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Design of a PID Speed Controller for BLDC Motor with Cascaded Boost Converter for High-Efficiency Industrial Applications

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ABSTRACT

Achieving high voltage and efficiency in brushless direct current (BLDC) motor applications is challenging, particularly in industrial settings where precise speed control is essential. This study addresses this issue by designing a cascaded boost converter with a Proportional–integral–derivative (PID) speed controller. The cascaded boost converter is first simulated in an open-loop circuit using MATLAB/SIMULINK, followed by integrating the BLDC motor and adding a PID controller to achieve precise speed control. The PID controller achieved a steady-state speed of 1500 rad/s with an input voltage of 15 volts, resulting in an output voltage of over 50 volts. The efficiency of the system was improved by 87.87% compared to traditional methods. While the PID controller effectively controls the motor speed, it may consume more power and require more complex tuning in certain operating conditions. The proposed system is suitable for high-voltage industrial applications, such as electric vehicle drives and renewable energy systems, where precise speed control and high efficiency are critical. The PID controller is user-friendly and easy to implement, making it suitable for various industrial applications. The system was tested under varying load conditions and input voltages to ensure robust performance and reliability. Future work will optimize the PID controller for real-time applications and integrate advanced control strategies to enhance system performance. A cascaded boost converter is a type of DC-DC converter that boosts the input voltage to a higher level, while a PID controller is a control loop feedback mechanism widely used for precise control of dynamic systems.

1. Introduction

BLDC motors are characterized by not requiring high maintenance costs. They operate with high reliability and low power compared to their high efficiency, and their operation is stable in terms of vibration and noise, i.e. their operation is silent. In the past periods, much data has been documented indicating the existence of problems in the operation and operation of this type of motor, such as variable speeds, how to handle them, and the use of speed control systems. The development in science and technology has also included this field, and semiconductors have emerged as devices that help improve a specific performance according to a function within different systems. Electronic power converters of various types have emerged to meet the need to modify, change, and regulate electrical quantities as required to cover loads in a manner that suits them. However, these motors have faced problems in operating at variable speeds over the past decades, as continuous technological development in energy semiconductors, microprocessors, and control systems for adjustable speed motors have been combined. The production of brushless electric motors with permanent magnets has been used to enable a reliable and cost-effective solution for a wide range of adjustable speed applications. It has a low cost compared to traditional transformers, in addition to high reliability and efficiency. The systems that include the electric motor and control systems, in addition to electronic power transformers, have entered into many applications, including household applications such as washing machines, vacuum cleaners, and others.

Due to the portability and simplicity of DC converters, especially isolated converters, they are widely used in applications and conventional boost converters are the most common model for this purpose. The input and output voltages are regulated based on the duty cycle, the conversion efficiency is limited at high duty cycle values and depends on the parameters in the circuit.

Cascaded boost converter: The structure of the cascade boost converter consists of two stages. The first stage doubles the input voltage to obtain a high conversion ratio using dual-mode capacitor cells (SCC). The second stage enhances efficiency by providing high-voltage conversion with two inductors and a diode-capacitor (DC) snubber. [1] In Luo, three-series converters, a technique is used to increase the voltage when designing DC converters, where the voltage increase is observed step by step as a mathematical process, this increase works to raise the voltage gain step by step despite the increases of circuit elements, the series boost converter with positive output gives a simplified structure.

These converters work to enhance the voltage transfer gain [2]. The two-phase boost converter uses the current division into two branches using an inductor and switches to boost the voltage level, which reduces the stress on the switching device, and high voltage is achieved efficiently due to the parallel sequence of the boost converters. In [3] it explained the relationship between conduction losses and average voltage (output voltage converter of the first stage). The series system provides lower conduction losses than conventional single-ended DC-DC converters, higher efficiency is provided with a very high voltage boost ratio with one switch. The DC-DC converter relies on series boost converters and Luo converters in the continuity of the inrush current waveform, making it suitable for use in renewable energy sources in addition to reducing the voltage and current pressure on the power switch and diodes compared to quadrature DC-DC converters [4]-[6].

Brushless Motor: Brushless DC motors have proven their superiority in operating at the same loads and speeds as conventional motors, making them the focus of researchers and efforts to develop them. They are widely used in several applications in industry due to their high speed and compact size, making them suitable for applications such as hard disk drives, DVD players, electric devices and hybrid vehicles, modeling of the aerial, and CNC machines. Among their most important advantages are their use in a closed-loop circuit with a Hall effect sensor or back EMF detection. They are inexpensive, easy to use, and have less output control than brushless DC motors. Changing the input voltage is the only way to adjust the rotational speed and output torque, the disadvantages include low efficiency and brushes that wear out due to friction and sparks. There are some benefits if not using these motors such as cost, simpler handling than other techniques, and very limited maintenance.

Brushless DC motors operate in fast sequential steps, designed to operate at high speeds [7]-[10]. A control system was created periodically by comparing the external voltage as a reference signal suitable for the motor windings to obtain power. In [11], [12] a control circuit is connected so that it gives a constant low voltage resulting from the process of entering two signals, the reference voltage for the parts of the motor control circuit and the voltage resulting from the circuit (the inductor) to obtain a stable and required signal and from any changes or increases that may occur in the high voltage, as this signal provides the energy input to operate the control circuit correctly. It was assumed that the BLDC motor connected with the controller would not take a suitable reference to the input, different sensors for the rotation of the motor position were used to work the signals induced in the windings when the motor was operated starting. In [13] the proposed controller uses the output voltage and input current of the system with numerical simulation results to illustrate the performance of the closed-loop system using a combination of fuzzy and PID methods, [14] presents different control structures with system line programming to compile, modify and simulate intelligence to control BLDCMs where the graphical user interface (GUI) of multi-controllers, traditional proportional integral derivative (PID) controllers, and fuzzy techniques based on intelligent controller, BLDCM are used. [15] presents different control structures with system line programming to compile, modify, and simulate intelligence, where the graphical user interface of many controllers, traditional PID controllers, and fuzzy techniques based on intelligent controller BLDCM are used. Another controller is used widely for applications in control systems and leads the motor to operate at a speed very near to the speed of the reference, also enhances performance and robustness, they work better than the system using a traditional PID controller [16]-[19].

The PID controller: PID controller: It is a reliable and convenient technology for linear system control and is good for pulse width adjustment of boost converter switch where the voltage is available to the DC motor the PID controller is implemented and the DC motor has low input voltage is compared with the DC motor operating at high constant DC voltage [20]-[22]. In [23], [24], The iterative least squares algorithm is implemented with a set of determinants to perform the tuning process and is called self-tuning. This is a complex process to reset the gains of the PID controller, and it can get an adaptive control module (APID) to implement the simulation of the circuit in the motor to be fed by a chopper.

The controller PID is used in many applications for automatic control, especially in industry. When using PID technology, the problem of non-linear systems appears after adding loads and changing dynamics after long-term operation, which affects the speed, and external noise, which requires changing the parameters dynamically, which makes the controller non-ideal, especially in BLDC motors. In [25]-[27] presents a new method by determining a particle swarm to optimize the optimal PID controller parameters in the speed of DC motors.

In [28], [29] present a digital design of PID and a fuzzy controller to achieve the required transient and steady-state response to improve the performance of servo motors (BLDC) that are used in aerospace, instrumentation systems, spacecraft, electric vehicles, robotics, and industrial control applications, where traditional controllers such as P, PI, and PID are used. [19], [30] A dual-loop control system, including an inner current loop and an outer speed loop, was used to ensure flexible control, and the motor performed well at both high and low speeds.

In [31]-[33], It proposed many methods for the controllers based on fuzzy logic for BLDC motor, artificial neural network (ANN), and PSO for the motor to obtain better performance for motor speed control, also techniques of Pulse width modulation were used to control the speed of the BLDC motor via a microcontroller.

In [34]-[37], An expanded Kalman filter was used for the sensor that slows the speed control of a BLDC motor, and a speed control method based on model predictive control (MPC) and a proportional-integral (PI) controller based on a modified DE algorithm was proposed. using DSP and Hall effect sensors to control the speed of the brushless DC motor, these methods are based on lessening the overshoot, rise-time, and steady-state error, also the stability indicator improved for the motor system [38]-[40]. The ANFIS was used depending on the low-resolution hall effect sensors for speed control systems [41]-[44].

Despite the widespread use of cascaded boost converters and BLDC motors, achieving high efficiency and precise speed control remains challenging, particularly in high-voltage applications. This study addresses this issue by designing a cascaded boost converter with a PID speed controller. Conventional boost converters suffer from limited conversion efficiency at high-duty cycles, and BLDC motors often face issues with non-linear dynamics and external noise, which affect their performance and stability. This study aims to design and optimize a cascaded boost converter with a PID speed controller for a BLDC motor to achieve high efficiency and precise speed control.

This study provides a cascaded boost converter with proportional-integral-derivational (PID) controllers using MATLAB. In Section 2, how to design the cascaded boost converter circuit for a non-linear was carried out using the open loop to choose the parameters in the circuit. Section 3 shows the open and closed loop Controller simulation with BLDC Motor. In Section 4, the results of simulations were made in the closed-circuit case for the proportional control unit. In Section 5, the conclusion is presented for the MATLAB program.

2. Method

2.1. Design of Cascaded Boost Converter

The designing of the parameters of the cascaded boost converter is considered in terms of per unit ripple in the inductor current ($\Delta I_L/I_L$) and per unit ripple in the capacitor voltage ($\Delta V_C/V_C$) During the ON time of the switching, the voltage drops across the inductor L_1.

$$V_{L1} = L_1 \frac{di_{L1}}{dt} \tag{1}$$

Where, T_S is the switching period and equal ($\frac{1}{f_s}$), from the equation below, it can be calculated L_1

$$L_1 = \frac{D(1-D)^4 T_S R_L i_{L1}}{\Delta i_{L1}} \tag{2}$$

The inductor L_2 value can be calculated from:

$$L_2 = \frac{D(1-D)^2 R_L T_s\, i_{L2}}{\Delta i_{L2}} \tag{3}$$

The current of the capacitor i_{C1} when the switch is on :

$$i_{C1} = C_1 \frac{dv_{C1}}{\mathrm{dt}} = i_{L2} \tag{4}$$

$$C_1 = \frac{\Delta V_{C1}}{DT_S} = \frac{v_{in}}{(1-D)^3 R_L} \tag{5}$$

$$C_1 = \frac{V_{C1} DT_S}{(1-D)^2 \Delta V_{C1} R_L} \tag{6}$$

$$C_2 = \frac{V_{C2} DT_S}{\Delta V_{C2} R_L} \tag{7}$$

The gain, G can calculate from these equations:

$$V_{\mathrm{C}1} = \frac{V_{in}}{(1-D)} \tag{8}$$

$$V_{out} = \frac{V_{in}}{(1-D)^2} \tag{9}$$

$$G = \frac{V_{out}}{V_{in}} = \frac{1}{(1-D)^2} \tag{10}$$

D is the duty ratio.

