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Performance Enhancement of BLDC Motor Drive Systems Using Fuzzy Logic Control and PID Controller for Improved Transient Response and Stability

Zainab B. Abdullah [a,1,*], Salam Waley Shneen [b,2], Hashmia Sharad Dakheel [a,3]

[a] Department of Electro-Mechanical Engineering, University of Technology–Iraq, Baghdad, Iraq
[b] Energy and Renewable Energies Technology Center, University of Technology–Iraq, Baghdad, Iraq
[1] Zainab.B.Abdullah@uotechnology.edu.iq; [2] salam.w.shneen@uotechnology.edu.iq;
[3] Hashmia.S.Dakheel@uotechnology.edu.iq
* Corresponding Author

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ABSTRACT

Currently, systems generally need control units, which requires designing them to analyze the behavior of the system when there are suitable characteristics of the motor according to the required application. The electric motor is very important in many applications and is widely used because of the high-efficiency mechanical power, small sizes, and relatively high torques that these electrical machines have. Improving the performance of systems requires control units, which are of the types of traditional PID, expert Fuzzy, and intelligent control systems. Two systems were proposed, a system that relies on a traditional control unit and a system that relies on fuzzy logic to improve and raise the efficiency of performance and handle system fluctuations resulting from disturbances and different operating conditions. Simulation tests were conducted using MATLAB. The effectiveness of the proposed controllers is evaluated through measurement criteria including efficiency improvements, torque ripple reduction, or settling time. Simulation results for both the closed-loop system using the conventional controller and the expert controller showed that the improvement in system performance can be determined according to criteria that include response speed as well as the overshoot and undershoot rates. Specifically, the settling time using the conventional controller was 3.05 msec. The rise time using the conventional controller was 205.406 msec, while using the expert controller it was 205.406 msec. The overshoot rate (%) using the conventional controller was 18.452%, while using the expert controller it was 6.989%. The undershoot rate using the conventional controller was 6.633%, while using the expert controller it was 1.987%.

1. Introduction

Electric motors are generally used in a variety of applications, including those requiring mechanical energy, such as moving a train or elevator. When a motor is added to produce mechanical energy, operating conditions may change, requiring analysis of these conditions and their impact on system operation. Any changes that could reduce performance must be addressed, along with solutions to improve performance. System disturbances can cause poor performance, including transients and torque changes. Specialists develop and run simulation models to conduct tests that enhance the identification and validation process for testing under various conditions, as well as demonstrate and analyze the system's response to these conditions.

There is increasing interest in using Brushless DC (BLDC) motors widely in industrial production due to their many advantages such as simple structure, robust design, high stability, torque density, high efficiency, low noise, and low maintenance. BLDC motors are used in aerospace, medical, automotive, disk drives and variable speed drive systems for electric vehicles and industrial applications. Achieving continuity of BLDC motor speed control under different operating conditions require the design of a modern and efficient controller. This design involves a complex process of modeling, selecting the best control system, simulation and adjusting controller parameters [1]-[5]. There are many solutions to control the speed of a BLDC motor and fast braking operation that have been recently proposed to adjust the parameters of the controller, thus obtaining optimal motor performance [6]-[12].

Systems are classified into open-loop systems, which operate without feedback. Through this, the system's behavior can be observed without a control unit. The system's performance is somewhat weak compared to the other case, which is a closed-loop system. Both open-loop and closed-loop systems can be built, and a control unit with a reference value can be added, such as conventional, expert, or intelligent. Conventional PID controllers are simple and suitable for linear systems, but they are weak for nonlinear systems. Therefore, an intelligent or expert controller is required to improve the performance of nonlinear systems, such as fuzzy logic.

The PID control unit is a traditional unit of widely used control units in control systems in industrial fields due to the strength and simplicity of design, reliability and high accuracy. Parameters can be switched (kd, kp, ki) effectively good output and stable response can be obtained when the parameters are set correctly. The application of the traditional PID control algorithm for speed control faces major problems, namely the effects of non-linear characteristics of DC motors, including saturation, changing some variables, and the difficulty of adjusting the parameters of the PID control unit, which leads to inaccurate control and poor optimal performance of the motor [13]-[21]. In [22], two types of sliding controllers FOSMC and FSMC were used to obtain the best performance of BLDC motor in terms of speed control and braking operations. The research proved the superiority of FOSMC controller over FSMC to obtain the best performance of BLDC motor by optimizing the parameters through GA.

