretizing a plant model. The function of the predictive controller collects the input signals to predict the desired model control signal, eliminating the error between the desired and the measured input $(i_{dc}^{*} - i_{dc})$ at the beginning of each sampling period, i_{dc}^{*} is the reference current, which is usually provided by the speed controller (not included in this paper). In the BLDC motor control system, the deadbeat predictive controller based on discretizes the electrical equation (9). To discretize equation (9), assume T_s is the sampling period, from kT_s to $(k+1)T_s$ using forward difference method, we can get the current differential value [6]:

$$\frac{d}{dt}i_{dc} = \frac{i_{dc}(k+1) - i_{dc}(k)}{Ts} \quad (10)$$

The current is sampling into k sampling periods, the current i_{dc}^{*} is the reference state of the k sampling period, so it can make the $k+1$ tracking the calculated reference value at the k sampling period as [14]:

$$i_{xy}(k+1) = i_{dc}(k+1) = i_{dc}^{*}(k) \quad (11)$$

$$v_{xy}(k+1) = v_{dc}(k+1) = v_{dc}^{*}(k) \quad (12)$$

$$v_{dc}(k+1) = 2Ri_{dc}(k) + 2L\left(\frac{i_{dc}(k+1) - i_{dc}(k)}{T_s}\right) + 2E \quad (13)$$

$$v_{dc}(k+1) = v_{dc}^{*}(k) = 2Ri_{dc}(k) + 2L\left(\frac{i_{dc}^{*}(k) - i_{dc}(k)}{T_s}\right) + 2K_b\omega_r(k) \quad (14)$$

Equation (14) represents the deadbeat control voltages. Ideally, the deadbeat control output (voltages) tracks the desired current with zero error within one sampling interval T_s, but the digital signal processing which is used to implement the deadbeat control algorithm in the physical drive system cause an inherent calculation delay. The deadbeat control voltages have predicted at the beginning of the $k+1$ interval, if the delay is not taking into account, an oscillation is presented in the current loop response. This delay in predicting voltage can be beaten by using the current predictor that predicts the currents by one sampling period and then use the predicted currents to calculate the deadbeat control voltages. The predicted current can be calculated by rearranging the equation (13) for the current at the next sampling instant [11]. The discretized model is shown as:

$$\hat{i}_{dc}(k+1) = \frac{T_s}{2L}v_{dc}(k) + \left(1 - \frac{T_s * R}{L}\right)i_{dc}(k) - \frac{2T_s}{L}k_b\omega_r(k) \quad (15)$$

$$v_{dc}^{*}(k) = 2R\hat{i}_{dc}(k+1) + 2L\left(\frac{i_{dc}^{*}(k) - \hat{i}_{dc}(k+1)}{T_s}\right) + 2K_b\omega_r(k) \quad (16)$$

For the current controller, the two approaches of PWM were used which are; bipolar PWM and unipolar PWM, bipolar PWM method controls six switches as shown in figure 4; unipolar PWM controls only three switches. When the upper switches are controlled and the lower is permanently ON, this is called U-PWM-L-ON as shown in figure 5, the reverse case is called U-ON-L-PWM as shown in figure 6; both of U-PWM-L-ON and U-ON-L-PWM have the same dynamic response. The output of the current controller is the deadbeat control voltage, which is compared with a triangular carrier signal in the PWM generator [15]. A schematic diagram of the proposed control system is illustrated in figure 7.

