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Comparative Performance Analysis of BLDC Motor Speed Control Using CPLD-Based Implementation

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Abstract: The widespread usage of brushless motors in today's technological trend necessitates the occasional development of novel control techniques. This study compares the mathematical design of speed control for a brushless direct current (BLDC) motor using a complex programmable logic device (CPLD) with the implementation of speed control without CPLD modeling. A PWM technique is used to mathematically construct speed control by applying different duty cycles to a 3-ɸ inverter. The rotor position is determined via Hall sensors, which act as references to synchronize the PWM control signals. Verilog Hardware Description Language (VHDL) is used to write the control model, which is then validated by simulation of with CPLD. To evaluate the BLDC motor's speed performance under PWM control, an experimental setup is constructed. A 500W BLDC motor with a 48V rating is equipped with CPLD Max II devices to implement the control algorithm. This system generates PWM with a configurable duty cycle for a working frequency of roughly 20 kHz and commutates consecutively up to 400 RPM using a six-step commutation.

Keywords: CPLD - Complex Programmable Logic Device, ESC – Electronics Speed control, PI- proportional Integral, VHDL - Verilog Hardware Description Language, PWM–Pulse Width Modulation, PM- Permanent magnet, BLDC- brush less direct current motor, 3-ɸ- Three phase.

1 Introduction

Due to the variation in winding driving current waveforms, DC brushless motors are classified into two categories. One of these types is the square wave which is the trapezoidal wave, and the other is the PM synchronous motor, so named because the current flowing in the armature conductor is a sine wave [1].

BLDC motors have drawn a lot of interest because of their strong performance, high dependability, and enhanced efficiency in commercial, residential, and industrial settings. A BLDC motor may be able to transfer more electrical power into mechanical power for the same input power as a brushed motor because brushes don't produce friction. Its rotor is a permanent magnet, and to keep the motor going, an electronic controller must continuously change the phase of the winding. To do this, a power electronics switching circuit and a feedback sensor are required [2]. The most recent powerful CPLD / FPGA devices could be used in BLDC drives. 3-ɸ BLDC machines usually use power converters to implement control strategies. Despite the rapid development of special-purpose controllers, a programmable logic device or special-purpose processor is frequently needed to supply sufficient control signals to achieve the desired function [2]. There is a close relationship between the applied voltage and the motor's speed. By altering the average voltage across the windings, the speed can be changed. PWM signals are utilized to regulate the duty cycle since commutation is provided by electronic switches [2].

In order to create PWM signals, this study simulates a BLDC motor control system using CPLD as the principal controller. An integrated hall-effect sensor calculates the commutation sequence and tracks the position of the BLDC motor rotor.

The application of CPLD provides more advantages than micro-controller or FPGA when compared to other works. For such parallel processing, CPLDs operate faster than microcontrollers. The FPGA use case will overrate resources due to the design's simplistic algorithm. Additionally, when the system is first powered up, there is no requirement for programming or configuration because CPLD is a non-volatile device [3].

This paper's remaining contents are structured as follows. MATLAB modeling simulink comparison with and without CPLD based BLDC Motor speed Control Systemis thoroughly explained in Chapter II and the respectively simulation results are explained in Chapter III.

2 MATLAB modeling simulink comparison with and without CPLD based BLDC Motor speed Control System

A brushless DC motor is built similarly to a DC motor without brushes. It can have different winding layouts or 3-ɸ arrangements like a star or delta design. 3-ɸ BLDC motor control will be the main topic of this study.

The MATLAB Simulink model of BLDC motor speed control using CPLD is depicted in the block diagram below

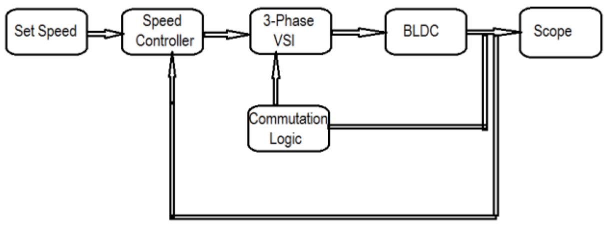

Figure 1 shows BLDC motor Drive

2.1 Modeling and simulation of BLDC motor Drive Without CPLD

Rotor position feedback is a feature of permanent synchronous brushless DC motors. Typically, a 3-ɸ power semiconductor bridge controls the brushless DC motors. It takes a rotor position sensor to start the motor and supply the right commutation sequence to turn on the inverter bridge's power components [4].