In [23], A simulation model combining fuzzy controller and PID was used to control the speed of BLDC motor better than traditional PID controller and several types of commutation tests of BLDC motor were used. The torque was improved by choosing the suitable commutation type of the sinusoidal of third harmonic component. In [24], This paper presents a comparison between PID conventional controller and fuzzy controller for controlling the speed of BLDC motor for the purpose of addressing uncertainty and nonlinearity in real applications. The simulation results demonstrate the ability to eliminate interference and improve the static and dynamic response of the system. In [25], Presents the use of PSO controller based on PID to control the speed of BLDC motor using different (speeds and loads). The performance of PSO-PID control system was compared with other controllers and the results showed improvement in response speed and reduction of electromagnetic torque ripple and current ripple of BLDC motor. In [26], the work focused on two main aspects, the first: a simulation system for controlling the speed of a BLDDC motor using a fuzzy logic controller. This fuzzy system's rules are defined based on the Lyapunov function. The "Chameleon Swarm" algorithm was used to optimize gain coefficients of fuzzy controller. Second part included practical tests using a low-power electronic device. This device contains:1- Microcontrollers (STM32-ARM) were used for the purpose of measuring variables, calculating the control algorithm and generating the control signal 2- Microcomputer to define the parameters, apply the control and the reference value. Fuzzy logic is an artificial intelligence technique that relies on thinking using linguistic terms and thus analyzing and interpreting inaccurate information [27]-[28]. In fuzzy logic, little mathematical formulas are used because it

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relies on the use of linguistic terms, which leads to reducing the complexity of the system. Fuzzy logic is superior to traditional controllers (PID, PI) in non-linear systems and is very similar to human logic because it allows the use of human experience and expertise in the design of controllers. Compared with PID controllers, fuzzy logic has shorter stability time and more adaptive control system. Fuzzy logic is based on IF-THEN rules which focus on human operators in decision making and knowledge process [29]-[33]. Fuzzy logic is used in wide industrial applications in control systems, traffic signals, air conditioners and many large economic systems. There are several things that must be specified when designing a fuzzy logic control system, the first is monitoring and modifying the input and output variables, i.e. the controlled plant can be observed and controlled. The second is the presence of input and output data from which rules can be extracted. FLC operates on the assumption that there is a solution that is not necessarily optimal but within an acceptable range of accuracy [34]-[41].

In this study, the researchers propose developing a simulation model to conduct tests involving open-loop and closed-loop systems with no-load, constant-load, and variable-load conditions to represent linear and nonlinear systems. By analyzing the simulation results, the system's behavior for all proposed test cases is identified, which will be detailed later. The present research contributes to the tuning of gain constants by presenting and designing a conventional proportional integral derivative (PID) controller. Another contribution to the tuning of gain constants is the presentation and design of an expert Fuzzy Logic Controller (FLC) type. Through simulation and using the prototype and the proposed model according to the system results, this aims to experimentally verify the effectiveness of the proposed system.

Brushless DC motors (BLDC motor) are machines that have important applications in many fields. Applications for systems that require an electric motor as part of this system. The system also needs a power source to operate the electric motor from suitable power sources that may change with different working conditions. Therefore, it requires the addition of a boost-type power converter with the possibility of adding control systems to deal with disturbances in the system. A system has been designed with specifications that suit and represent the contribution of the research in processing the high starting current and working to determine it through a control unit at the output of the converter that feeds the motor and the other contribution in improving and processing the amount of energy needed by the system. The speed of the BLDC motor is controlled using electronic switching of electronic inverter switches pulses called voltage source inverter (VSI). Simulation was conducted using MATLAB to verify the effectiveness of the system through factors including improving the system behavior and raising the level of performance indicators in real-time operating conditions that suit the proposed process. The simulation was conducted to test the system optimization using the conventional controller and the expert controller with different setup conditions and different loading conditions, i.e. the case of a linear system and a non-linear system. In comparison, the linear system proved to be effective with different control systems, while in the non-linear system, the expert outperformed the conventional one. The comparison was conducted according to measurement criteria such as the excesses of the specified amount above and below, response speed, rise time and settling time. The expert systems responded faster than the conventional ones.