Fig. 1 shows the typical converter (CBC), input voltage V_{in} =15 V, the output voltage V_{out}= 50 V, the switching frequency f_s = 10 kHz, and the duty ratio D =0.45, the other parameters of the converter are shown in Table 1.

Table 1. Basic values of converter

Parameters	Symbol	Value
Input voltage	V_{in}	15v
Output voltage	V_{out}	50V
Frequency	f_s	10khz
Duty ratio	D	0.45
Inductor Input	L_1	160µH
Inductor	L_2	100µH
capacitor	C_1	47 µF
Capacitor output	C_2	276µF
Load resistance	R_L	22Ω
Voltage gain	G	3.3

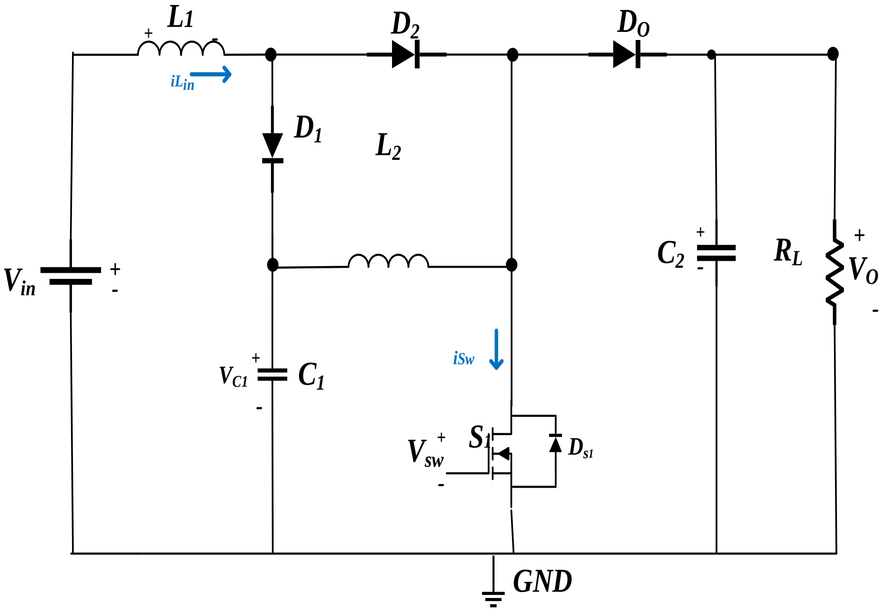


Fig. 1. The typical circuit of the cascaded boost converter

2.2. BLDC Motor Model

The BLDC motor model was built. [7], [45] It is similar to the conventional motor except that there are phases in the brushless DC motor in which the speed is regulated by modifying the three-phase pulse width by the inverter. The equations (11)-(15), [12], [46], show how to calculate the function of the motor with the control system:

$$\frac{\omega(s)}{V_{app}(s)} = \frac{K_t}{L.j.S^2 + (LD + Rj).S + K_t K_b} \tag{11}$$

$$V_{app}(t) = L\frac{di(t)}{dt} + R.i(t) + V_{emf}(t) \tag{12}$$

$$V_{emf}(t) = K_b.\omega(t) \tag{13}$$

$$T(t) = K_t.i(t) \tag{14}$$

$$T(t) = J\frac{d\omega(t)}{dt} + D.\omega(t) \tag{15}$$

Where $V_{app}(t)$ is the applied voltage, ω(t)t is the motor speed, L is the inductance of the stator, i(t) is the current of the circuit, R is the resistance of the stator, V_{emf}(t)is the back electromotive force, T is the torque of the motor, D is the viscous coefficient, J is the moment of inertia, Kt is the motor torque constant, andK_b is the back electromotive force constant. The PID control algorithm shown in Fig. 2.

The BLDC Motor model depends on the value of motor parameters. Fig. 3 show the ability to measure the current speed, compare it with the setpoint, and change the output signal frequency accordingly. As a result, the speed of the motor will stabilize at the desired level [47]-[50].

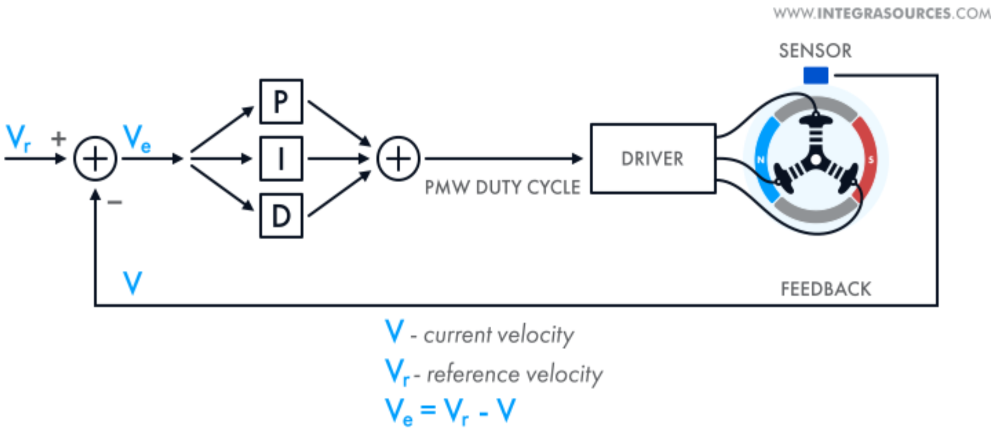
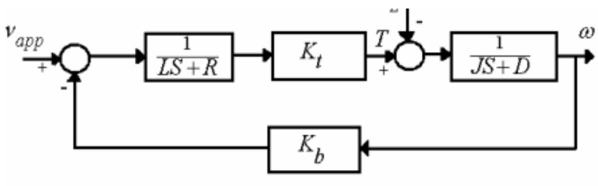


Fig. 2. The PID control algorithm [50]

2.3. PID Controller Design

Based on the Ziegler-Nichols method, a PID controller is designed, which depends on the rule of test-trying and error, to adjust the units (KP, KI and KD.) where a BLDC motor is used in the open circuit state. Then the circuit parameters are determined to calculate the values of the third gains of the PID controller, through which the required response is obtained [11], [51]. This method was used to give the desired speed and torque of the motor for its high reliability. Fig. 3. (a), (b) shows the block diagram of the BDCM system with the PID controller [13], [52], [53], the control function is expressed as follows:



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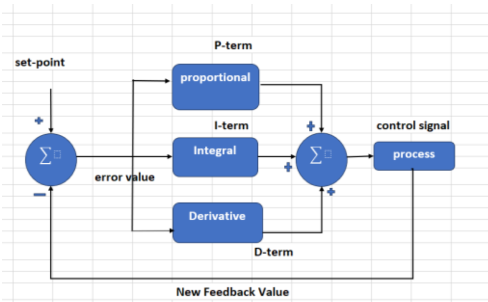


(b)

Fig. 3. (a), (b) The diagram of the PID controller system [13], [48]

Using the PID unit technology, in brushless DC motors, a special technique called error control can be used to control the motor's operation in terms of speed, torque, and current or reduce the error through the following equations:

$$e(t) = \omega d(t) - \omega a(t) \tag{16}$$

$$P_{\text{error}} = K_P e(t) \tag{17}$$

$$I_{\text{error}} = K_I \int_0^t e(t)\, dt \tag{18}$$

$$D_{\text{error}} = K_D \frac{de(t)}{dt} \tag{19}$$

$$u(t) = K_P . e(t) + K_I . \int_0^t e(t)\, dt + K_D . \frac{de(t)}{dt} \tag{20}$$

$$u(t) = K_P + \frac{K_I}{S} + K_D \mathrm{S} \tag{21}$$

Where, $K_{P,} K_I, K_{D,}$ referred to as the proportional, integral, and derivative constant gain respectively. $u(t)$ Is the output of the PID controller,$e(t)$ and is an error signal between the input reference and the process output.

There are many methods for tuning conventional PID. The major difference between the traditional DC motor and the BLDC motor is the increasing complexity of parts, which impacts the BLDC motor's general results.

3. Simulation Models

3.1. Open Loop Simulation

The behavior of the system can be identified by adopting the open loop model and knowing the overall performance of the system. The open loop system is important because it provides the initial performance of the system. It is a basic foundation for knowing and analyzing the behavior of the system and is important in the system design process as it represents an initial measure of the system and its capabilities. The responses of any system can be determined to help in the process of building a stable system by striving to reach the ideal state of operation of the system in addition to the process of exploring the permissible limits for high performance. The open loop concept represents the state of the system when the feedback loop is open. This state is important in control systems to avoid instability and to determine the stability and accuracy of the system with the possibility of designing according to the operating conditions and system variables Which helps to identify the appropriate applications according to the system's response to the model being designed.

3.1.1. Simulation of the Cascaded Boost Converter Circuit with Pulse Width Modulation (PWM) (Open Loop)

Fig. 4 and Fig. 5 represent the cascaded boost converter circuit with pulse width modulation in the case of an open loop. Table 2 shows the simulation results of the output and input voltage and current.

3.1.2. Simulation of the Cascaded Boost Converter Circuit with Pulse Width Modulation PWM, and BLDC Motor, without Controller (Open Loop)

It is difficult to operate the motor effectively or smoothly without a controller, and due to the complex motor's characteristics, regulating the current and the rotor position, it is necessary to tune the speed and torque of a BLDC motor. It can obtain the speed by modifying the PWM signal's duty cycle, but it does not want speed.

Fig. 6, and Fig. 7 show the speed of the motor, and its change when it works without using the controller circuit (open loop), and Table 3, the result of the circuit.