The information required to synchronize the rotor position with the motor excitation in order to generate continuous torque is provided by the Hall Effect sensors. It detects changes in the magnetic field. The hall sensors are activated by the rotor magnets. The stator frame has three hall sensors positioned each 120^0 apart. The location of the rotor is sensed using digital data from the hall sensors [4].

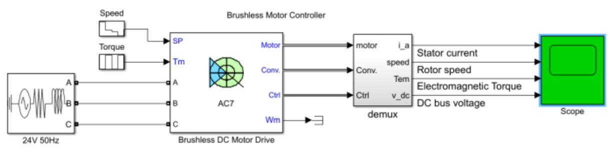

Figure 2 shows Modeling and simulation of BLDC motor Drive

A PI controller regulates the speed of a brushless DC motor in figure 2, which shows the BLDC motor drive modeled in MATLAB 2018b version. The BLDC motor's rotor position is determined by integrated hall sensors, and its speed is controlled by a potentiometer. An encoder or Hall-effect sensor can be used as a speed sensor [5].

This article discusses the K_p and K_i parameters of the PI controller for the BLDC motor speed control system. When compared to other traditional methods, the benefits of PI tuning include computational efficiency due to its ease of implementation and speedy processing [6].

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This modeling is a traditional technique. Using this technique, the performance of the motor is studied or its result is compared with the result that has been modeled using CPLD controlled PWM signal.

Error of the PI controller is the difference between the reference speed (ω_{ref}) and the actual speed (ω_{act}). The PI controller processes the error to generate a control signal:

$u(t) = K_p\, e(t) + K_i \int e(t)dt$ -------------------- (1)

Where K_p : proportional gain

K_i : integral gain.

In this method we have kept the value of K_p = 36 and value of K_i = 0.08, for tuning.

2.2. Brushless DC motor drive mathematical modeling and simulation using CPLD

The position of the rotor and stator electronically controls the BLDC motor's commutation. We must control the voltage on the driver since the applied voltage affects the speed of the BLDC motor[3]. To adjust the voltage, the pulse width modulation technique will alter the duty cycle of the PWM signals using CPLD.

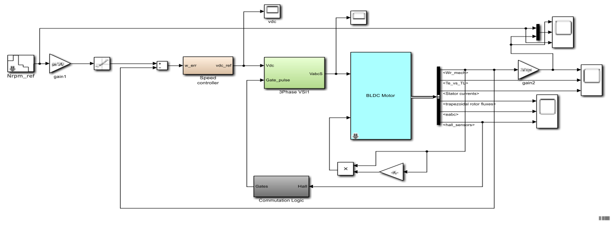

Figure 3 BLDC motor drive simulation and mathematical modeling using CPLD

Figure 1 displays BLDC motor control system's general architecture. Our system has speed controlled by PI controller and a position signal sense by sensors. As the brain of our system, the PWM logic signal component will be managed by the complex programmable logic device (CPLD).

Block diagram explanation for the BLDC motor driving system

a) **Speed controller:-** The controller regulates the speed of the brushless DC motor. Due to its great efficiency, longevity, and little maintenance needs, BLDC motors are popular. By reducing the gap between the set and actual speeds, a PI controller can be utilized to match a desired reference speed. A PI controller can be used to match a desired reference speed by decreasing the difference between the reference and real speeds. Here, back-EMF-based approaches are used to estimate speed sense without sensors.

The equation (1) represents PI controller output u(t) is used to modulate the PWM signals for the inverter and PWM signal is controlled or generate by CPLD.

b) **Brushless DC motor:-** BLDC motors can be efficiently controlled by a complex programmable logic device (CPLD). Motor control applications can benefit from CPLDs, a form of programmable logic device, which provide deterministic timing, high-speed operation, and parallel processing capabilities.

With the use of a mathematical formula, we have constructed a brushless DC motor. The brushless DC motor is symbolized by the transfer function block's drawer. There in CPLD block also the function of CPLD has been expressed through numerical equation. In this CPLD is given two inputs one of which is three phase voltage (V_a, V_b, V_c) or the other input is three phase back EMF (e_a, e_b, e_c). CPLD controlled PWM signal through combined input of voltage and back EMF which provides three phase current I_{abc} to the motor. This current is used in the electrical torque of the motor. Electrical torque requires an angle along with the current, hence in the modeling the electrical angle of each phase which is 120 degrees apart from the other has also been generated[7].