2. Method

In this section there are two part include the first is Brushless DC (BLDC) motors that show in subpart number (A). Second is Speed Control Performance in BLDC Motor that show in subpart number (B). Control systems are typically used with electric motors specifically to control and regulate the rotational speed, rotor position, and torque variation.

2.1. Brushless DC (BLDC) Motors

The three phase BLDC motor like the permanent magnet in dynamic features and different from traditional DC motor because it has three phase windings and a permanent magnet rotor as in

Fig. 1 [42]-[44]. Similarly, equations (1)-(5) and Fig. 2 represent the mathematical model of BLDC motor [45]-[49].

$$\frac{\omega(s)}{V_{app}(s)} = \frac{Kt}{L.j.s^2 + (LD + jR).s + Kt + Kb} \quad (1)$$

$$V_{app}(s) = L.\frac{di(t)}{dt} + R.i(t) + V_{emf}(s) \quad (2)$$

$$V_{emf}(s) = Kb.\omega(t) \quad (3)$$

$$T(t) = Kt.i(t) \quad (4)$$

$$T(t) = J\frac{d\omega(t)}{dt} + D.\omega(t) \quad (5)$$

Where: - $V_{app}(t)$ is input voltage, ω(t)t is instants motor speed, (L) is stator inductance, i(t) is circuit current, R is resistance of stator, $V_{emf}(t)$is back electromotive force, (T) is motor torque, (D) is viscous coefficient, (J)is moment of inertia, (K_t) is motor torque constant, and (K_b)is back electromotive force constant. The transfer function of BLDC motor as shown in Fig. 2.

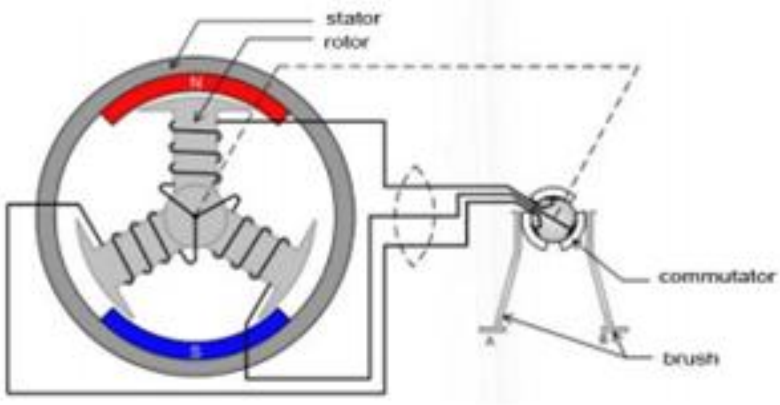

Fig. 1. Internal structure of BLDC motor

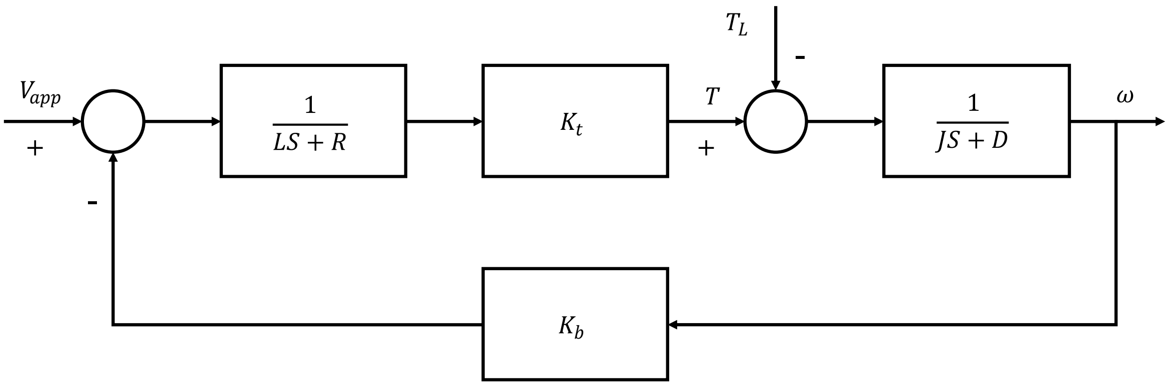

Fig. 2. Transfer function of BLDC system

2.2. Speed Control Performance in BLDC Motor by Proportional–Integral–Derivative (PID) Controller

One of the most important applications of the traditional controller (PID controllers) is its use in controlling the movement and position of robots by controlling the electric motor. This is done by controlling the rotational speed and setting it to the appropriate reference value. There is another application for controlling the position of the rotor and the torque.

