CPLD Controller Based Speed Control of BLDC Motor Drive

Sadhak Juli Singh[1], Bhusnur Surekha[2], Dubey S. P[3]

[1]Research Scholar, Department of Electrical Engineering , BIT Durg, CG, India,
Email: singh.juli@gmail.com
[2]Professor, EEE Department, BIT Durg, CG, India, Email: sbhusnur@yahoo.co.in
[3]Vice-Chancellor, ICFAI University Raipur, CG, India, Email: spdubeyfee@gmail.com

Received: 17.04.2024 Revised : 19.05.2024 Accepted: 25.05.2024

ABSTRACT
In today's time, to work in all fields, we need a motor with low power consumption and efficient work that is why BLDC motor is very famous in the new trend. Therefore it is important to understand the control techniques and have been explored electronic commutation method of BLDC motors. In this, the combination of traditional method and new method using hybrid commutation is understood. The traditional method is Zero Cross Detection Back EMF method and the innovative method is based on PID controller plus CPLD control technique. This paper shows the tabulation of torque and various features of PID plus CPLD control technique. Using these techniques together greatly improves the performance of the BLDC motor, discussed in this research work.

Keywords:BLDC-Brushless DC Motor, ECC- Electronic Controller Circuit, PCB- Printed Circuit Board, ZCD-zero cross detector, PID- Proportional integral and derivative, CPLD-Complex Programmable Logic Device, PWM- pulse width modulation

1. INTRODUCTION

The current era marks the start of the industrial revolution, which was sparked by the development of the motor. In industrial applications, two types of DC motors are typically configured. In the first form, the static pole structure's field coil generates the necessary magnetic flux, whereas in the second type, a permanent magnet provides the necessary air gap flux [1,2].

A multitude of motor types have been developed throughout the years, but they can be broadly divided into two categories: AC motors and DC motors. In a DC machine, the commutator and brushes are essential components. An advantage of utilizing a DC machine is that high speed and high current can destroy brushes; a brushless DC motor was developed to get around this restriction. The tiny size, higher efficiency, and large speed range of BLDC motors have made them quite popular in today's world [2].

Here Better speed versus torque characteristics, high efficiency, excellent dynamic response, long working life, noiseless operation at greater speed ranges, and cheap maintenance are the key benefits of brushless DC motors (BLDC) over conventional brushed DC motors. Thus, BLDC is becoming more and more common. BLDC motors are used extensively in many industries, particularly those that produce appliances, treat patients, fly in airplanes, manufacture medical equipment, work in chemicals, manufacture automobiles, make textiles, and automate industrial processes. Digital audio recordings, computer disc drives, tape recorders, and other visual devices frequently use small motors with external rotors [3].

The speed control is crucial for BLDC motors. Effective controllers for digital control of the BLDC are necessary to meet a variety of control requirements. The most widely used controllers are fuzzy logic controllers (FLU controllers), PID controllers, and combinations of these controllers, such as fuzzy-genetic algorithms, fuzzy-neural networks, and so forth. The PID controller is chosen as the primary control algorithm based on the requirements of the actual application as well as stability and reliability principles [1,2,3,4,5].

The designing and implementation of a closed-loop control system for a high power BLDC motor. Using the K_p, K_i, and K_d parameters of the PID controller, one can adjust the algorithm through tuning. Using this method, receive a steady and dependable speed. Experiments demonstrate the robustness of the system's operating performance both before and after adding load, as well as the dependability of the hardware and software control algorithms. The system has a wide range of potential applications and can be further expanded to additional application areas [3].

An ultra-light electric vehicle can utilize the three-phase BLDC motor controller. A Programmable Logic Device (CPLD) is used to perform the control, and no additional processor is needed. In this manner, a reliable and simple control is achieved. Additionally, a phase advance circuit is used to increase the BLDC's speed range. The controller's extremely low power consumption is an intriguing feature for battery-powered applications [6].

1.1 PID Controller

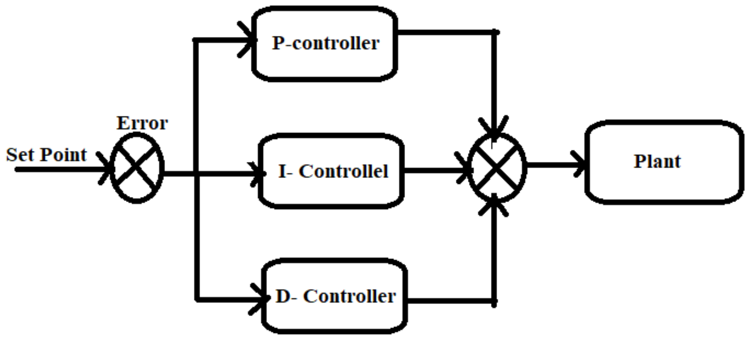

Fig 1. Schematic diagram of PID controller

A common feedback loop technique in industrial control systems is the PID controller.
-A feedback control technique that modifies motor speed in response to deviations from the set-point and actual speed.
- To reduce inaccuracy, three properties are used: proportional (P), integral (I), and derivative (D).
- Widely used in numerous applications [1].