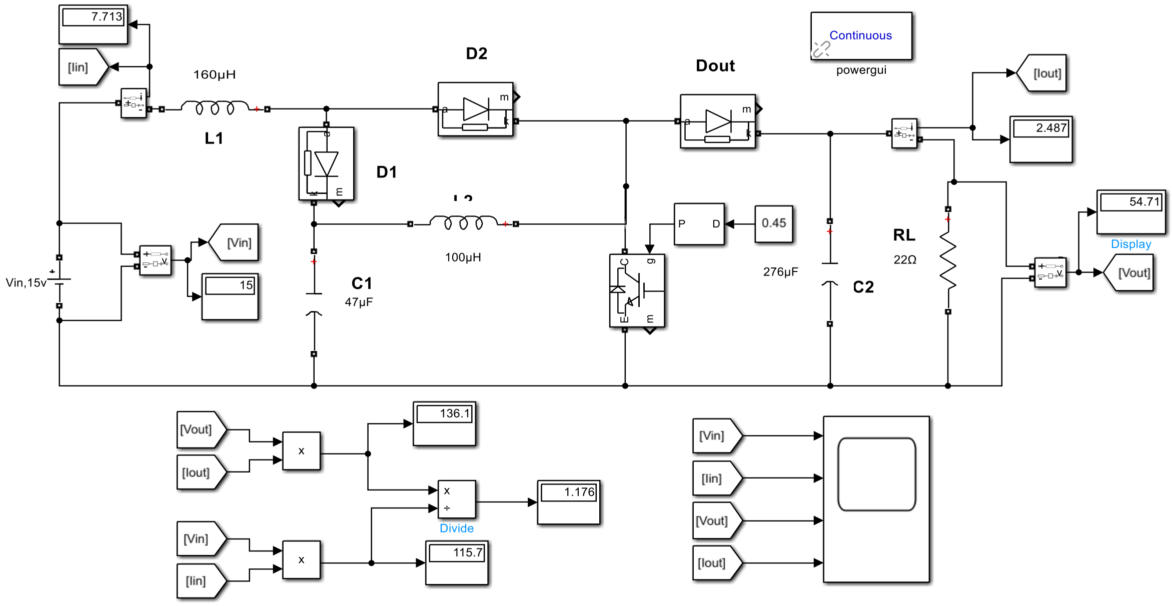
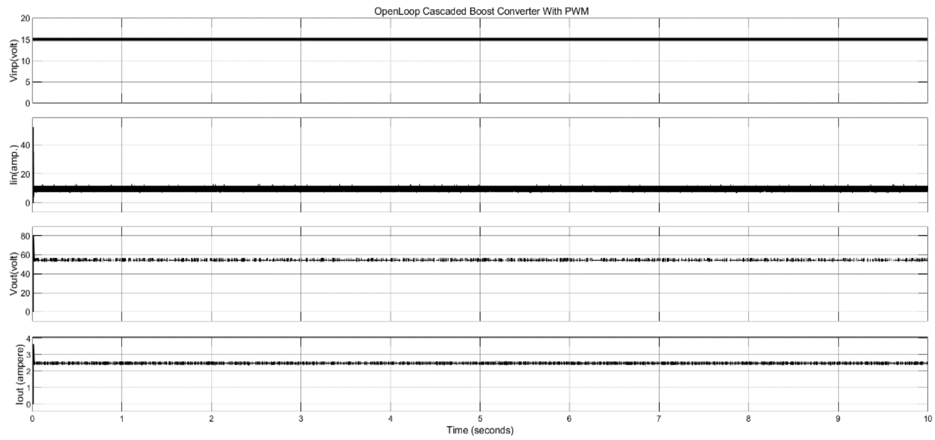


Fig. 4. Cascaded boost converter in MATLAB Simulink open loop using (PWM), Vin=15v, Vout=54.71v, Iin=7.713amp., Iout=2.487amp., Pin=115.7w, Pout=136.1w, efficiency =1.176%



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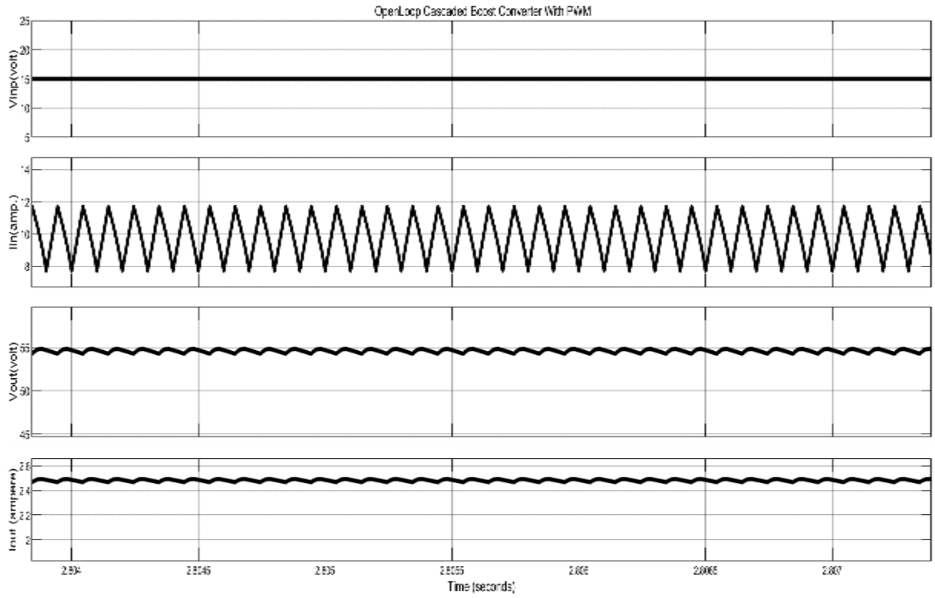

(b)

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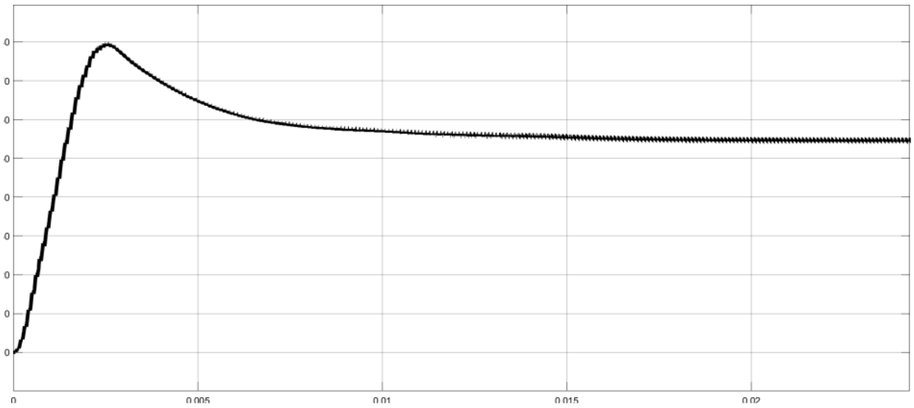

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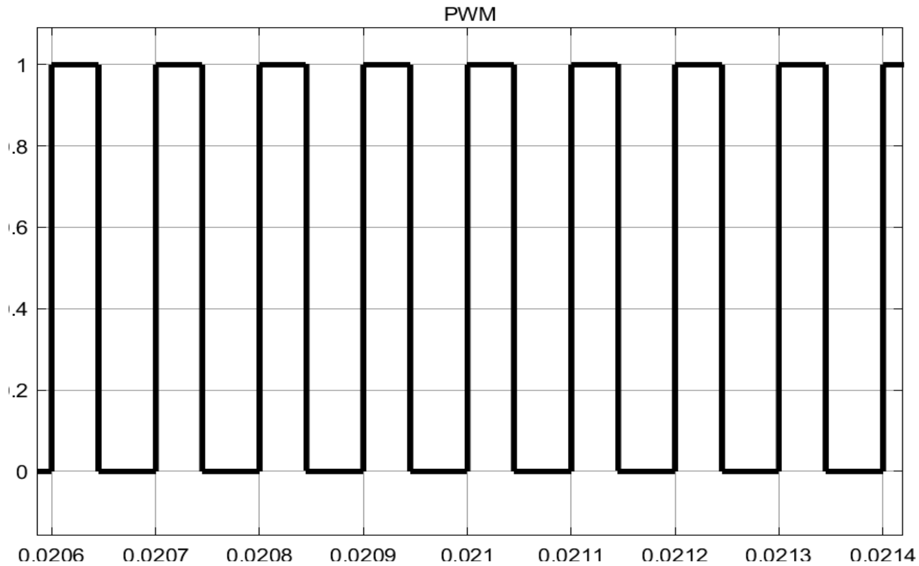


(d)

Fig. 5. The waves of input and output voltage, current (a) Value at the time from (0-10) sec and (b)Value at the time from (2.804-2.807) sec, (c) the waves of the output voltage, the Value at the time from (0-0.02) sec, (d) pulse width modulation (PWM) (open loop)

Table 2. The result of the Simulation, V_{in}, V_{out}, I_{inp}, I_{out}

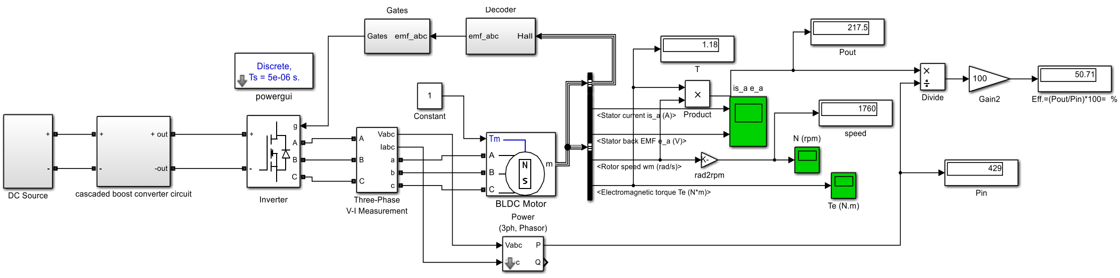
Details Transitions	Input Voltage	Output Voltage	Input Current	Output Current
Rise time(ms)	--	1.005	581.638u	1.005
Slew time(/ms)	---	43.100	50.988	1.959
Fall time(us)	---	--	540.124	---
Slew Rate(/ms)	---	--	-53.938	---
high	1.500e+01	5.454e+01	4.552e+01	2.480e+00
Low	1.500e+01	3.9818e-01	9.104e+00	1.810e_02
Amplitude	-----	5.414e+01	3.642e+01	2.462e+00
Overshoot%	-------	46.324	17.857	46.324
Undershoot%	-------	1.637	11.426	1.637
Preshoot%	------	0.735	25.000	0.735
Settling time	------	14.391	----	14.391

3.2. Closed Loop Simulation

3.2.1. Simulation of the Cascaded Boost Converter Circuit with Pulse Width Modulation PWM and BLDC Motor Using Controller PID

The feedback system works as a control system that monitors the outputs compares them with the required results and adjusts the inputs. Therefore, feedback is called a closed loop. It adjusts and adapts to changes in the conditions and corrects its performance over time, thus gaining accuracy and reliability in work. It includes a sensor, Controller, and Actuator. The purpose of feedback is to make the output signal follow the input signal where the error signal is processed after comparing it with the input signal by the control unit to operate the motor where the motor output passes through the feedback to form a feedback signal, which is returned to the comparator to complete the closed loop.

Fig. 8, Fig. 9, and Table 4. show the controller PI method by adjusting the circuit of the simulation models and wave diagrams of the results, which show the values through which appropriate and satisfactory results were obtained for operating the circuit. Fig. 10 shows the values with the controller PID method.