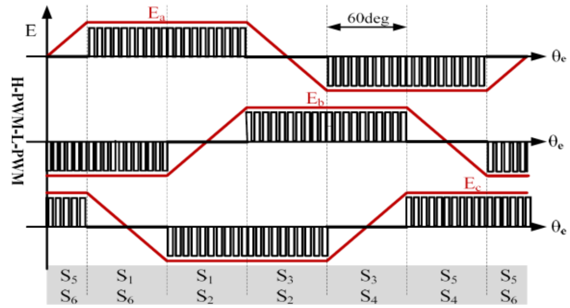

Figure 4: Bipolar PWM waveform for BLDC motor

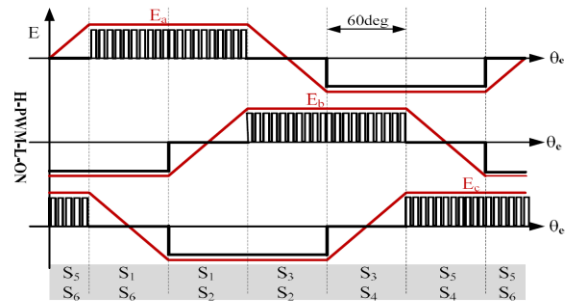

Figure 5: Unipolar H-PWM-L-ON waveform for BLDC motor

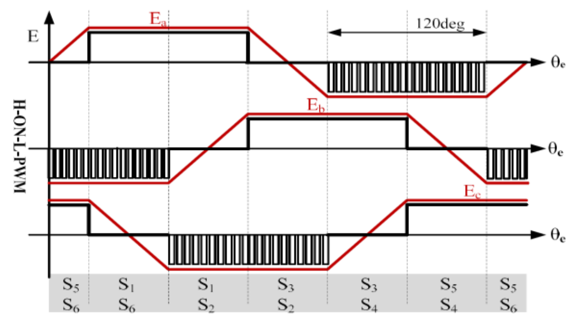

Figure 6: bipolar H-ON-L-PWM waveform for BLDC motor

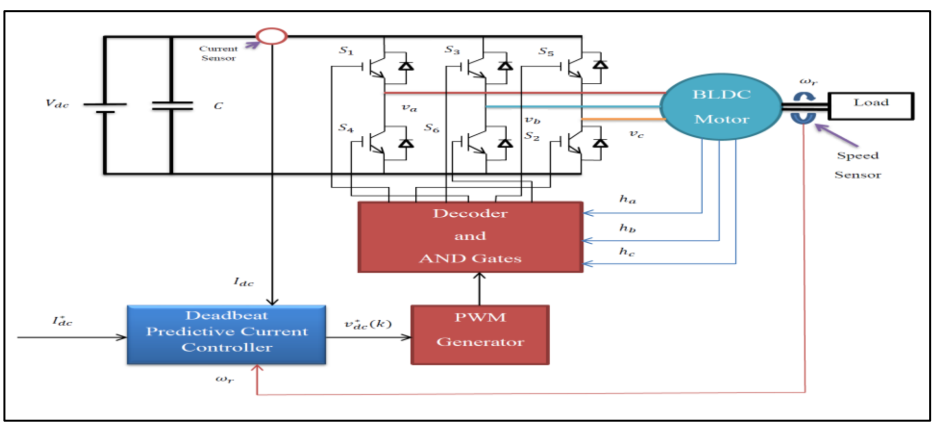

Figure 7: block diagram of the proposed control system

4. SIMULINK AND RESULTS

The control system is simulated using the MATLAB software (version R2018b) as shown in figure 8, details of the Simulink block diagrams are shown in the following figures: decoder circuit is described in figure 9, ANDS gate circuit for the bipolar PWM modulator is shown in figure 10, bipolar (H-PWM-L-ON) modulator and bipolar (H-ON-L-PWM) modulator are shown in figure 11 and figure 12, respectively, while the deadbeat predictive current controller is shown in figure 13. The parameters and constants of the BLDC motor are listed in table II. To examine the validity of the proposed controller, the system is tested at various speed and load conditions, and the obtained results are compared with another controller which is the conventional PI controller.