Advantages

1. Ease of Implementation: PID controllers are relatively simple to implement and widely understood.
2. Flexibility: They can be tuned for different types of control requirements.
3. Cost-Effective: PID controllers can be implemented using low-cost microcontrollers or digital signal processors (DSPs).
4. Robust Performance: PID controllers provide stable and accurate control for a wide range of applications.

Disadvantages

1. Tuning Complexity: Finding the optimal parameters (K_p, K_i, K_d) can be time-consuming and may require trial and error.
2. Limited Adaptability: PID controllers may not perform well under varying system dynamics or disturbances.
3. Computational Delay: Depending on the implementation, PID control loops may introduce computational delays, especially in high-speed applications.

Applications

Widely used in industrial automation, process control and motor control where high precision is not critically required.

1.2 CPLD Controller

The digital portion is based on the XC2C64 Complex Programmable Logical Device (CPLD), which has 33 I/O that can be rearranged as needed. An essential feature when employing analog produced inputs is the ability to customize each input with an inbuilt Schmitt trigger. This is fairly simple to accomplish with Xilinx's Integrated Software Environment (ISE). Because all inputs and outputs are processed in parallel in a CPLD, there are almost no speed restrictions, allowing one to select a motor with a high number of poles and rpm. Concentrated pole BLDC motors, which often have a large number of poles and frequency above 500 Hz, benefit from this [6,7].

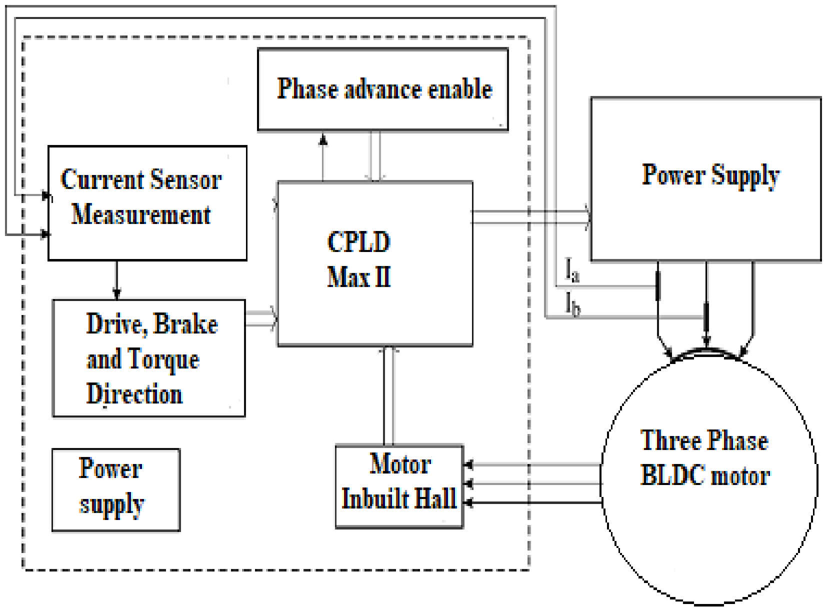

Fig 2. Structure of Complex Programmable Logic Device

As shown in figure 2 the BLDC motor's phase currents, I_a and I_b, are measured using the current measurement. Therefore, two phase currents are corrected and measured. The sum of the negative currents in the first two phases equals the current in the third phase. The maximum of all absolute current values is used to generate a signal. To be consistent with the positive set value for drive and braking torque, the voltage at point A is moved to point B, which is positive [6]. In relation to the rear emf, the required phase advance on phase current. Without phase advance, the BLDC cannot generate the same torque at high speeds, resulting in poor acceleration as the vehicle drives quickly. A phase advance can counteract this phase lagging, increasing torque and efficiency at high speed [6,8].

CPLD MAX-II Block input and output waveform

the control algorithm according to the proposed system. Logic control was then implemented to CPLD Max II: EPM240T100C5 using JTAG via Quartus software, a 500W, 48V and 13.5 Ampere rated BLDC motor without gearbox.