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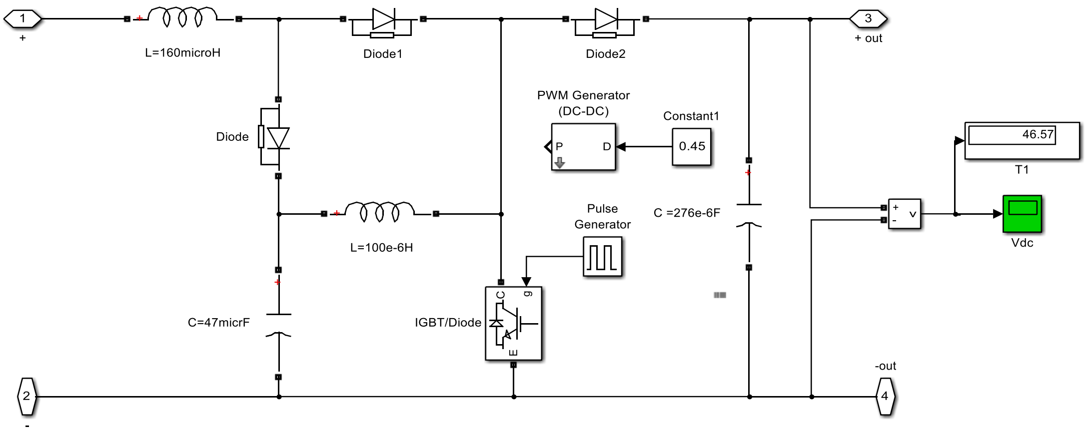
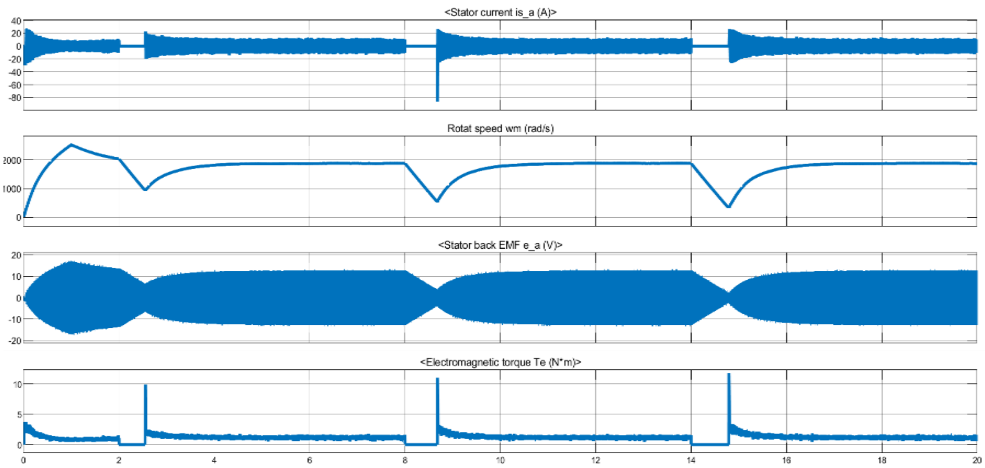


(b)

Fig. 6. (a) The simulation of CBC circuit with PWM and BLS motor open loop, Vin=15v, Vout=46.57v, Rotate speed=1760 rad/s, torque =1.18 N.m, Pin=429-watt, Pout=217.5watt, Eff.=50.71, (b) cascaded boost converter circuit



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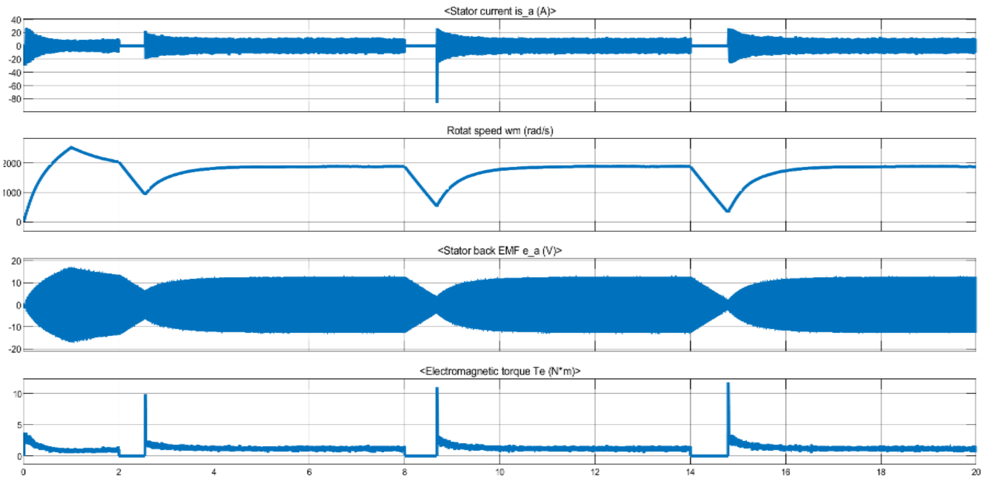

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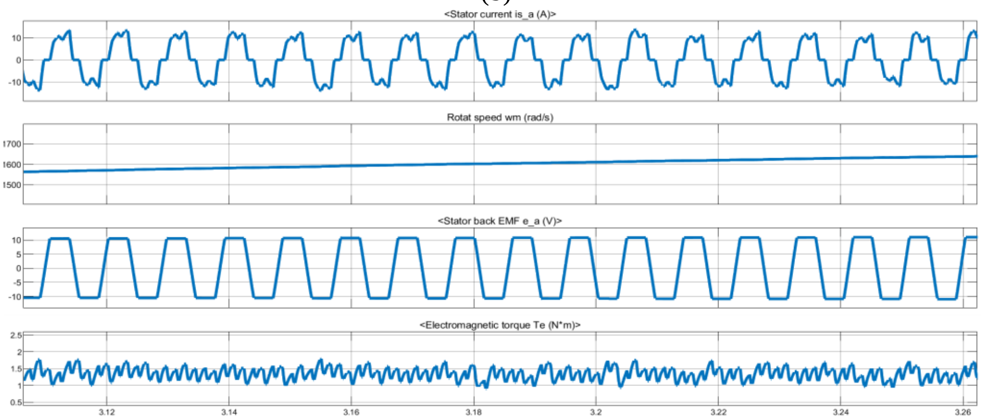


(c)

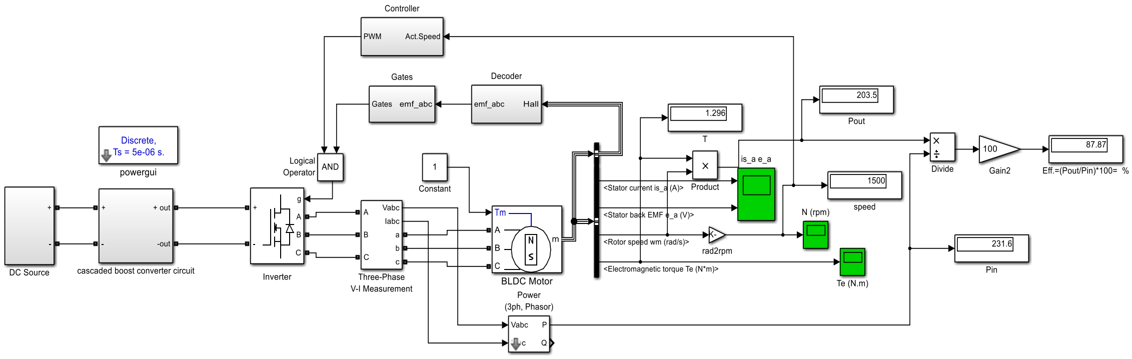
Fig. 7. Response of stator back EMF and stator current, as well as the speed and torque, (a) Value at the time from (0-20) sec, and (b)Value at the time from (2-8) sec, and(c) Value at the time from (3.12-3.26) sec

Table 3. The simulation results are stator current, EMF, speed, and torque

Details	Stator Current is -a (amp)	rotate speed v m(rad/s)	stator back EMF e-a(v)	Electromagnetic torque Te(N*m)
Rise time(ms)	2.966	961.132	1.021	553.042us
Slew time(/s)	23.115	912.995	20.262	14.297
Fall time(ms)	655.322us	249.402	1.021	185.384
Slew rate(/ms)	-104.618	-2.025	-20.261	-1.277
high	5.311e-01	1.881e+03	1.269e+01	9.771e+00
Low	-8.517e+01	1.250e+03	-1.268e+01	5.396e-02
Amplitude	8.570e+01	6.312e+02	2.537e+01	9.717e+00

Table 4. The results are stator current and EMF, speed, and torque

Details	Stator Current is -a(amp)	rotate speed v m(rad/s)	stator back EMF e-a(v)	Electromagnetic torque Te(N*m)
Rise time(ms)	509.919u	284.578	1.271	4.911
Slew time(/s)	22.112	4.180	12.740	545.912
Fall time(ms)	552.705	---	1.271	335.372
Slew rate(/ms)	-18.142	---	-12.740	-7.994
high	7.179e-02	1.495e+03	1.008e+01	3.363e+00
Low	-9.829e+00	8.644e+03	-1.008e+01	1.41e+00
Amplitude	9.901e+00	1.487e+03	2.016e+01	3.351e+00



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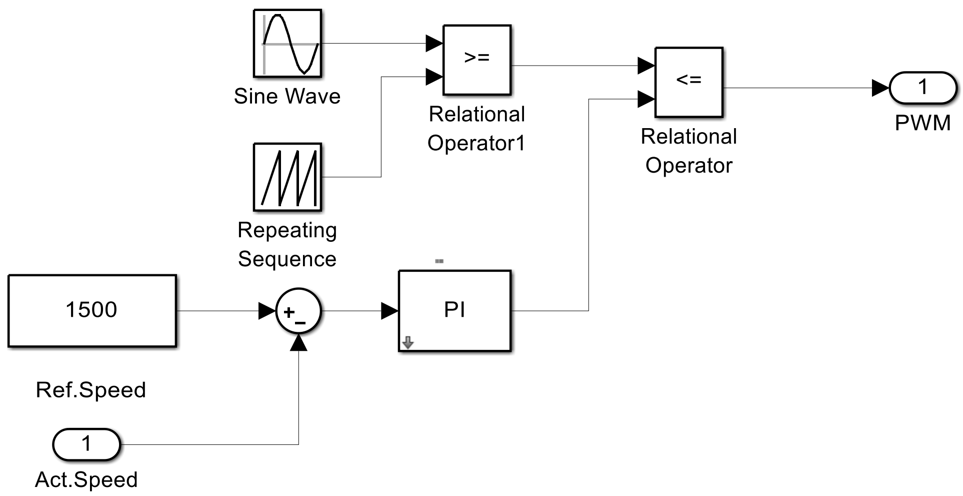

(b)