The control system has two types, open loop (no feedback) a system has output only and close loop (with feedback) a system that uses sensors to minimize error. In close loop type output becomes more optimized as shown in Fig. 3. The equations (6) Represent mathematical formulae for the PID controller.

$$C(s) = Kp + \frac{Ki}{s} + Kd.s \tag{6}$$

$$C(s) = \frac{Kp.s + Ki + Kd.s^2}{s} \tag{7}$$

$$u(t) = K_P.e(t) + K_I.\int_0^t e(t)\,dt + K_D.\frac{de(t)}{dt} \tag{8}$$

$$u(t) = K_P + K_I/s + K_D.s \tag{9}$$

Where, the proportional (KP), integral (Ki), derivative(KD), constant gain respectively. (t) Is the output of the PID controller, $e(t)$ is the error signal between input reference and output process [50]-[55].

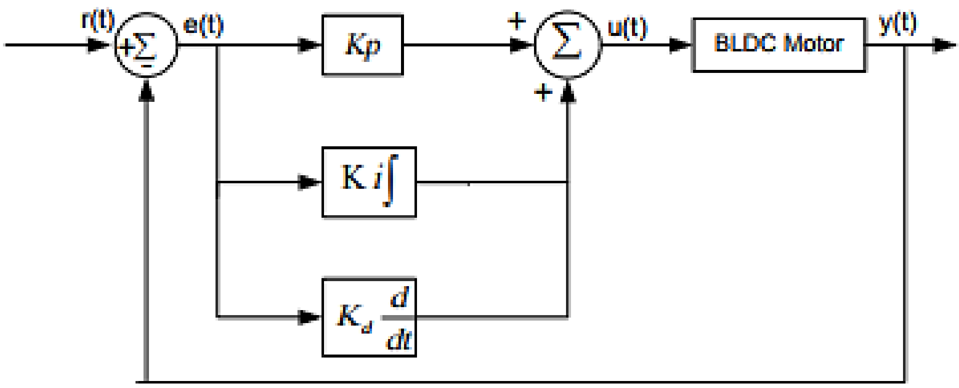

Fig. 3. Block diagram of PID controller

2.3. Speed Control Performance in BLDC Motor by Fuzzy Logic control (FLC)

The traditional control pid adjusts the frequency but faces difficulties in dealing with the large and fast changes. The performance improved fuzzy algorithm combing the pid-fuzzy control applied in this research to rapid and stable speed and torque control. A fuzzy-pid controller is used to adjust a pid controller parameters (kp, ki, kd) automatically. This modification allows fuzzy logic controller to work to meet the specified system requirements as shown in Fig. 4, where fuzzy logic controller receives two inputs: - the error e(t) and error change Δe(t) and gives three outputs: (kp, ki, kd). Error signal is generated by comparing real speed with required speed of stand-alone SG, while the change in error is calculated from the differentiation of error signal. The two signals are an income for fuzzy logic block. The system uses a knowledge base for fuzzy reasoning, where the system generates immediate corrections to the PID controller parameters Δkp, Δki, Δkd. These corrections enable the PID controller to adjust its parameters depending on the working conditions faced of the BLDC motor [56]-[62].

3. Results and Discussion

This section explains two parts include Modeling for open loop BLDC motor, Modeling closed loop of BLDC motor with PIDC or FLC.