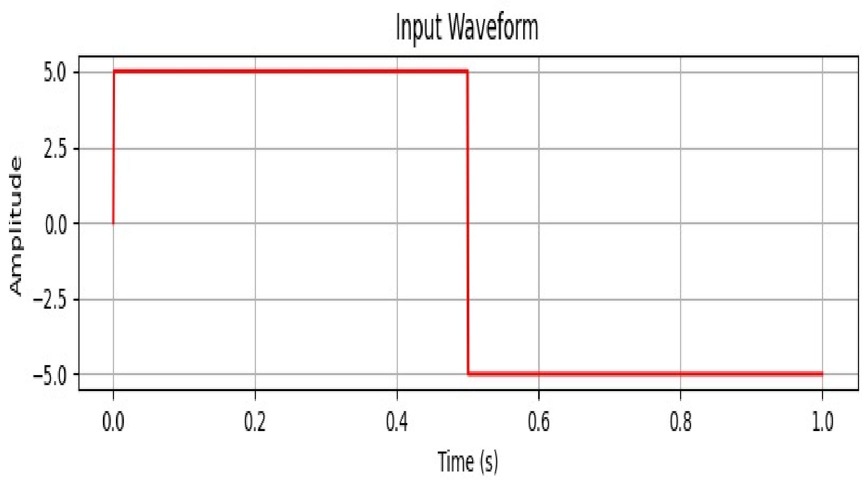

Fig 3. CPLD MAX-II Block input waveform

Figure 3 represents input waveform of CPLD Max II and the output of Micro controller. This programming/code provides a basic implementation of a PWM generator for a three-phase BLDC motor control. The PWM duty cycle is determined by **pwm_input**, and the phases are sequentially enabled according to the phase shift required for BLDC motor operation.

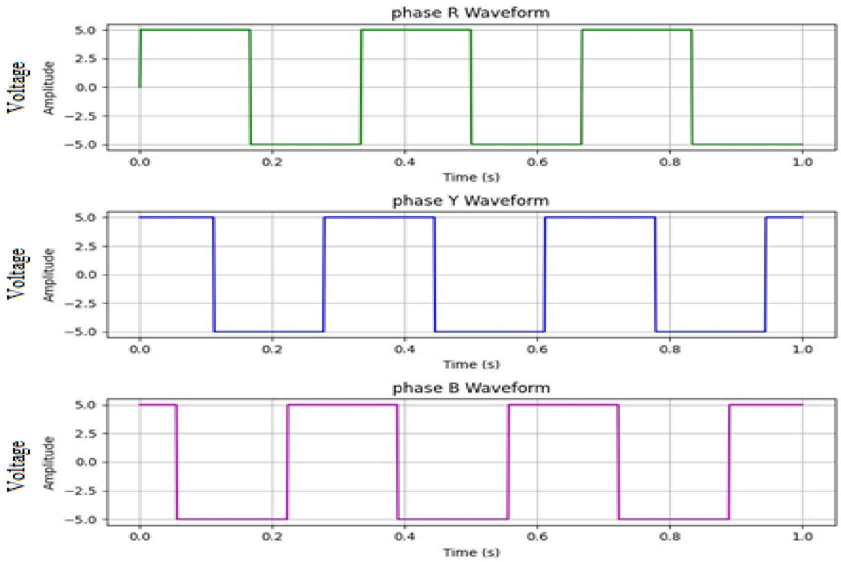

Fig 4. CPLD MAX-II Block output waveform of Phase R, Y and B is fed to MOSFET

In such a above figure 4 setup, the CPLD would generate three output signals corresponding to the phases R (Red), Y (Yellow), and B (Blue). These signals would be pulsed in a specific sequence to control the motor.
In this waveform:

- Each phase signal (R, Y, B) alternates between high and low states.
- The sequence of pulses in each phase determines the rotation direction and speed of the motor.

Figure shows the specifics of waveform, including pulse width, frequency, and duty cycle, would depend on the motor control algorithm implemented in the CPLD MAX II. This demonstrates CPLD devices like the MAX II series can indeed be utilized for generating complex waveforms to control electromechanical systems, including the switching of MOSFETs for driving Brushless DC (BLDC) motors [7].

Advantages

1. High Speed: CPLDs offer faster processing capabilities compared to microcontroller-based PID controllers, making them suitable for high-speed motor control.
2. Deterministic Performance: CPLDs provide deterministic and predictable timing, which is crucial for precise control.
3. Parallel Processing: CPLDs can execute multiple control algorithms simultaneously, enhancing performance.
4. Customization: They can be highly customized for specific control applications, optimizing performance for particular tasks.

Disadvantages

1. Complexity: Designing and programming CPLDs requires specialized knowledge and tools.
2. Cost: Initial development and programming costs can be higher compared to PID controllers.
3. Flexibility: Once programmed, CPLDs are less flexible to changes compared to software-based controllers.

Applications

Suitable for applications requiring high-speed and precise control, such as robotics, advanced motor control systems, and real-time signal processing.

Table 1. Key Differences in Speed Control of BLDC Motors [1,2,6,9,10,11,12]