Controller Parameters

	Tuned	Block
P	0	0
I	-1	-1
D	0	0
N	100	100

Performance and Robustness

	Tuned	Block
Rise time	0 seconds	0 seconds
Settling time	0 seconds	0 seconds
Overshoot	Inf %	Inf %
Peak	0	0
Gain margin	Inf dB @ NaN rad/s	Inf dB @ NaN rad/s
Phase margin	Inf deg @ NaN rad/s	Inf deg @ NaN rad/s
Closed-loop stability	Unstable	Stable

(c)

Fig. 8. (a) Simulation of the speed controller BLDCMotor closed loop, Pin=231.6 watt, Pout=203.5watt, torque =1.296 N.m, rotate speed=1500 rad/s, Eff=87.87((b)subsystem with controller PI (c)Controller parameters; P=0, I= -1,N=100

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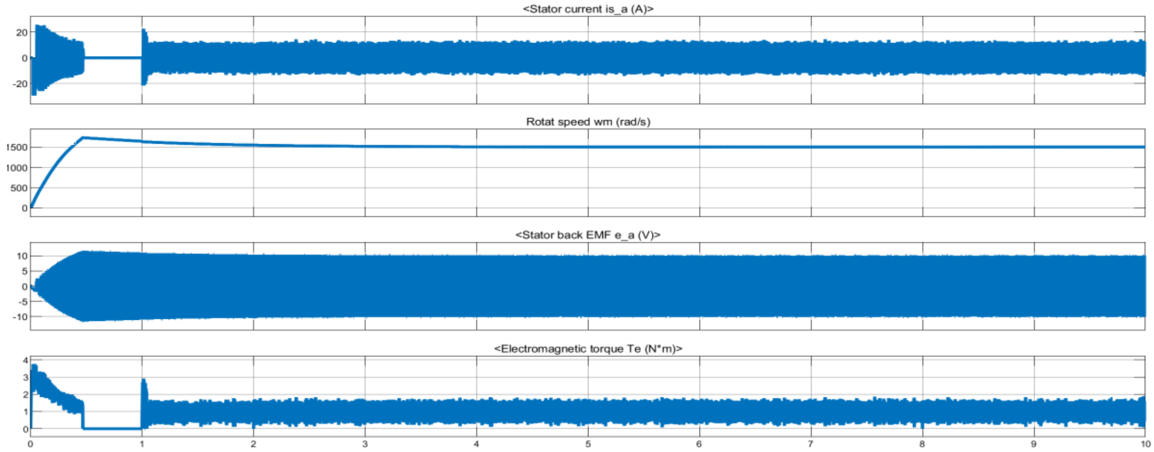
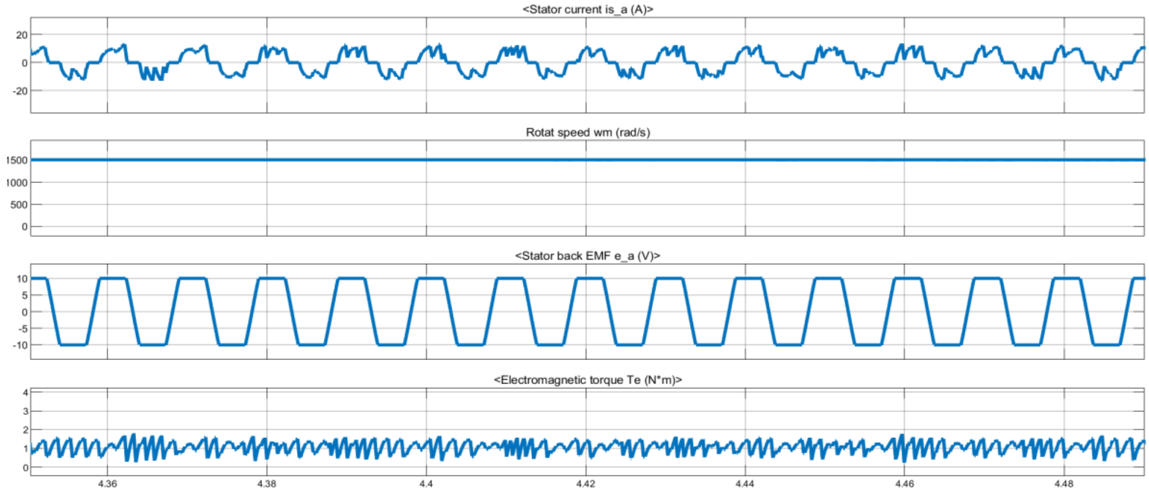


(a)



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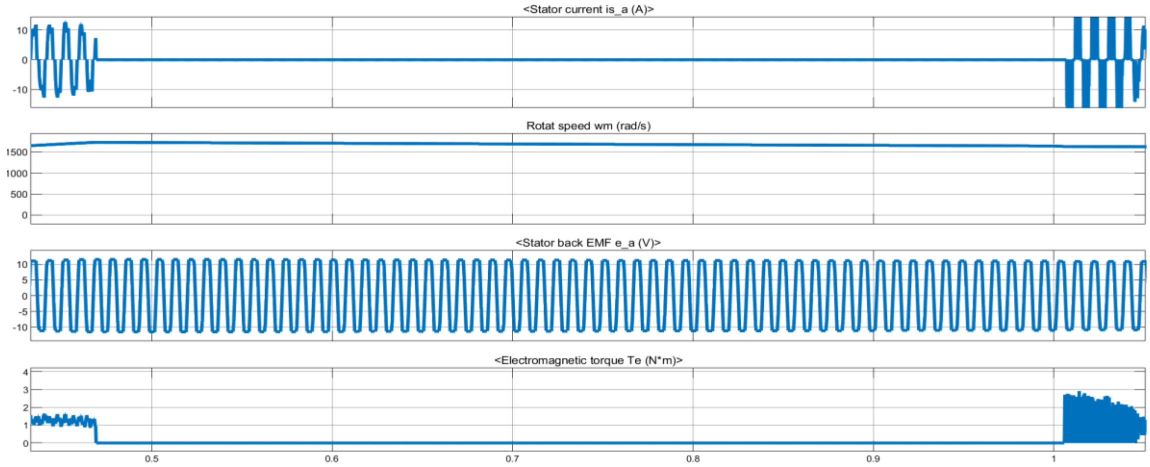
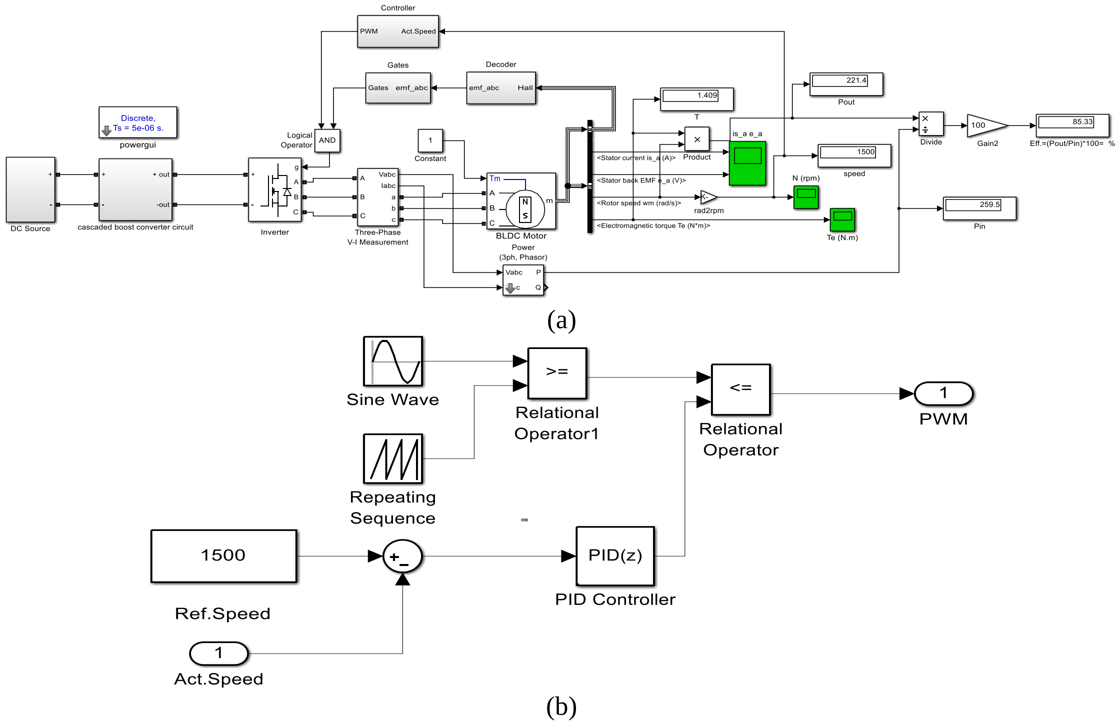


(c)

Fig. 9. Response of stator back EMF of stator current, as well as the speed and torque, (a) Value at the time from (0-10) sec, and (b)Value at the time from (4.36-4.48) sec, (c) Value at the time from (0.5-1) sec

3.2.2. The Cascaded Boost Converter with BLDC Motor Using Controller PID

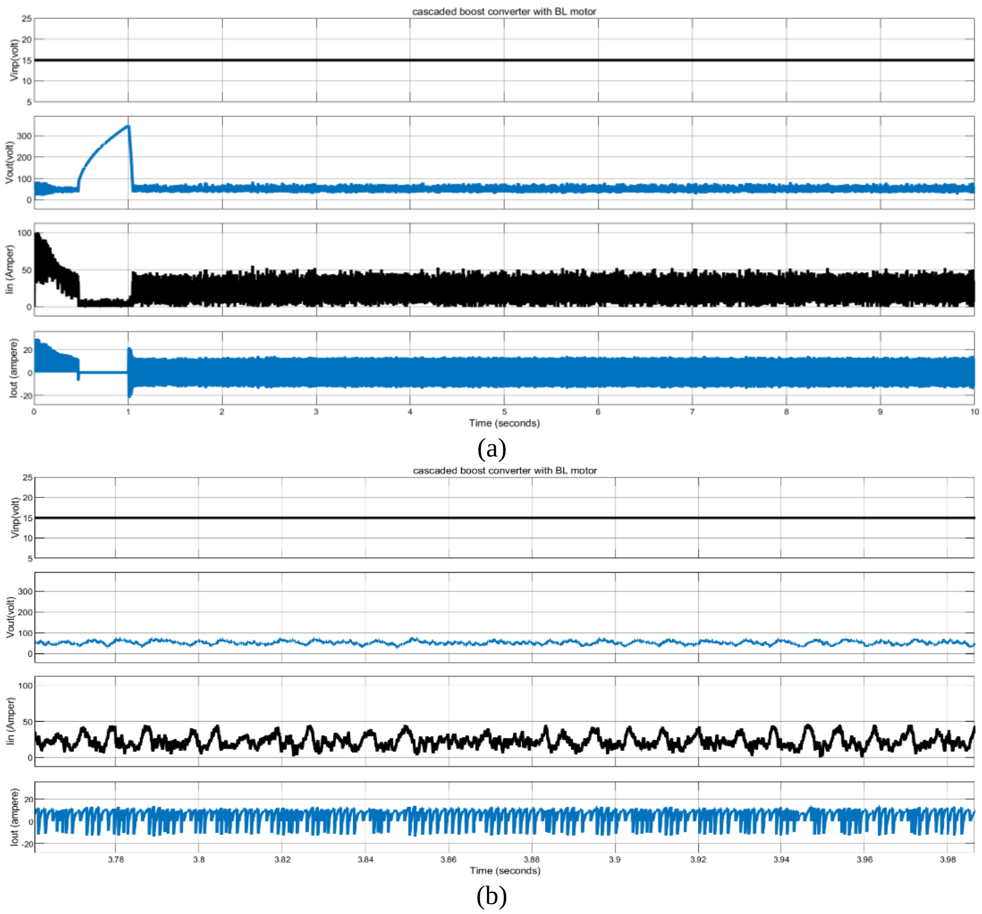
Fig. 11 (a), (b) shows the input and output voltage, current when simulations, and the results when the cascaded boost converter is connected to the BLDC motor. The result of the simulation of the cascaded converter in the closed loop with controller shown in Table 5.