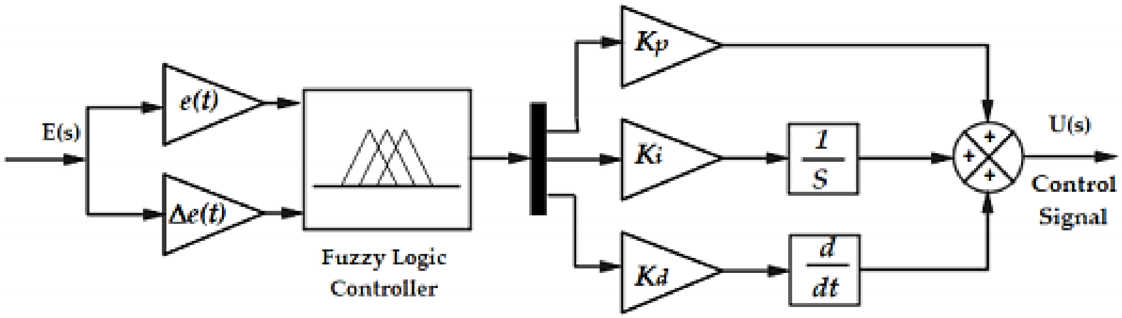

Fig. 4. Block diagram of Fuzzy-PID controller

3.1. Modeling for Open Loop of BLDC Motor

In the current study, system tests are conducted under various conditions to identify the system's behavior for each of the proposed test cases. The first test case involves an open-loop system, which can be represented as a model in Fig. 5 and in Fig. 6, where the reference signal is the supply voltage, which is a positive input to the comparator with the actual value. The comparator's output is then input to the electrical component. An electrical current is then obtained at the electrical component's output and multiplied by a specified constant to obtain the torque, which is compared to the load as a mechanical torque. The comparator's output is then input to the mechanical component of the electric motor. The actual output is then obtained, allowing the motor to operate according to a specific behavior. This behavior is achieved by placing sensors for these quantities, as in Fig. 5 and in Fig. 6, which represent two test cases: a load and a constant load. In this part there are two test by using the modeling in Fig. 5 and in Fig. 6 that show the test at no load and at load bellow:

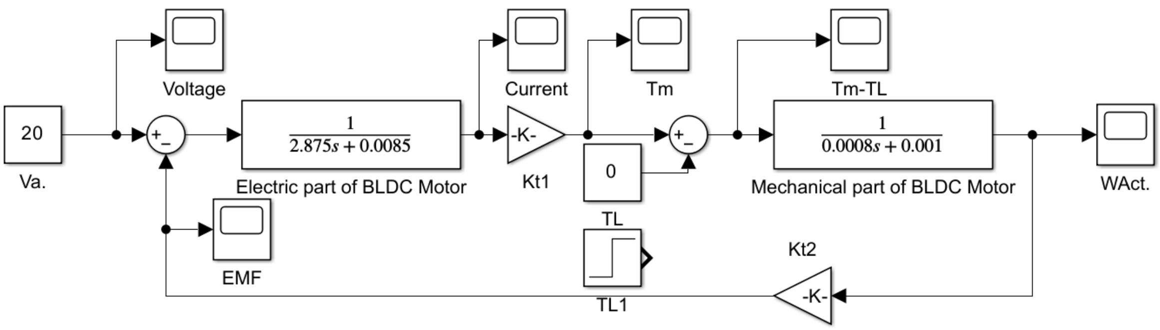

Fig. 5. Modeling for open loop of BLDC motor at no load

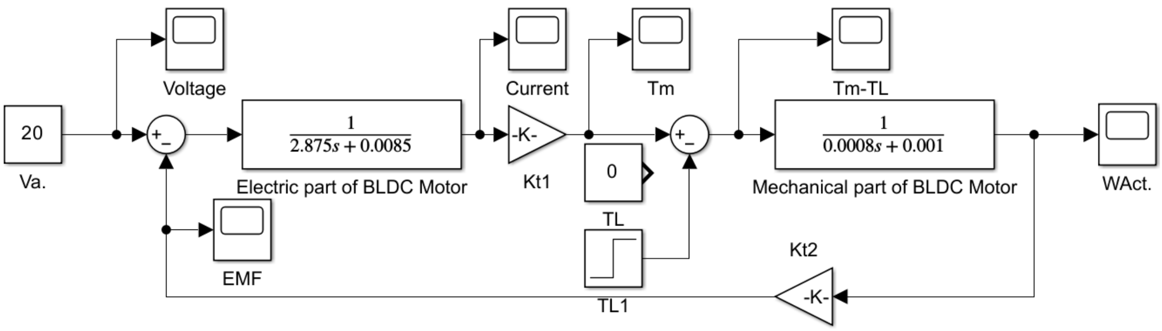

Fig. 6. Modeling for open loop of BLDC motor at load

3.2. Simulation Results for Open Loop of BLDC Motor

The system behavior for two initial open-loop test cases can be identified using the simulation models in the previous paragraph by drawing the reference voltage waves followed by the actual voltage value, current, and torques as shown in the Fig. 7, Fig. 8, Fig. 9, Fig. 10.