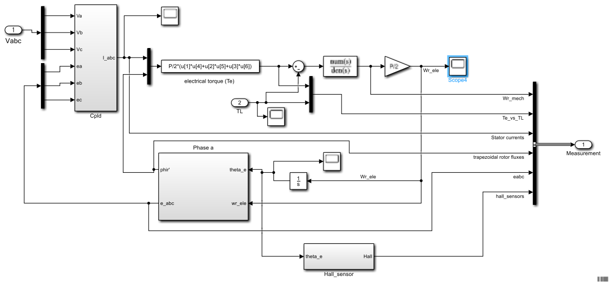

Figure 4 represent in MATLAB brushless DC motor block with CPLD

Electrical torque for each phase

$$T_a = k\, I_a \cos \emptyset$$

$$T_b = k\, I_b \cos(\emptyset - 120)$$

$$T_c = k\, I_c \cos(\emptyset - 240)$$

Resultant electrical torque

$$T_e = T_a + T_b + T_c$$

c) **Mathematical CPLD (Complex Programmable Logic Device)** – The term "CPLD" describes the usage of a CPLD to implement mathematical algorithms and operations in hardware. Because CPLDs are programmable logic devices that build digital circuits, they can be employed for activities like arithmetic operations, logic processing, and mathematical transformations as shown in figure 5 that call for quick, deterministic calculations. Designing a mathematical CPLD to control a BLDC motor involves implementing the necessary logic for commutation, PWM generation, speed control, and possibly advanced features like torque control.

In CPLD dynamic equation for controlling Brushless DC motor and represents the electrical dynamic of stator winding in a two phase stationary reference.

Stator resistance Rs :- -Rs/Lls*Ia this term of CPLD block represents the voltage drop brought on by the stator winding's resistance and current (Ia) normalized by the inductance (Lls)

Voltage inputs (Vab , Vbc):- 2/3/Lls*Vab and 1/3/Lls*Vbc these terms represents the contribution of the phase voltage applied to the motor. They are weighted factors based on the symmetrical component transformation.

Back EMF (eab, ebc):- -2/3/Lls*eab and -1/3/Lls*ebc these terms represents the induced electromagnetic force (Back EMF) in the stator winding. Generated Back EMF of BLDC motor is directly proportional to rotor speed.

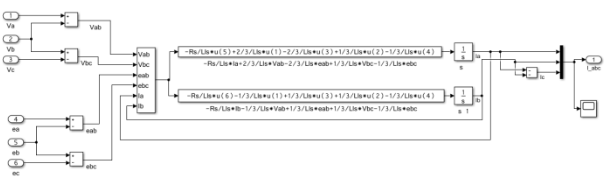

Figure 5 represent the CPLD block Mathematical Equation of BLDC motor

d) Calculating BLDC motor transfer function:-

To describe a Brushless DC (BLDC) motor theoretically, the electrical, mechanical, and electromagnetic subsystem equations must be determined. Below is a detailed explanation of the BLDC motor's mathematical model

Electrical Model:-

Using differential equations, the three stator windings (phases A, B, and C) of the BLDC motor may be represented [8] [1].

The voltage formulas for the 3-ϕ of a trapezoidal back-EMF BLDC motor are as follows [5] [9]:

$v_a = R\cdot i_a + L\frac{di_a}{dt} + e_a$ ------------------------- (1)

$v_b = R\cdot i_b + L\frac{di_b}{dt} + e_b$ --------------------------- (2)

$v_c = R\cdot i_c + L\frac{di_c}{dt} + e_c$ ---------------------------- (3)

Where:

V_a, V_b and V_c = 3-ϕ voltages

i_a, i_b, i_c = 3-ϕ currents

R = Respective Phase resistance

L = Respective Phase inductance (assumed identical for all phases)

e_a, e_b, e_c = 3-ϕ Back-EMF voltages

Mechanical Model

Newton's second law governs the motor's mechanical dynamics:[8][1][7]

$J\frac{d\omega_r}{dt} + B\cdot \omega_r = T_e - T_L$ --------------------------- (4)

$T_e = J\frac{d\omega_r}{dt} + B\cdot \omega_r + T_L$ ------------------------- (5)