S.N.	parameters	PID Controller	CPLD Controller	PID + CPLD Controller
1.	**Speed and Responsiveness**	Appropriate for standard speed control scenarios where a high response speed is not essential. The microcontroller's processing speed and tuning parameters have an impact on the response time.	Faster and more deterministic control is available, making it perfect for high-speed applications that need quick and accurate reactions.	Quick response and processing times from the PID Plus CPLC controller. Advanced logic and decision-making capabilities.
2.	**Implementation Complexity**	Simpler to use and necessitates less specialist knowledge. Although difficult at times, tuning is a manageable process.	Designing and implementing something more complicated calls for familiarity with digital design concepts and hardware description languages (HDLs).	PID + CPLD requires knowledge of both PID control and CPLD programming, making it more difficult to design and implement.
3.	**Flexibility and Adaptability**	More versatile and adjustable to various control situations. Modifications to software can be made with reasonable ease	After installation, less adaptable. Reprogramming the hardware is necessary for any changes, and it can be a laborious and complicated process.	More customization and adaptation to shifting motor circumstances are possible with PID + CPLD control algorithms.
4.	**Cost**	More economical in general, especially when needs low to medium performance are met.	More expensive initially because of programming and development, but it performs better in some high-speed applications.	Compared to basic PID controllers, PID + CPLD solutions are typically more expensive.
5.	**Performance Under Disturbances**	Under different system dynamics or outside disturbances, performance may deteriorate.	The CPLD controller is known for its reliable and steady operation, which keeps control precision under all kinds of circumstances.	Its sophisticated logic and processing capabilities, PID + CPLD provides improved performance, precision, and stability.

BLDC Motor Specifications

- Rated Voltage: 48 Volt DC.
- Supply voltage : 24 V
- Rated Power: 500W.
- No Load Current: 4.0A.
- No Load Speed: 516 RPM.
- Rated Torque: 102Kg-cm. or 10 Nm
- Rated Speed: 450 RPM.
- Rated Current: 13.4A.
- Efficiency: 80%.

Hardware data tabulation of BLDC motor torque

First, let's convert the motor's power from watts to volts times amps ($P=VI$). Assuming the motor operates at its rated power and voltage, we can use Ohm's Law (V = I R) to calculate the current (I) here I is motor current and it denoted by $I_m$and V is supply voltage given to BLDC motor and its denoted by S_V:

$P = S_V * I_m$[8,13,14]

$I_m = P / S_V$

Given:

- Motor power (P) = 500 watts
- Supply voltage (S_V) = 48 volts

We calculate:

$I_m=500/48$

Motor rated current $I_m \approx 10.42$ amps

Now, we can use this current (I_m) and the motor's power (P) to estimate the back EMF (E).

$E = S_V - I_m * R$

Given:

- Rated Supply voltage (S_V) = 48 volts
- Rated Current (I_m) ≈ 10.42 amps

The BLDC motor proposed in this project is used in electric vehicles, in which the gear box has been removed because our hardware does not require it. The rating of BLDC motor is 48 volt, 13.4 amp, 500 watt and 450RPM. Due to unavailability of 48 volt source, a 24 volt 10 amp supply has been applied to the hardware through SMPS of our project.

The torque calculation of BLDC motor at no load condition, Let us assume to be friction and windage losses and heat losses are negligible, because motor are operating at no load condition.

$T = \frac{P*60}{2\pi N}$[14,15]

Where,

T= Torque is measured in Newton meter (NM)

P = BLDC Motor Power ($S_V * I_m$) measured in Watt (W)

Hybrid techniques used hardware model Results

PID (Proportional-Integral-Derivative) control and CPLD (Complex Programmable Logic Device) techniques are new methods used for commutating the BLDC (Brushless DC) motors and CPLDs are programmable logic devices that can be configured to perform specific tasks.

Combining CPLD and PID for Sensor Input Processing in BLDC Motor Commutation to ascertain the rotor's position, the CPLD receives inputs from position sensors. The CPLD creates the proper commutation signals to energize the correct motor phases based on the rotor position. It regulates motor speed and torque, the CPLD can produce PWM signals with different and variable duty cycles according to load variations. A PID controller receives feedback from the motor's position or speed measurement. The PWM duty cycle is modified by the PID controller based on its calculation of the error between the desired and actual values. The control past of CPLD receives the output of the PID controller, such as a new duty cycle value for variation of speed.