(a)

(b)

Fig. 10. (a) Simulation of the speed controller BLDCMotor closed loop, Pin=259.5 watt, Pout=221.4 watt, torque =1.409 N.m, rotate speed=1500 rad/s, Eff=85.33,(b)subsystem with controller PID



(a)

(b)

Fig. 11. The waves of input and output voltage, current (a) Value at the time from (0-10) sec and (b)Value at the time from (3.78-3.98) sec

Table 5. The result of the simulation of the cascaded converter in the closed loop with controller, V_{in}, V_{out}, I_{inp}, I_{out}

Details Transitions	input Voltage	Output voltage	Input current	Output current
Rise time(ms)	--	421.106	1.293	682.621us
Slew Rate(/ms)	---	549.018	22.144	15.075
Fall time(us)	---	32.775	1.218	5.037
Slew Rate(/ms)	---	-7.054	-34.915	-17.156(/ps)
high	1.500e+01	3.430e+02	4.962e+01	1.009e+01
Low	1.500e+01	5.397e+01	1.948e+01	-1.605e-01
Amplitude	-----	2.890e+02	3.014e+01	1.025e+01
Overshoot%	-------	6.682	26.945	-107.561
Undershoot%	-------	6.698	43.886	108.829
Preshoot%	------	1.807	3.731	14.766
Settling time(ms)	------	19.304	20m	767.244us

3.3. Universal Bridge

The universal bridge is an instrument based on the bridge circuit balance, which is divided into three parts: DC bridge, AC, and AC / DC bridge, it can be used to measure parameters (resistance value, capacitance, inductance, quality factor, loss factor, impedance), it is suitable for measuring in DC or low-frequency range, the measuring accuracy is relatively high, they are used to simulate converters in motor drives, where the DC voltage is converted to a controlled AC signal to drive the motor, control schemes to improve performance [54]-[59].

The universal bridge consists of six power switches connected in a network to make them work to form the required bridge. It implements a three-phase power converter. Thus, the power switch can be selected to make the converter.

The converters are simulated electronic devices with switched or linearly switched power from diodes or thyristors, (GTO, IGBT, and MOSFET) with forced switching. It represents the basic structure for forming two-level voltage transformers (VSC).

Cascaded converters refer to a configuration where power conversion multiple stages transfer. The two main stages of the BLDC motor drive system are AC-DC Conversion (Converts the input AC power to a DC voltage), and DC-AC Inversion (Inverter Stage) Which converts the DC voltage into a three-phase AC signal that drives the motor.

For a naturally commutated three-phase converter (diode and thyristor), numbering follows the natural order of commutation, as shown in Fig. 12.

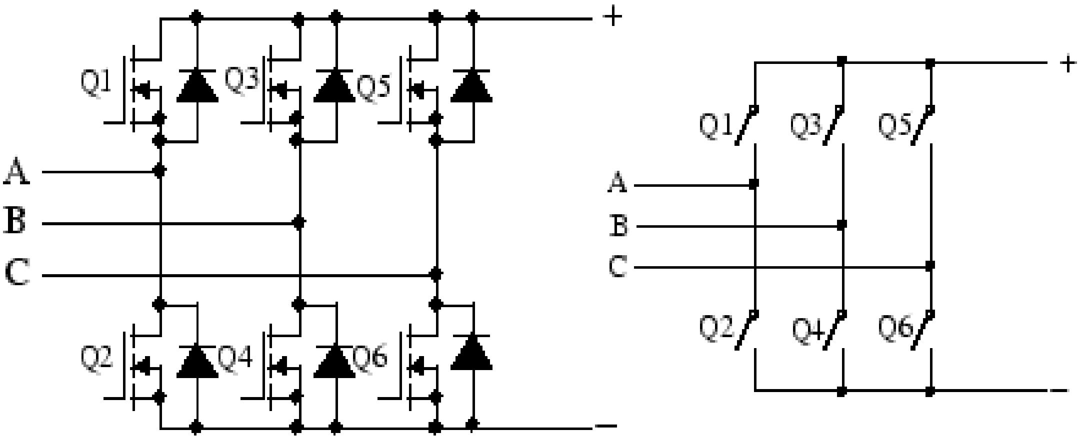
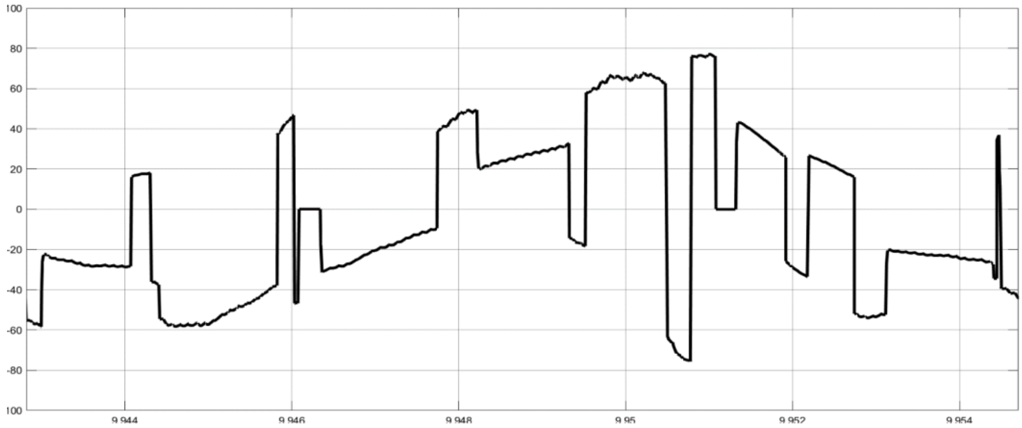
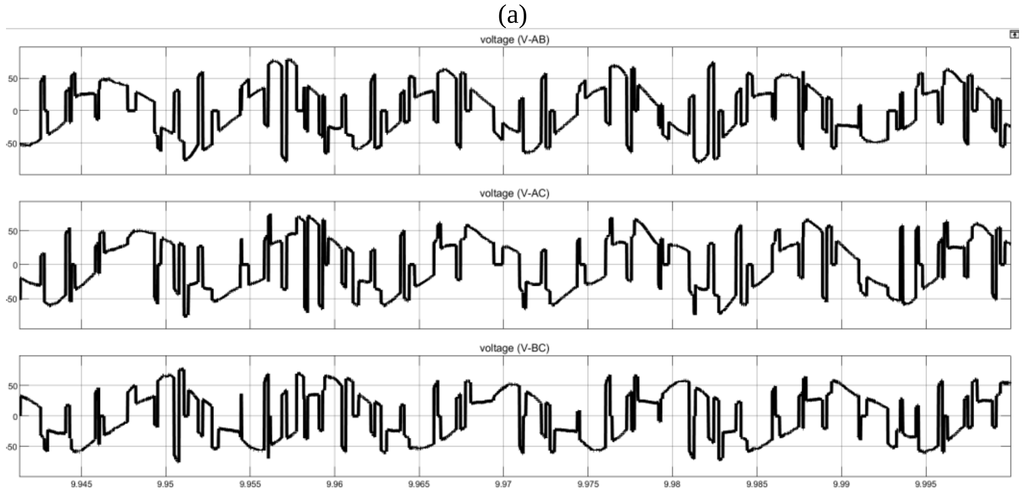


Fig. 12. MOSFET-Diode and ideal switch bridges

Fig 13, and Table 6 show the implementation of a universal power converter with selectable topologies and power electronic devices, electronics devices series RC snubber circuits are connected in parallel with each switch device.



(a)



(b)

Fig. 13. The waves of the voltage of Universal Bridge, V-AB =-24.15v, V-AC=30.22v, V-BC=54.37v, (a) V-AB Value at the time from (9.944-9.954) sec and (b)Value at the time from (9.945-9.995) sec

Table 6. The features of the universal bridge

Details	value
number of bridge arms	3
snubber resistance Rs	500Ω
snubber capacitance Cs	1e-6F
power electronic device	MOSFET/Diodes
Ron:	1e-6 Ω

3.4. Subsystem Models

Brushless DC (BLDC) motors have several subsystems, each providing specific advantages that enhance the motor's performance, efficiency, and reliability. BLDC motors often use Hall effect sensors or operate in a sensor less for position detection of the rotor and provide feedback to the controller for accurate commutation timing. Hall Sensors, provide precise position and speed feedback, improving the control accuracy to enable smooth operation at low speed. Sensor less Control reduces the cost of the motor and complexity, increases reliability, and is suitable for high-speed operations where the back electromotive force (back-EMF) is strong enough to provide position information.

The controller Subsystem manages the commutation, speed control, and other operational parameters, and provides programmable and customizable control for different applications, allowing for dynamic adjustment of speed, torque, and other factors. Incorporates safety features such as overcurrent protection, overvoltage protection, and thermal shutdown, enhancing the motor's reliability and longevity.

3.4.1. Subsystem with PID

Fig.14, and Fig. 15, show the implantation of the subsystems with PID to control the circuit, it contains the input signal and the output duty cycle.