$e = k_e * \omega_r$ -- (6)

$T_e = k_t * i_a$ -------------------------------------- (7)

Where:

Electromagnetic torque is denoted by T_e,

Viscous friction coefficient by B,

Rotor's moment of inertia by J,

torque under load by T_L,

Angular velocity of the rotor (ω_r),

Back emf Constant (k_e),

Continuous torque (k_t)

Electromagnetic Torque

The back-EMF and phase currents have a direct relationship with the electromagnetic torque Te. [8][10]

$Te = \frac{1}{\omega_r}(e_a * i_a + e_b * i_b + e_c * i_c)$ -------------------- (8)

Alternatively, for a balanced system, this can be simplified to:

$T_e = K_t * \sum_i i_i * f_i(\theta_e)$ -------------------------------- (9)

Where K_t is the torque constant, and $f_i(\theta e)$ represents the back-EMF shape.

Electrical Angle

The electrical angle θ_e is related to the rotor mechanical angle θ_m by:[8][7][10]

$\Theta_e = \frac{P}{2} * \theta_m$ --------------------------------------- (10)

Where P is the number of pole.

From equation (1) and (6)

$\frac{di_a}{dt} = -\frac{R}{L} * i_a - \frac{k_e}{L} * \omega_r + \frac{1}{L} v_a$ --------------------- (11)

From equation (4) and (7)

$\frac{d\omega_r}{dt} = \frac{T_e}{J} - \frac{T_L}{J} - \frac{B}{J} \cdot \omega_r$

$\frac{d\omega_r}{dt} = \frac{T_e}{J} - \frac{T_L}{J} - \frac{B}{J} \cdot \omega_r$ --- (12)

Using Laplace transform of equation (11) and (12)

$L\{ \frac{di_a}{dt} = -\frac{R}{L} * i_a - \frac{k_e}{L} * \omega_r + \frac{1}{L} v_a \}$

$s\, i_a = -\frac{R}{L} * i_a - \frac{k_e}{L} * \omega_r + \frac{1}{L} v_a$

$s\, i_a + \frac{R}{L} * i_a = -\frac{k_e}{L} * \omega_r + \frac{1}{L} v_a$

$i_a (s + \frac{R}{L}) = \frac{1}{L} (V_a - k_e * \omega_r)$ --------------- (13)

$L\{ \frac{d\omega_r}{dt} = \frac{kt * ia}{J} - \frac{T_L}{J} - \frac{B}{J} \cdot \omega_r \}$

$s\, \omega_r = i_a \frac{kt}{J} - \frac{T_L}{J} - \frac{B}{J} \cdot \omega_r$ ----------------------- (14)

at no load $T_L = 0$ put the value in equation (14)

$s\, \omega_r = i_a \frac{kt}{J} - \frac{B}{J} \cdot \omega_r$

$i_a = s\, \omega_r \frac{J}{kt} + \frac{B}{J} \cdot \omega_r \frac{J}{kt}$

$i_a = \frac{s\ \omega r + \frac{B}{J} \cdot \omega r}{\frac{kt}{J}}$ ------------------------------ (15)

put the value of i_a in equation (13)

$\left(\frac{s\, \omega r + \frac{B}{J} \cdot \omega r}{\frac{kt}{J}}\right) (s + \frac{R}{L}) = \frac{1}{L} V_a - \frac{1}{L} k_e * \omega_r$

$V_a = \omega_r \left(\frac{JL\, s^2 + s\, JR + s\, LB + RB + K_e K_t}{K_t} \right)$

Transfer function of the is obtained as an take a ratio of angular velocity ω_r and voltage

$G(s) = \frac{\omega_r}{V_a} = \frac{K_t}{JL\, s^2 + s\, JR + s\, LB + RB + K_e K_t}$

$= \frac{K_t}{JL\, s^2 + s\,(JR + LB) + RB + K_e K_t}$ --------- (16)

Let it be assume some assumptions

a) friction constant B is very small therefore B tends to be 0

b) $JR \gg RB$

c) $K_e K_t \gg RB$

Consider above assumption and rewrite the equation (16)

$$G(s) = \frac{K_t}{s^2\,JL + s\,JR + K_e K_t}$$

$$G(s) = \frac{\frac{1}{K_e}}{s^2 \frac{RJ}{K_e K_t} \frac{L}{R} + s\frac{JR}{K_e K_t} + 1} \text{ ---------------------------- (17)}$$