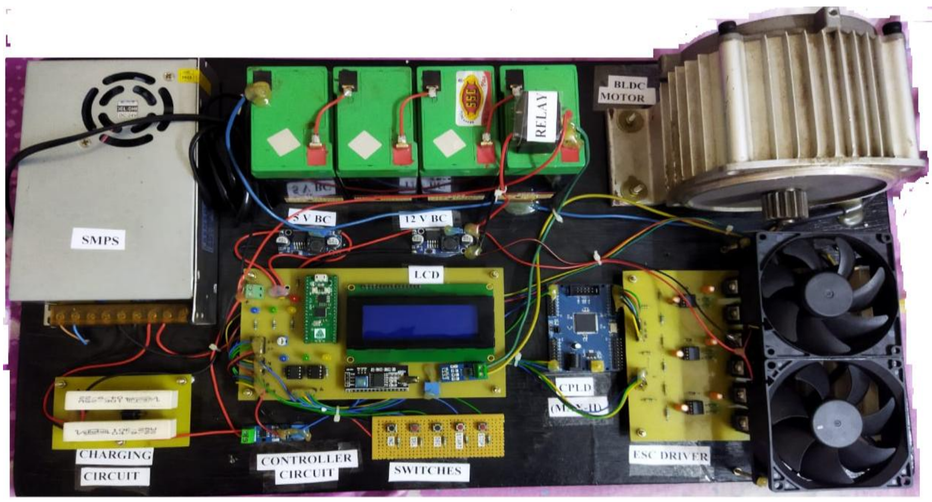

Fig 5. Hardware setup of PID plus CPLD control Technique of BLDC motor Drive

A BLDC motor can be operated efficiently by combining a Raspberry Pi Pico (RPI2040) microprocessor circuit with a CPLD MAX II circuit. The RPI2040 serves as the primary controller in this scenario, generating PWM signals and carrying out motor control algorithm execution. The CPLD MAX II is a helpful addition to the RPI2040 provides more logic resources for creating custom control logic and communication with peripherals. Gate drivers facilitate communication between the CPLD MAX II and the power MOSFETs that control the motor phases. The RPI2040 and CPLD MAX II generate signals that power MOSFETs use to switch the current passing through the motor phases.
Three PWM signals, one for each of the three motor phases, are produced by the RPI2040 and CPLD MAX II. The duty cycle of these PWM signals regulates the average voltage applied to each motor phase as well as the motor speeds. The synchronization and timing of the PWM signals, which switch the MOSFETs at the proper moments to match the rotor position, guarantee smooth spinning.

Table 2. Hardware Results of PID plus CPLD Control scheme
Supply voltage S_v = 24 Volt for clockwise direction

S.N.	**USP(Motor set speed) in RPM**	**MSP (N) Motor actual speed in RPM**	**I_m (motor current) in Amp**	**I_c (Charging current) in Amp**	**Torque** $T = \frac{P*60}{2\pi N}$ (NM) = $(24*I_m*60)/(2\pi N)$
1.	at start	0	0	0	0
2.	50	50	2.1	3.1	9.63
3.	70	62	2.1	3.1	6.88
4.	90	75	2.1	3.1	5.35
5.	100	88	2.1	3.1	4.81
6.	120	112	2.0	3.1	4.09
7.	150	138	2.0	3.1	3.32
8.	170	162	2.0	3.1	2.73
9.	200	188	2.0	3.1	2.44
10.	230	212	1.9	3.1	2.05
11.	250	238	1.9	3.1	1.83
12.	270	262	1.9	3.1	1.66
13.	300	288	1.8	3.1	1.43
14.	350	338	1.8	3.1	1.22
15.	400	388	1.6	3.1	0.95

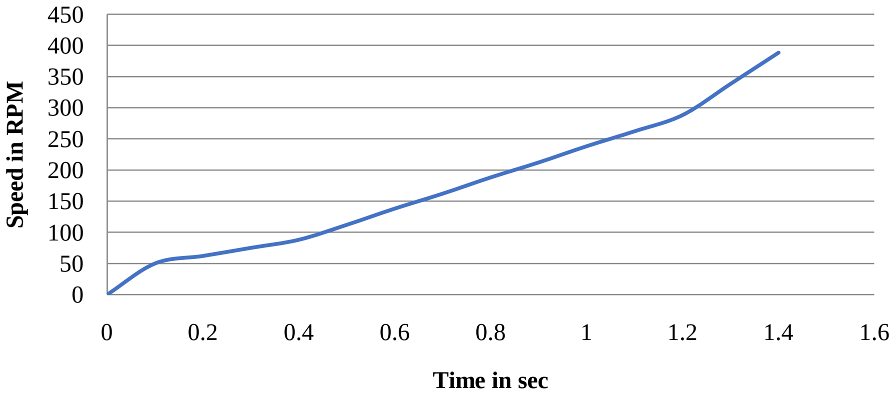

Fig 6. Speed verses time

Looking at the waveform given above, we understand that as the Brushless DC motor rotates, the speed of the motor continues to increase with respect to time. Approximately linear behavior shows the given BLDC motor of speed with time is seen.

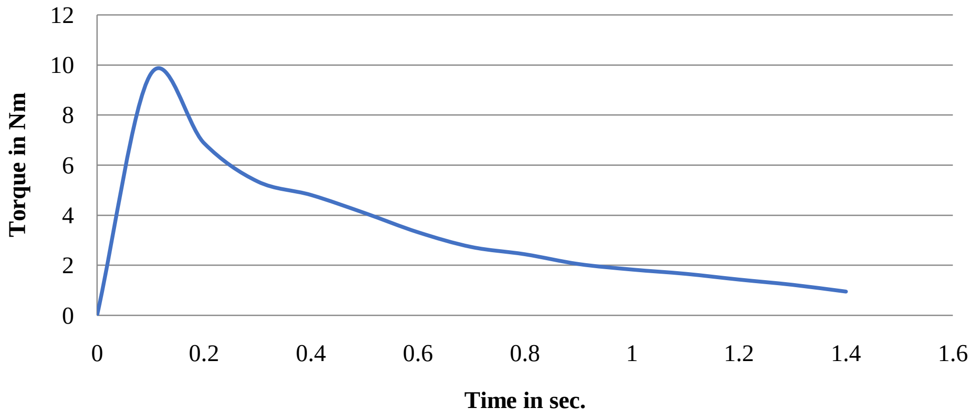

Fig 7. Torque verses time

Looking at the graph given above, we understand that when a Brushless DC motor starts rotating, the torque of the motor becomes very high means maximum, as the speed of the motor increases, the torque of the motor starts decreasing. The given figure shows how the torque changes with time.