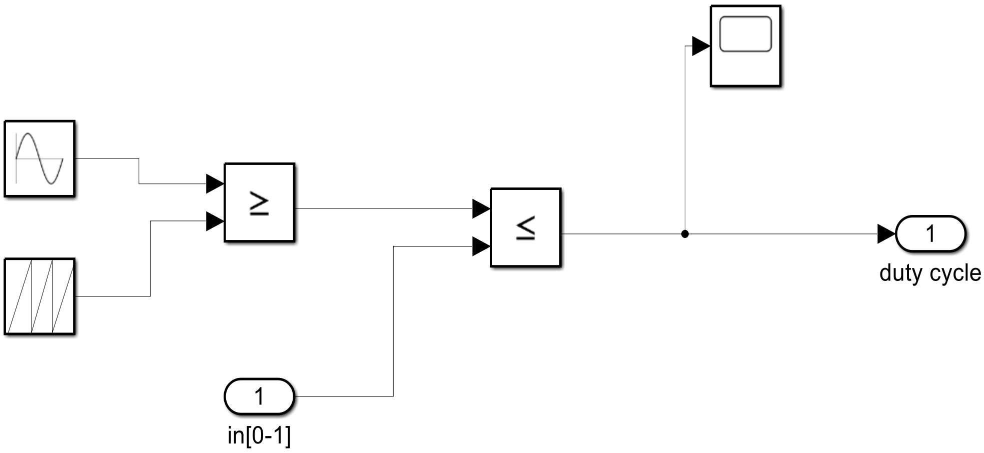


Fig. 14. The circuit of the Subsystem, Signal, input [0 1], out (duty cycle)

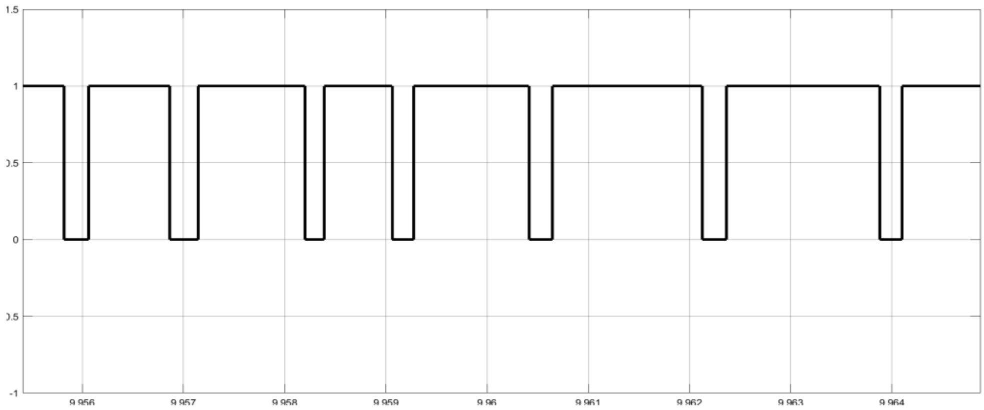


Fig. 15. The waves of the subsystem, time values from (8.956 - 9.964) sec

3.4.2. Gate

Fig. 16, and Fig. 17, show the implantation of the subsystem Gate to control the circuit, it contains the input with six compare and the output, and Table 7 shows BLDCM Gate Logic.

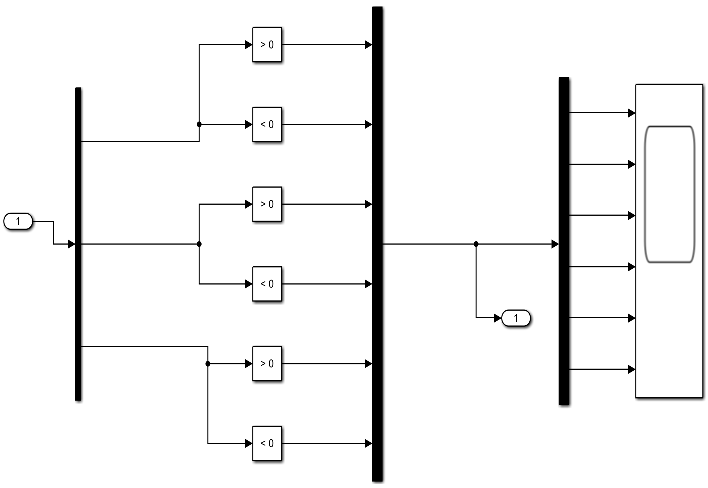


Fig. 16. The circuit of the subsystem for the Gate unit (inverter switching for MATLAB drive), (1) Emf-ABC, (1) Gates

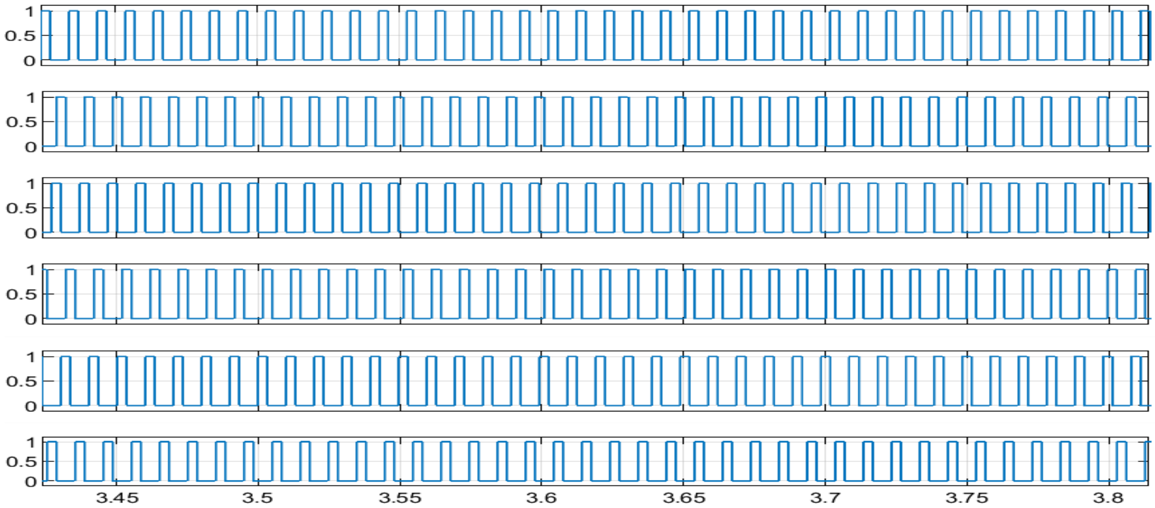


Fig. 17. The waves of the subsystem Gate, time values from (3.45-3.8) sec

Table 7. The model implements the following true tables of the subsystem Gate (BLDCM gate logic)

Emf-a	Emf-b	Emf-c	Q1	Q2	Q3	Q4	Q5	Q6
0	0	0	0	0	0	0	0	0
0	-1	+1	0	0	0	1	1	0
-1	+1	0	0	1	1	0	0	0
-1	0	+1	0	1	0	0	1	0
+1	0	-1	1	0	0	0	0	1
+1	-1	0	1	0	0	1	0	0
0	+1	-1	0	0	1	0	0	1
0	0	0	0	0	0	0	0	0

3.4.3. Decoder

Fig. 18, shows the model implementation of the subsystem Decoder to control the circuit, it contains the input with six converters and the output, and Table 8 shows the truth of the subsystem clockwise BLDCM Rotation, Fig. 19, shows the voltages of three-phase input obtained from the inverter. Table 9. shows the Specifications of the BLDC Motor used in the simulation circuit for speed control.

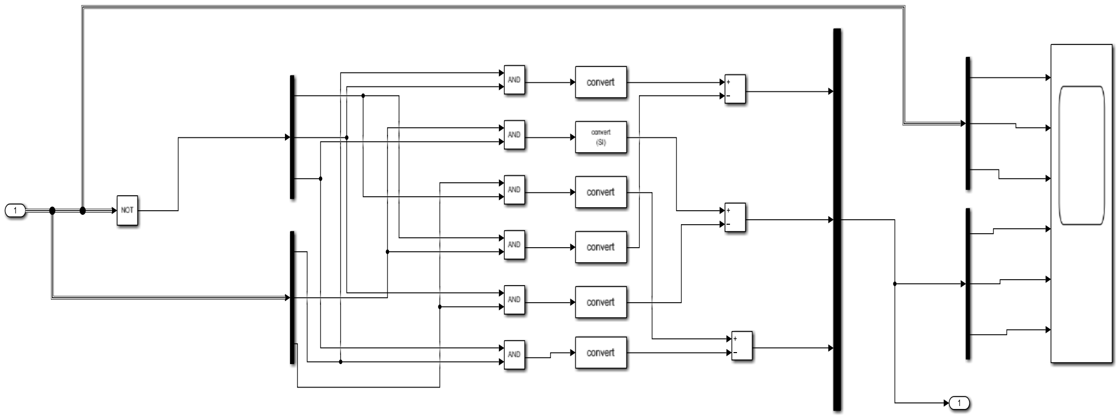


Fig. 18. The circuit of the subsystem for the decoder unit

4. Results and Discussion

Fig. 4. shows the design of a cascade boost converter using an open loop circuit with pulse width modulation and frequency of 10 kHz using MATLAB program. Fig. 5. shows the response of the

input and output voltages, where an output voltage of Vout = 54.71v was obtained from using the cascade boost circuit with an input voltage of Vin = 15 v. Table 2. also shows the rise and fall time, and overshoot, undershoot.

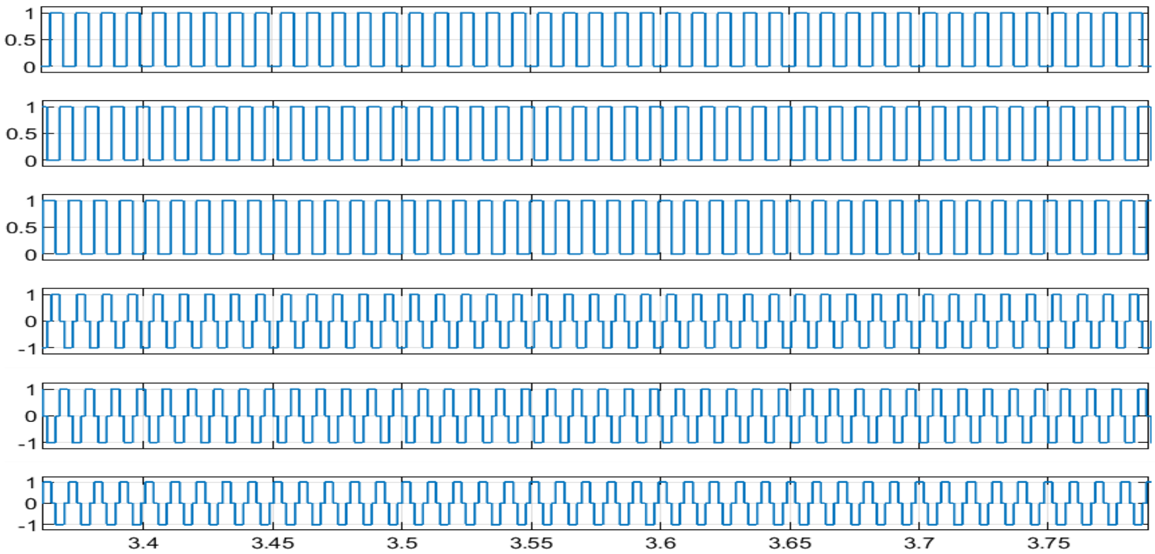


Fig. 19. The waves of the subsystem Decoder, time values from (3.4-3.75) sec

Table 8. The model implements the following true tables of the subsystem decoder (clockwise BLDCM)