For 3-ф BLDC motor Mechanical constant

$$\tau_m = \frac{3RJ}{K_e K_t}$$

Electrical constant $\tau_e = \frac{L}{3R}$

Again rewrite the equation (17)

$$G(s) = \frac{\frac{1}{K_e}}{s^2 \tau_m \tau_e + s\,\tau_m + 1}$$

G(s) represents the BLDC motor's transfer function and provides the values of all the parameters. Using G(s) means modeling and simulation is done so that all the performance of the motor can be observed through the scope. As shown in figure

For BLDC motors, the connection between the torque constant K_t and the back EMF constant K_e is that electrical power equals mechanical power

$$\sqrt{3} * E * I = \frac{2\pi}{60} * N * T$$

$$\frac{E}{N} = \frac{T}{I} \frac{2\pi}{60} \frac{1}{\sqrt{3}}$$

$$K_e = K_t \frac{2\pi}{60} \frac{1}{\sqrt{3}}$$

$$K_e = K_t * 0.0605$$

$K_e = \frac{E}{N}$ is measured in $\frac{VX\,sec}{rad}$ or volt/RPM

$K_t = \frac{T}{I}$ is measured in $\frac{N\,X\,m}{A}$

BLDC motor electrical and mechanical parameter

Voltage = 24 V

Resistance of Rotor = 1.43 ohm

Inductance of Rotor = 9.4 X 10^{-3} H

Flux of Rotor = 0.2158 wb

Inertia of Rotor J = 5.5 X 10^{-3} kg m^2

Friction coefficient B = 2X 10^{-3}

Number of pole = 4

The above mathematical computations are related to how a brushless DC motor operates. Using this calculation, simulation has been done in MATLAB 2018b version; the results have been studied using the mechanical parameters given above.

3. Simulation result

Outcomes of a CPLD-based BLDC motor drive simulation

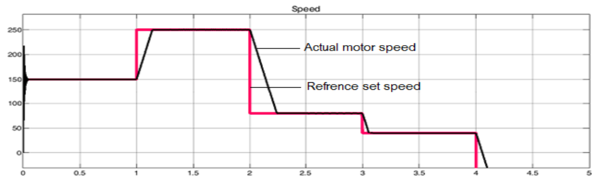

Figure 6 speeds controlled of BLDC motor with CPLD (speed (RPM) verses time (sec.))

The reference set speed is given in the input of brushless DC motor, in which the motor is started from 150 rpm in the initial stage. At this set speed, the motor is started from 150 rpm with a variation of a few sec 0.1sec. After this refrence speed is set to be 250 rpm at 1 sec, it takes approximately 0.1 sec for the actual speed of the motor to reach 250 rpm, which we can see in the wave form from the middle of the sleep. The motor's speed was adjusted to 80 rpm after two seconds, and the waveform shows how long it takes for the motor to reach that speed. Similar to this, the waveform in Figure 6 shows how the motor's speed varies over time. Here figure 6 shows the difference between of motor set speed and motor run speed.

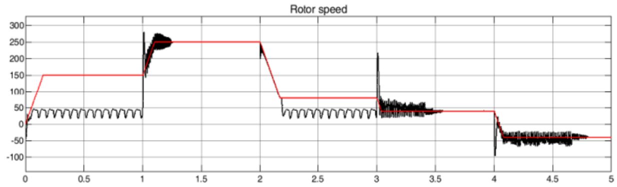

Figure 7 shows the speed controlled BLDC motor without CPLD (speed in RPM verses time in sec.)

When CPLD is not utilized, the brushless DC motor's speed is measured. In Figure 7, its wave shape is displayed. It is evident that the engine requires some time to attain the desired speed. Although the motor's fixed speed is 150 rpm, it actually approaches 50 rpm. where speed error is visible. Likewise, if the motor's specified speed rises or falls, the real speed may likewise exhibit inaccuracy.