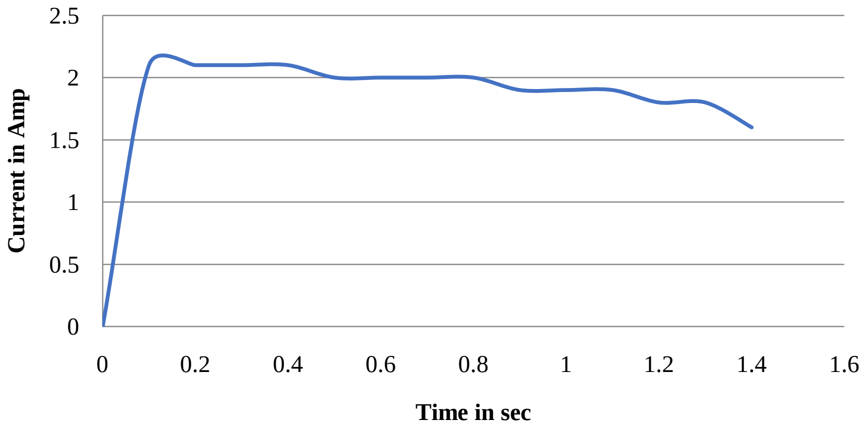

Fig 8. Current verses time

By looking at the graph given above, we can understand that when Brushless DC motor is started, it takes heavy current in motor starting, when the motor reaches the set value then the current of the motor starts decreasing slowly.

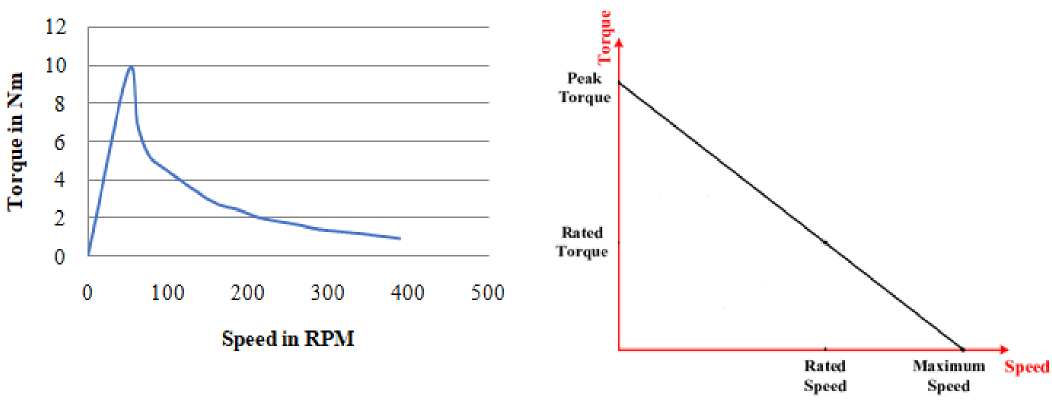

Fig 9. Speed verses Torque

The relation between torque and speed can be understood in the graph given above. The magnitude of torque at the time of starting speed is very high, the magnitude of torque decreases as the speed of the motor reaches its desired value.
The ideal torque versus speed characteristics of the brushless DC motor is as shown. The waveform of the hardware of our Brushless DC motor has also been improved in the same way. The waveform of the tabulated torque versus speed characteristics of the motor has been shown in figure 9.

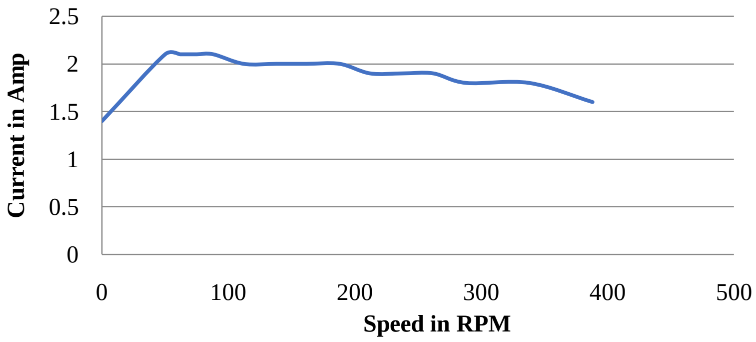

Fig 10. Speed verses current

Similarly, the graph given above shows the relation between speed and current. In starting the motor, the motor takes 1.4 amp current. At that time, the value of speed becomes 0. As the motor speed increases, the value of motor current becomes slightly stable or decreases at the same time.