Hall a	Hall b	Hall c	emf-a	emf-b	emf-c
0	0	0	0	0	0
0	0	1	0	-1	+1
0	1	0	-1	-1	0
0	1	1	-1	0	-1
1	0	0	+1	0	-1
1	0	1	+1	-1	0
1	1	0	0	-1	-1
1	1	1	0	0	0

Table 9. BLDC motor specification

Parameters	Symbol	Value
Stator phase resistance	R_S	0.94 Ω
Stator phase inductance	L_S	1.19mH
Torque constant	T_C	0.128 N.m/A$_{\text{- peak}}$
Back EMF flat area	EMF	120^{o} (Degrees)
Inertia	I	0.0051 Kg^2
Viscous damping	Vd	0.00042924 N.m.s
Pole pairs	P	4
Static friction	S_f	0 N.m
[0,0,0,0]		
Aligned with phase A axis (original Park)		

Fig. 6 and Fig. 7 show the cascade boost circuit when connecting a BLDC motor in the open loop circuit without the control system unit, a rotation speed of up to 1875 /s will be obtained with a change in response to each of the stator current, EMF, and torque, but it is variable, the efficiency is (50.71%). It is also noticed that the output voltage decreases to (Vout = 46.57 v)for the cascade boost converter circuit and is unstable depending on the voltage input to the motor. Fig. 8 and Fig. 9 show the speed response of the BLDC motor and its stability to a value of 1500 rad/s, which is the required value after using the PID control, the efficiency is (87.87%). Fig. 10 (a),(b) also represents a change in the cascade boost converter in the output voltage and its increase to a value of approximately (350 volts) and then stability to a value of (Vout=46.57v). Fig. 14, Fig. 15, Fig. 16, Fig. 17, Fig. 18, Fig.19, shows the use of Subsystem models and the tables. It concludes from this that the response in the values (rotation speed, stator current, EMF, and torque) of the motor depends on various factors, including the motor design, the quality of the sensors, the capabilities of the motor control unit, and the load on the motor.

The response is fast and stable, with minimal overshoot or delay in reaching the desired speed. The speed of the BLDC motor is stable at 1500 rpm. The torque output is improved through control algorithms that adjust the current and voltage of the motor windings to increase the electromagnetic torque output while reducing losses resulting from flux leakage and eddy currents. The results show that the electromagnetic torque of the BLDC motor and the use of sensors represent an essential part of knowing the motor's performance, efficiency, and suitability for a specific application.

The current control techniques were adjusted based on what was obtained (P=0, I=-1, D=0.) with pulse width modulation (PWM). The sensors affect the motor to tune the controller to the current and voltage thus adjusting the motor to maintain a constant speed and position. Fig. 20, Fig. 21, and Fig. 22 represent the differences in response (external voltage, torque, speed) when the controller PID is not used and the second case when the controller PID unit is connected.

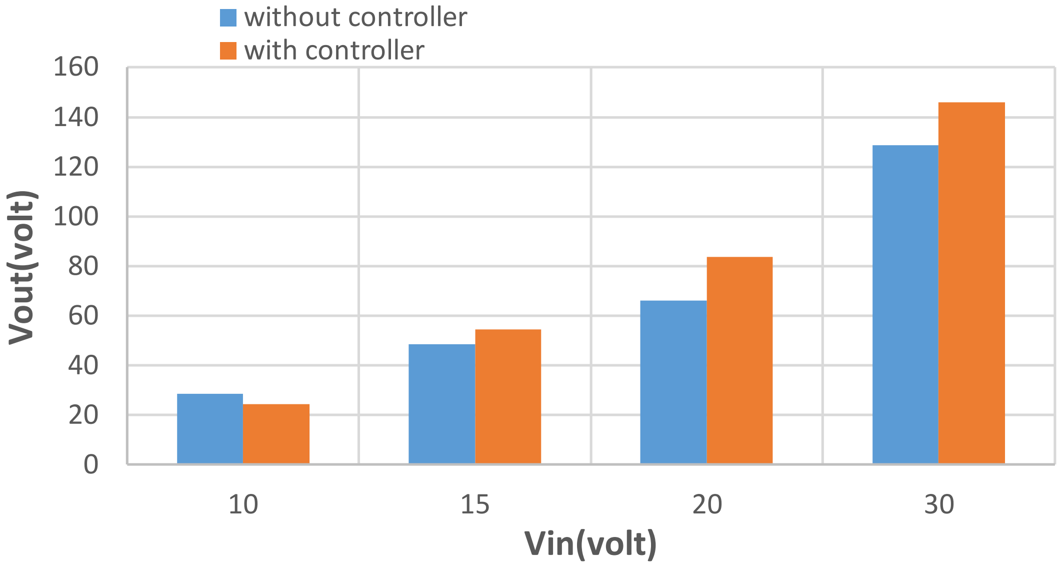


Fig. 20. The Output voltage response with input voltage

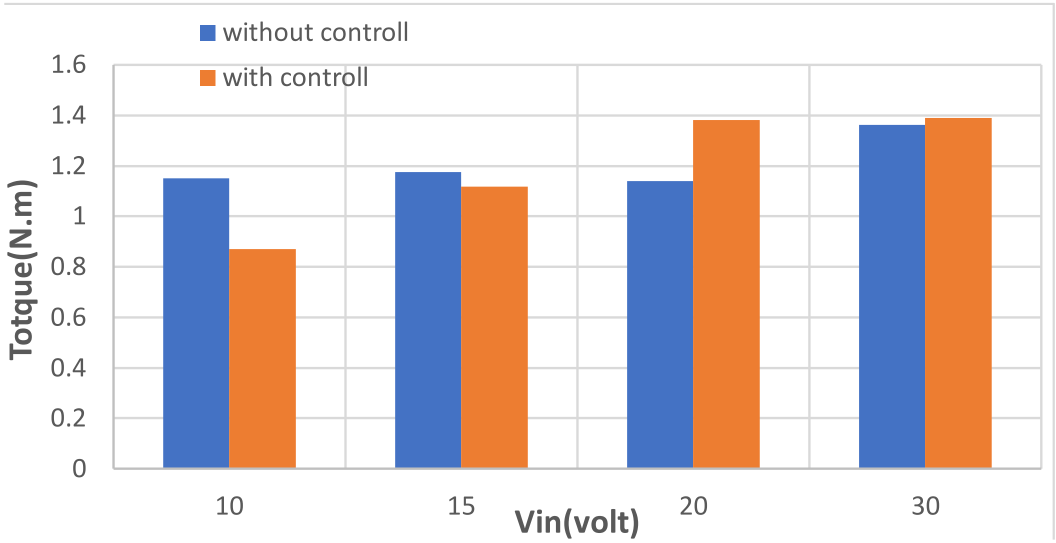


Fig. 21. The torque response with input voltage

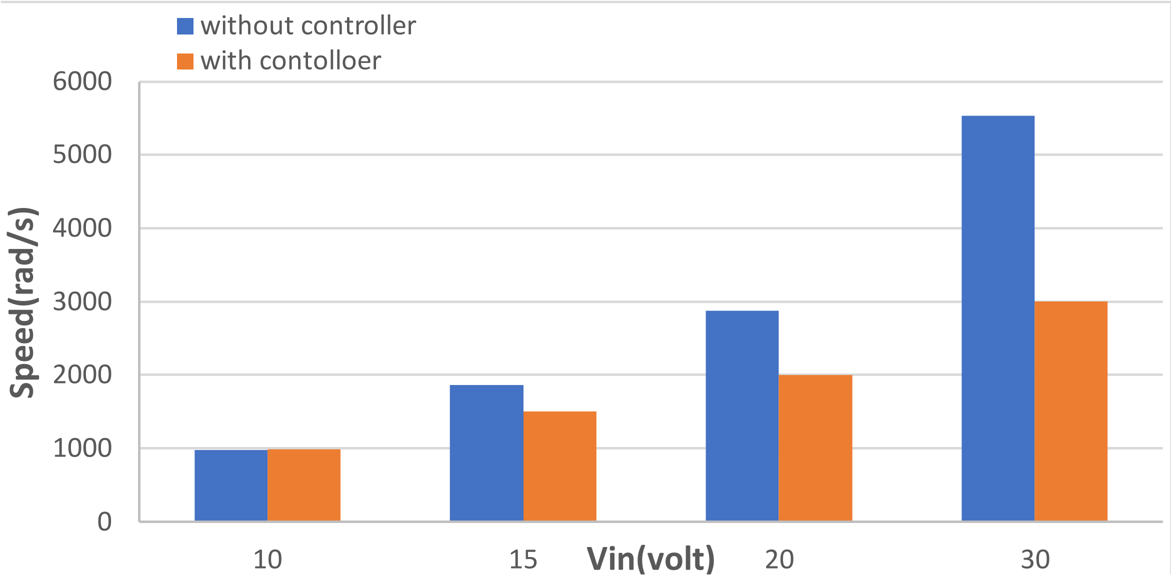


Fig. 22. The Speed response with input voltage

5. Conclusion

The BLDCM step-up converter circuit was implemented and tested in open-loop and closed-loop circuit conditions. The modeling and design of the step-up converter PID controller were performed using MATLAB/Simulink software. The PID controller provided better dynamic response characteristics with conventional CBC, this was demonstrated by achieving the required output voltage (54V) from 15V. It was found that using the controller, the motor could maintain a constant speed and generate much more power with the step-up converter. The motor behavior was studied through simulation to ensure the system was working. In addition to (torque, back EMF, stator current of the motor), it was observed that the motor speed can be increased by increasing the input voltage and the speed can be decreased by decreasing the voltage. From the results obtained, it was found that the PID controller is more suitable and efficient than the control techniques for controlling the speed of the BLDC motor, and the simulation process was completed within (10) seconds to obtain the waveforms by recording the rise time and stability time of the motor parts.

Improved voltage can enhance motor performance, increasing efficiency and responsiveness. If the ripple in the output voltage is significant, it can cause the motor to operate erratically, potentially leading to vibrations, noise, and reduced lifespan. PID controller is crucial to mitigate these effects(Torque and Speed Control). The output voltage affects the torque-speed characteristics of the motor, the higher voltages generally result in higher speeds, while lower voltages may provide more torque but less speed.

Overall, a cascaded boost converter can significantly enhance the performance of a BLDC motor by providing higher voltage and improved efficiency. However, careful design and implementation are crucial to mitigate potential downsides, such as ripple effects and overheating, ensuring reliable and optimal operation in various applications, such as electric vehicles and robotics.

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