Comparative table:

Table 1 Represents BLDC motor Speed comparison by using with and without CPLD

Parameters	BLDC motor Speed with CPLD	BLDC motor Speed without CPLD
+Rise time	**1.592ms**	**45.400 ms**
- Fall time	**-**	**6.196 ms**
+Slew rate	**55.453 /ms**	**19.517 /ms**
-Slew rate	**-**	**-14.296 /ms**
+Preshoot	**35.920%**	**20.996%**
-Preshoot	**-**	**-1.244%**
+Overshoot	**61.184%**	**82.600%**
-Over shoot	**-**	**1.997%**
+Undershoot	**7.356%**	**1.983%**
-Undershoot	**-**	**27.757%**

BLDC motor Speed control by using CPLD improves response speed, faster acceleration and with less overshoot.

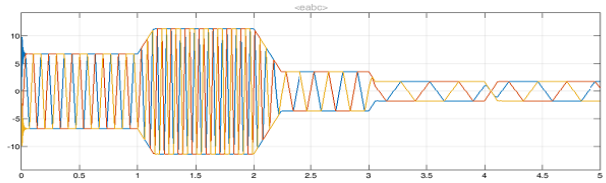

Figure 8 Back EMF verse time with CPLD

We can also observe a change in the motor's back emf by varying its speed. The connection between motor speed and back emf is straightforward.Through the examination of waveform figure 8, we can deduce that the motor's back emf is roughly 7 volts while the motor is operating at 150 rpm and grows to 250 rpm in 1 second. moves. About 12 volts are supplied to the motor. Through the wave form, we can observe that the motor's back emf drops to roughly 3.5 and 2 volts when its speed drops from 80 rpm to 40 rpm. We can determine the proper back emf of a BLDC motor or the speed behavior of the motor depicted in the image by examining this wave pattern.

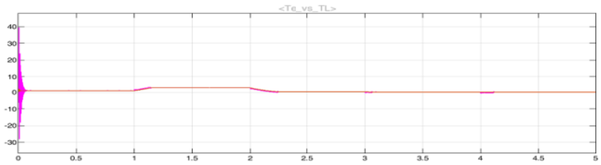

Figure 9 shows the torque verses time curve of BLDC Motor with CPLD controlled

As we can see from the waveform above in figure 9, the torque of the motor likewise depends on the speed velocity, indicating that the back emf of the motor is reliant on the motor's speed.

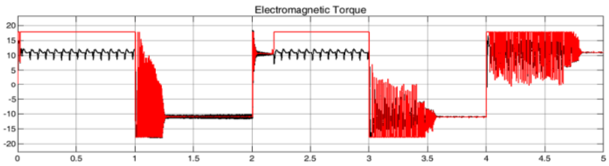

Figure 10 shows the torque verses time curve of BLDC Motor without CPLD controlled

By looking at the above figure 10 graph or waveform we can clearly say that when CPLD is not being used to control the motor, there is a lot of variation in the torque of the motor. By looking at Figure 9, it becomes clear that by using CPLD, the variation in the values of torque and magnitude also reduces significantly.

As a result, torque ripple is reduced using the CPLD Control technique's precise phase commutation; but, without CPLD Control, torque ripple is increased because of wasteful switching and delayed response.

Comparative table:

Table – 2 Represents BLDC motor Torque comparison with and without CPLD

Parameters	**BLDC motor Torque with CPLD**	**BLDC motor Torque without CPLD**
+Rise time	346.715 µs	1.724 ms
- Fall time	314.491 µs	1.148 ms
+Slew rate	12.527 /ms	5.236 /ms

-Slew rate	-14.026 /ms	-7.798 /ms
+Preshoot	157.775%	64.739%
-Preshoot	130.308%	16.406%
+Overshoot	118.370%	12.415%
-Over shoot	5.594%	1.935%
+Undershoot	0.966%	1.969%
-Undershoot	150.704%	64.710%

Faster torque response (rise time, fall time, and slew rate) is offered by CPLD. Preshoot, overshoot, and undershoot are all significantly increased by CPLD. Vibrations, inefficiencies, and mechanical wear could result from the large torque changes.

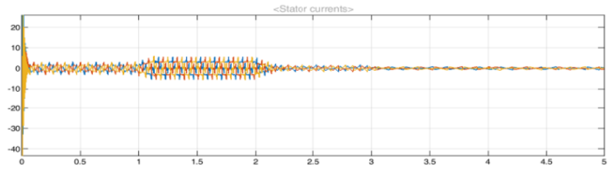

Figure 11 Stator current verses time curve shows with CPLD Control strategies

The brushless DC motor's stator current draws a lot of current when it first starts, but it is thereafter managed by a 3-ϕ current voltage source inverter. The location of the motor's rotor is also established by properly sequencing the BLDC current through CPLD, which enables the motor's phases to be triggered one at a time and yield information.