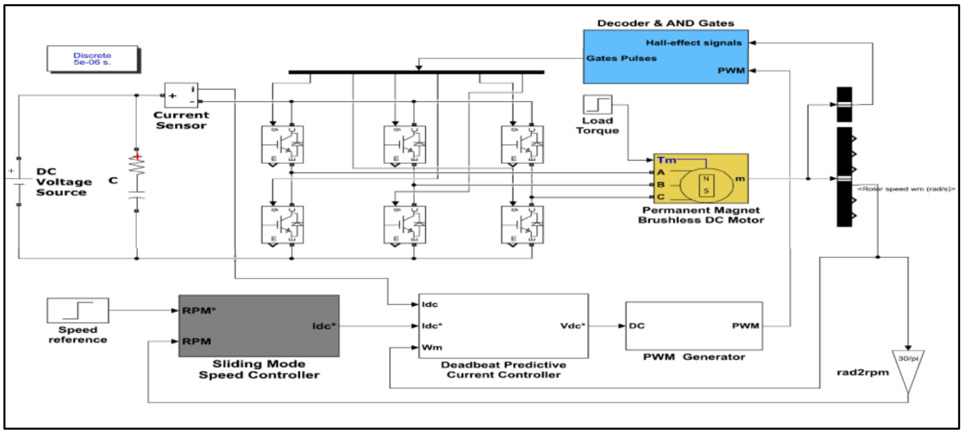

Figure 8: Simulink diagram of the proposed control system

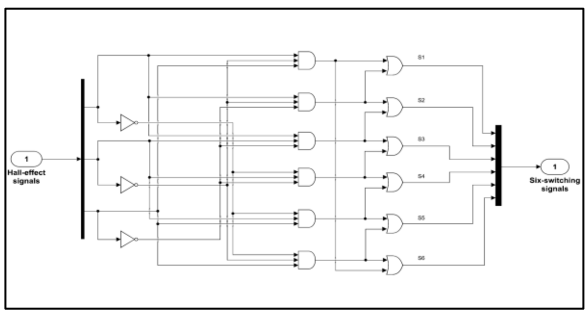

Figure 9: Simulink diagram of the decoder

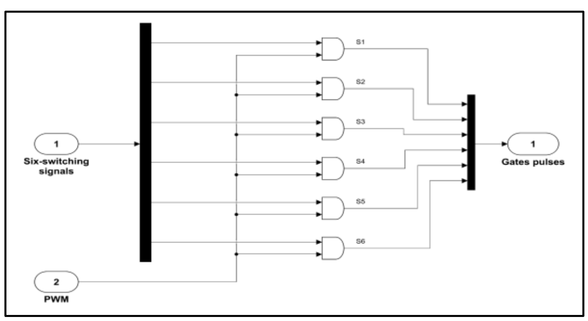

Figure 10: ANDs gates circuit for bipolar PWM modulator

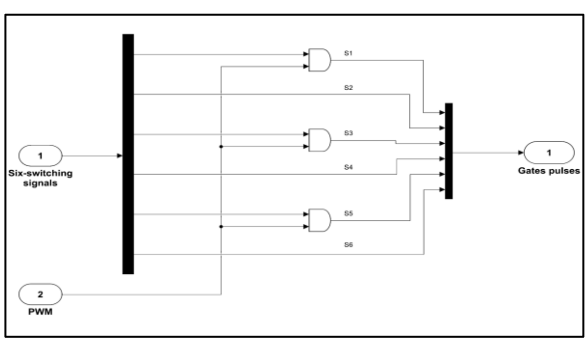

Figure 11: ANDs gates circuit for unipolar PWM (H-PWM-L-ON) modulator

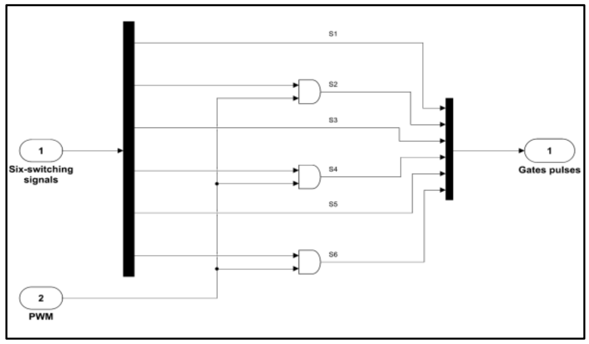

Figure 12: ANDs gates circuit for unipolar PWM (H-ON-L-PWM) modulator

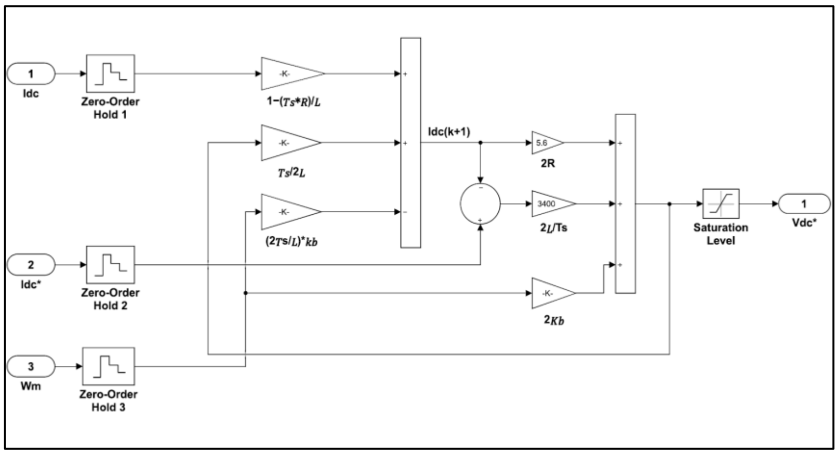

Figure 13: Simulink diagram of the deadbeat predictive current controller

TABLE II: specifications of the BLDC motor

Parameters	Value
Rated voltage (V)	500
Rated power (kW)	1
Rated Torque (N.m)	3
Rated Speed (rpm)	3000
Rated current (A)	10
Stator phase resistance (ohm)	2.875