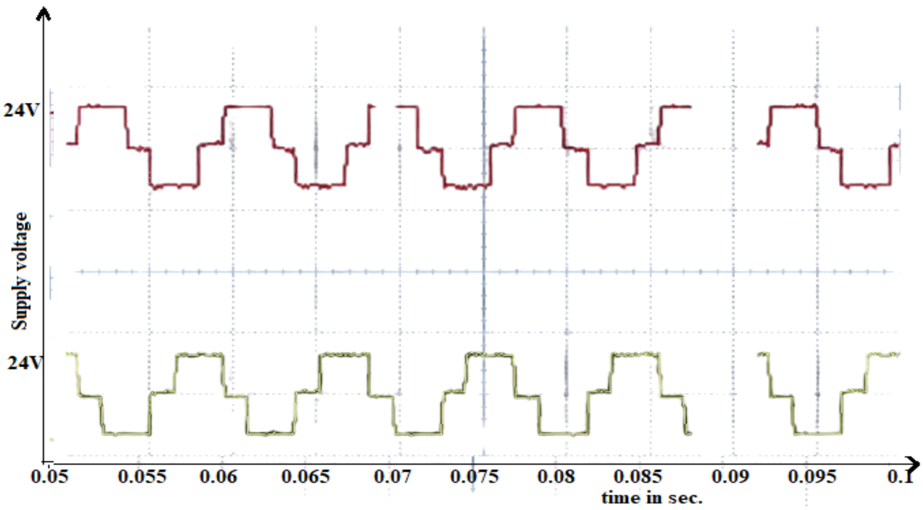

Fig 11. shows the voltage and time waveform of BLDC motor supply voltage at set speed 100 RPM.

A BLDC motor running at 100 RPM is shown in the above picture figure 11 with its voltage and time waveform. The motor is powered by a trapezoidal commutation technique. With this approach, each motor phase's applied voltage varies over time in a trapezoidal fashion.
The switching of the voltage received by the BLDC motor is done through the ESC driver circuit so that the output waveform of the ESC driver circuit will be the input voltage waveform of the brushless dc motor, which is in trapezoidal form. The motor supply voltages phase of each phase is at a phase difference of 120 degrees from the each other. As the voltage waveform appears, the current waveform will also appear according to the magnitude of the motor current.

CONCLUSION
The choice between PID and CPLD controllers for speed control of BLDC motors depends on the specific requirements of the application. For general purpose applications where ease of implementation and cost are of primary importance, PID controllers are suitable but for specific Brushless DC motor accurate speed application, PID plus CPLD method is used for better performance, other than PID controller.

However, for high-speed, high-precision applications requiring deterministic control, CPLD controllers provide better performance despite their higher complexity and cost. The results of comparing the performance of brushless DC motor with PID and PID plus CPLD show that the response of PID plus CPLD controller is much better than that of PID controller. In addition to high power density, minimal maintenance requirements and low noise compared to other motors, this high efficiency allows the production of more torque in a lower speed range. This study compares closed-loop speed control of a BLDC motor drive driven by a PID controller and BLDC motor drive driven by a PID plus CPLD controller.

REFERENCES

[1] Md Mahmud, S. M. A. Motakabber , A. H. M. Zahirul Alam , Anis Nurashikin Nordin, Control BLDC Motor Speed using PID Controller, International Journal of Advanced Computer Science and Applications, vol. 11, no. 3, (2020).

[2] Md Mahmud, S. M. A. Motakabber, A. H. M. Zahirul Alam and Anis Nurashikin Nordin, Adaptive PID Controller Using for Speed Control of the BLDC Motor, in International Conference on Semiconductor Electronics (ICSE), Kuala Lumpur, Malaysia,(2020).

[3] H. WANG, Design and Implementation of Brushless DC Motor Drive and Control System, in International Workshop on Information and Electronics Engineering (IWIEE), (2012).

[4] C. Wang, Z. Li, G. Kang and C. Zeng, BLDC Motor Torque Ripple Control Using Self-Tuning PID Fuzzy Control System,Appl. Mech. Mater. [CrossRef],(2016) pp.459–463.

[5] Djamel Eddine Beladjine, Djamel Boudana, AbdelhafidhMoualdia, A Comparative Study of BLDC Motor Speed Control Using PI and ANN Regulator, in 18th International Multi-Conference on Systems, Signals & Devices (SSD), Monastir, Tunisia, 22-25 March (2021).

[6] Bossche, Alex Van den,Bozalakov, Dimitar Vaskov, Vyncke, Thomas,Valchev, Vencislav Cekov, Programmable Logic Device Based Brushless DC Motor Control, in Proceedings of the 2011 14th European Conference on Power Electronics and Applications, Birmingham, UK, 30 August- 01 September (2011).

[7] XILINX, A CPLD VHDL Introduction, 30 august 2001. [Online]. Available: http://www.xilinx.com/support/documentation/application_notes/xapp105.pdf .

[8] R. Kirshnan, Electric motors drives: modeling, analysis and control, Prentice Hall, 2001.

[9] A. Tashakori, M. Hassanudeen and M. Ektesabi, FPGA Based Controller Drive of BLDC Motor Using Digital PWM Technique, in *IEEE* , Australia , Sydney, 9–12 June (2015).