Examining the waveform in figure 11 above, it is evident that the motor's input stator current varies in tandem with its speed. If the motor's speed drops, its current value will likewise drop, or if the motor's speed accelerates, its current value will likewise rise.

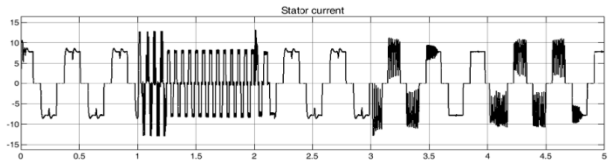

Figure 12 shows Stator current verses time curve shows without CPLD Control strategies

Figures 11 and 12 illustrate how a change in motor speed causes a corresponding change in the motor's current as well as a shift in the current's duty cycle.

By using CPLD the duty cycle of motor current becomes very low whereas without using CPLD when the motor is run the value of motor current also becomes high and the duty cycle also becomes high compare to other one as shown in figure 12.

The current waveform with CPLD would appear smoother and more stable, as seen in the figure 11 and 12 plots, while the waveform without CPLD would exhibit more oscillations and ripples.

Comparative table:

Table – 3 Represents BLDC motor Stator current comparisons with and without CPLD

Parameters	**BLDC motor Stator current with CPLD**	**BLDC motor Stator current without CPLD**
+Rise time	483.627 µs	2.389 ms
- Fall time	437.098 µs	2.868 ms
+Slew rate	14.347 /ms	4.208 /ms
-Slew rate	-16.191 /ms	-4.494 /ms
+Preshoot	144.144%	17.174%
-Preshoot	93.731%	2.626%
+Overshoot	66.976%	3.998%
-Over shoot	1.016%	3.220%
+Undershoot	1.357%	4.044%
-Undershoot	114.204%	18.763%

The motor's dynamic performance is improved, overshoot and undershoot are decreased, and response time is greatly increased by the CPLD.

4. CPLD algorithm output

The CPLD output waveform is shown in figure 13 below. The BLDC motor draws a lot of current at first before reaching the appropriate rated speed. This information is given to the stator of the motor through CPLD to change the current of the motor. The desired PWM sequence should be given to the motor correctly so that the running operation of the motor is best.

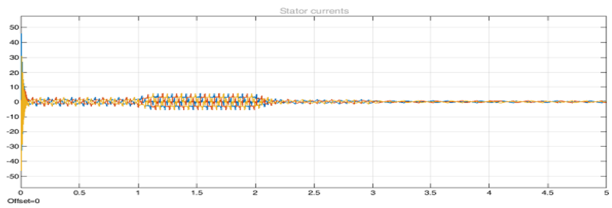

Figure 13 Modeling CPLD output in form of current

5. Conclusion

Different Simulink models have been created for modeling brushless DC motor in MATLAB without using CPLD or using CPLD. This is a comparison between the BLDC motor mathematical model created in MATLAB R2018b version using CPLD and the output of the BLDC motor model, which employs a PI controller for motor speed control.

By looking at Table 1, 2 and 3 we can understand that using CPLD significantly improves the performance of BLDC motor.

The main motivation behind creating this paper was to simulate BLDC motor drive in MATLAB through numerical mathematics. In this paper, all the sections have been implemented and simulated mathematically; these numerical values have also been used in our hardware model implementation. Because CPLD is used for control, any PWM signal that is applied to the motor for commutation is given with perfect precision or accuracy. As a result, the brushless DC motor's performance or efficiency is improved in comparison to when a BLDC motor drive without CPLD modeling is used.

In the future, CPLD can be paired with AI or fuzzy logic systems to create hybrid brushless DC motor technology. This can further enhance the brushless DC motor's efficiency or performance.

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Conflict of Interest

The authors don't have any conflict of interest among them. The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

Author Contributions

The Author Contributions section is mandatory for all articles, including articles by sole authors. The Author Contributions statement must describe the contributions of individual authors referred to by their initials and, in doing so, all authors agree to be accountable for the content of the work.

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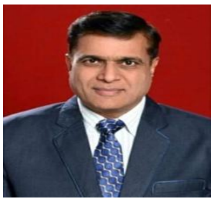

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