Stator phase inductance (H)	8.5×10^{-3}
Flux linkage established by magnets (V.s)	0.175
Voltage constant (V peak L-L/krpm)	146.6077
Torque constant (N.m/A peak)	1.4
Back-EMF flat area (degree)	120
Inertia (kg.m2)	0.8×10^{-3}
Damping factor (N.m.s)	1×10^{-3}
Pole pair	4

For deadbeat predictive bipolar PWM controller: figure 14 shows phase current profile of the BLDC motor at full load and 1000 rpm, figure 15 shows phase currents profile at full load and 3000 rpm.

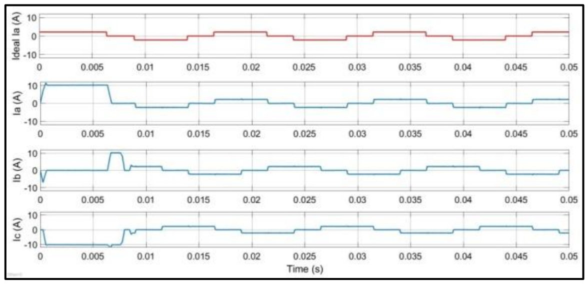

Figure 14: Phase current profile of the BLDC motor at 1000 rpm and 3N.m

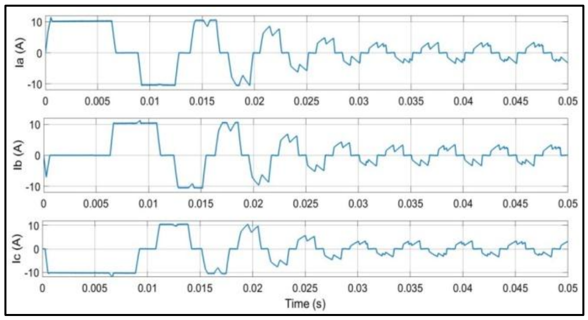

Figure 15: phase current profile of the BLDC motor at 3000 rpm and 3 N.m

Figure 16 and figure 17 show the motor electromagnetic torque at 1000 rpm and 3000 rpm, respectively.