[10] G. K. Giridharan, "FPGA Based Digital Controllers for BLDC Motors, International Journal of Engineering Research and Applications, (IJERA) ISSN: 2248-9622 Vol. 3, Issue 2, March -April (2013), pp. 1615-1619.

[11] Muhammad FajriSachruddin, Faizal Arya Samman and Rhiza S. Sadjad, BLDC Motor Control using a Complex Programmable Logic Device with Hall-Sensors, in International Conference on Smart-Green Technology in Electrical and Information Systems, (2021).

[12] Mohammed Zoheb, Vijeyta Sharma M, Mrs. Shalini Vashishtha, Mr. Mohammed Shahid, Implementation Of Brushless DC Motor Using FPGA Interface, International Journal of Engineering Research & Technology (IJERT) Vol. 2 Issue 5, May (2013).

[13] E. Joner, tytorobotics, 26 September 2023 [Online]. Available: https://www.tytorobotics.com/blogs/articles/brushless-motor-power-and-efficiency-analysis?srsltid=AfmBOopZcGAmbS9N1WkOXyBjeGyHFjLWuSwKJupAEv6g3fDlcDV2Z8mY.

[14] Kadhim, Adel A. Obed and Abbas K, Speed and Current Limiting Control Strategies for BLDC Motor Drive System: A Comparative Study, International Journal of Advanced Engineering Research and Science (IJAERS), vol. 5, no. 2, Feb (2018) pp. 119-139.

[15] Bambang Darmonoa, Hadi Pranotoa, Zainal Arifinb, Torque Analysis of 2 KW BLDC (Brushless Direct Current) Motor with Speed Variations in Electric Cars E-Falco, International Journal of Advanced Technology in Mechanical, Mechatronics and Materials (IJATEC), vol. 02, no. 02, (2021), pp. 76-86.

[16] J. Joya and S. Ushakumari, Performance Comparison of a Sensorless PMBLDC Motor Drive System with Conventional and Fuzzy Logic Controllers, Global Colloquium in Recent Advancement and Effectual Researches in Engineering, Science and Technology (RAEREST), (2016) pp. 643–651.

[17] R. R. S. R. Meghana, Sensorless Start up control for BLDC motor using initial position detection technique, in International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020), Cochin, India, 02-04 January (2020).

[18] R. Saranya, R. Baskaran, A. Roc and K. Sathiyasekar, Sensorless Operation of Brushless DC Motor Drive using Back EMF Technique, International Journal of Engineering Research, vol. 3, no. 40, 01 April (2014), pp. 255-257.

[19] N. M. Y. J. L,. M. K. a. A. E. Anand Sathyan, An FPGA-Based Novel Digital PWM Control Scheme for BLDC Motor Drives, IEEE Transactions On Industrial Electronics, Vol. 56, No. 8, August (2009).
[20] P. Damodharan and K. Vasudevan, Sensorless Brushless DC Motor Drive Based on the Zero-Crossing Detection of Back Electromotive Force (EMF) From the Line Voltage Difference, IEEE Trans. Energy Convers, *(*2010), pp. 661–668.
[21] A. Emadi, Handbook of Automotive Power Electronics and Motor Drives, Chicago, illinois, USA: taylor and francis, (2005).
[22] J. Gong, L. Liao and B. Ye, Brushless DC Motor Starting Based on High Precision Inductance Method and Study on the Stability of BEMF Synchronous Detection, Trans. China Electrotech, Soc. (2017), pp. 105–112.
[23] N. Gupta and D. Pandey, A Review: Sensorless Control of Brushless DC Motor in Esrsa Publications: Auckland,, New Zealand, (2012).
[24] S. Y. Jung, J. Y. Kim, J. Jae and J. Kim, Commutation Control for Low Commutation Torque Ripple in Position Sensorless Drive of Low-Voltage Brushless DC Motor, IEEE Transactions on Power Electronics, vol. 29, no. 11, Nov. (2014) pp. 5983 - 5994.
[25] P. &. Meenakshy, Modelling Of Brushless DC Motor Drive Using Sensored And Sensorless Control (back EMF zero crossing election, IET Electr. Appl., (2012).
[26] M. A. A. P. R. N. K. S. Y. Ramachandra, Analysis of Recent developments in Brushless DC motors controlling techniques, International Journal of Innovative Technology and Exploring Engineering (IJITEE), March, (2019).
[27] D. E. X. R. S. S. &. R. P.Kannan, Design Of Sensorless Drive Controller For Industrial Oriented Brushless Dc Motor, International Journal of Mechanical and Production Engineering Research and Development, (2020).
[28] Raspberry Pi Pico and Pico W, April (2024). [Online]. Available: https://www.raspberrypi.com/documentation/microcontrollers/raspberry-pi-pico.html.
[29] DroneBot Workshop,[Online]. Available: https://dronebotworkshop.com/transistors-mosfets/.
[30] Dejan, "how to mechatronics, [Online]. Available: https://howtomechatronics.com/how-it-works/how-brushless-motor-and-esc-work/.