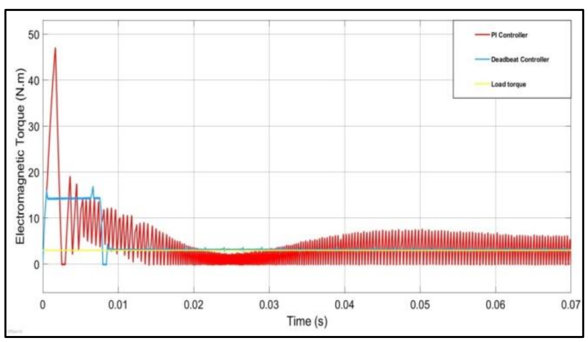

Figure 16: Electromagnetic torque profile of the BLDC motor at 1000 rpm and 3 N.m

Figure 16 illustrates the electromagnetic torque of the BLDC motor at 1000 rpm and 3 N.m based on direct DPCC with the bipolar PWM modulator. It has lower starting torque and smoother response comparing with the conventional PI current controller.

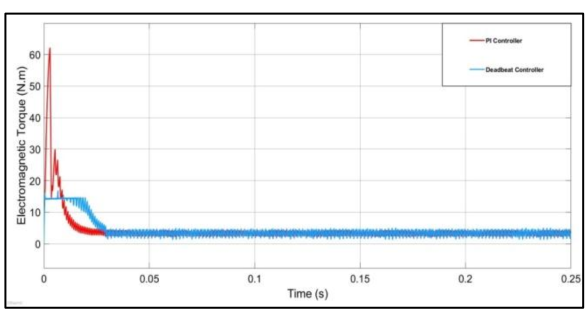

Figure 17: electromagnetic torque profile of the BLDC motor at 3000 rpm and 3 N.m

Increased speed leads to an increase in the torque ripple of the BLDC motor. Figure 17 shows the electromagnetic torque of the BLDC motor in case of full speed and full load conditions. It has a better response, lower starting torque, and lower torque ripple than conventional PI current controller.

For deadbeat predictive unipolar PWM controller: figure 18 shows phase currents profile of BLDC at full load and 1000 rpm, figure 19 shows phase currents profile at full load and 3000 rpm.

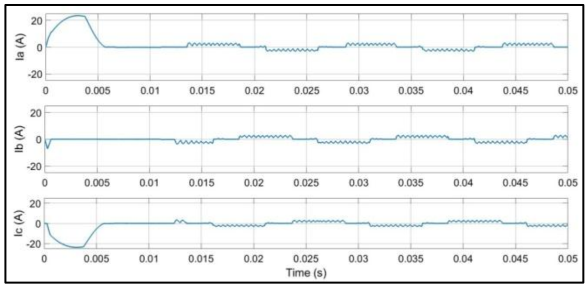

Figure 18: Phase currents profile of the BLDC motor at 1000 rpm and 3 N.m

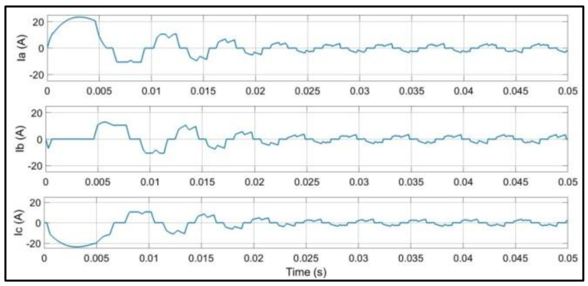

Figure 19: Phase currents profile of the BLDC motor at 3000 rpm and 3 N.m

Figure 20 and figure 21 show the electromagnetic torque of the BLDC motor at 1000 rpm and 3000 rpm, respectively.

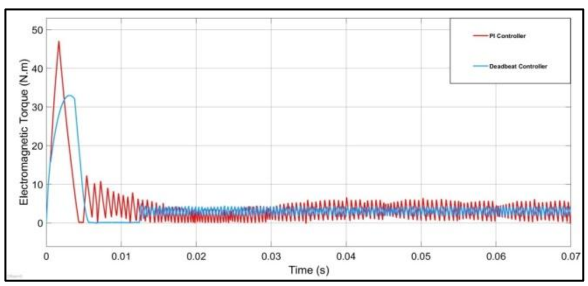

Figure 20: Electromagnetic torque profile of the BLDC motor at 1000 rpm and 3 N.m

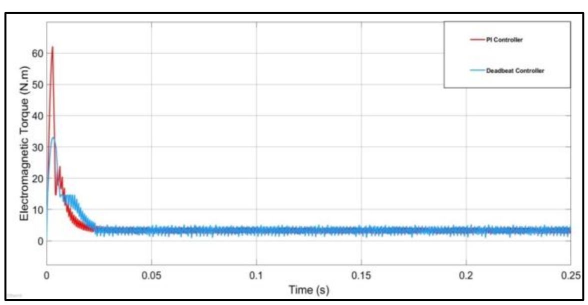

Figure 21: Electromagnetic torque profile of the BLDC motor at 3000 rpm and 3 N.m

The performance of the BLDC motor based on the proposed control system with a bipolar PWM method, which was shown in figure (17), is starting torque less than that is got with the unipolar PWM method. It is illustrated in figure (21).

The deviation of the motor electromagnetic torque from the reference (load) torque and the current from the reference (ideal) current will be calculated by using the root mean square rms method. The load torque is shown in figure (16) and the ideal current of phase a is shown in figure (14). A comparison between the performance of the PI controller and the proposed controller is illustrated in the table III for bipolar PWM and in the table IV for unipolar PWM technique.

TABLE III: Simulink results for bipolar PWM controllers

	1000 rpm				3000 rpm			
	Starting current (A)	Starting torque (N.m)	Current deviation rms (A)	Torque deviation rms (N.m)	Starting current (A)	Starting torque (N.m)	Current deviation rms (A)	Torque deviation rms (N.m)
PI controller	34	47	4.52	5.73	43	64	8.21	5.5
Deadbeat controller	10	15	2.86	3.72	10	15	4.4	3.33

TABLE IV: Simulink results for unipolar PWM controllers

	1000 rpm				3000 rpm			
	Starting current (A)	Starting torque (N.m)	Current deviation rms (A)	Torque deviation rms (N.m)	Starting current (A)	Starting torque (N.m)	Current deviation rms (A)	Torque deviation rms (N.m)
PI controller	34	47	5.13	6.26	43	64	8.8	5.62
Deadbeat controller	22	34	4.8	6.1	22	34	6.26	4.29

Tables III and IV show that the deadbeat controller has lower starting current and starting current, lower torque deviation rms, and current deviation rms than the PI controller. The deadbeat has better performance with bipolar PWM modulator than unipolar PWM modulator as illustrated in table III and table IV respectively.

5. CONCLUSIONS

In this paper, the proposed control technique is the deadbeat predictive controller, which is used to regulate the dc current by using fixed frequency bipolar and unipolar PWM control method. The controller is simulated by Matlab/Simulink program. The obtained results showed that the proposed control method for bipolar PWM and unipolar PWM methods have lower starting torque and lower torque ripple than the conventional PI controller; bipolar PWM control exhibits lower starting torque (15 N.m) and lower starting current (10 Amp), while, the unipolar PWM control has starting of 34 N.m and starting current of 22 Amp. The electromagnetic torque profiles of the BLDC motor showed that the current deviation rms and torque deviation rms values of the proposed controller are lower than that of the conventional PI controller. Generally, for the single dc-link current sensor system, the obtained results, certify the performance of the deadbeat current controller, which exhibits fast response, lower starting torque, lower starting currents, and more convenient for different conditions than a conventional PI controller.

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