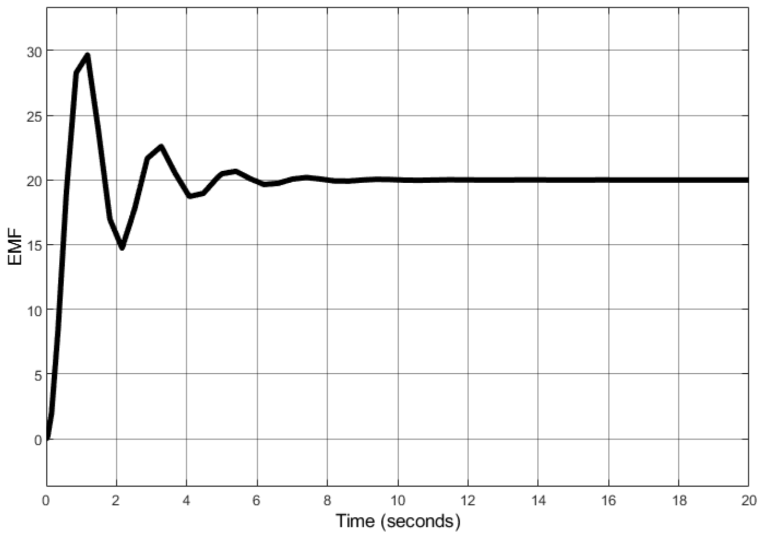

Fig. 7. Response of (EMF) for open loop BLDC at no load

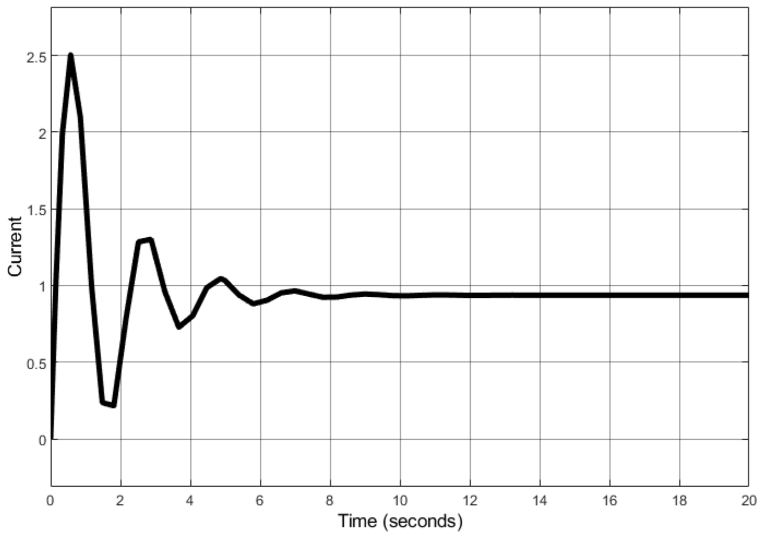

Fig. 8. Response of (current) for open loop BLDC at no load

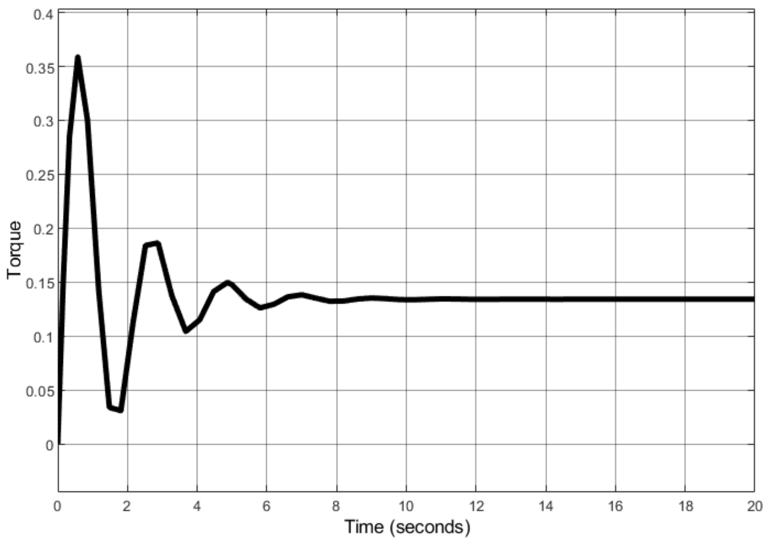

Fig. 9. Response of (torque) for open loop BLDC at no load

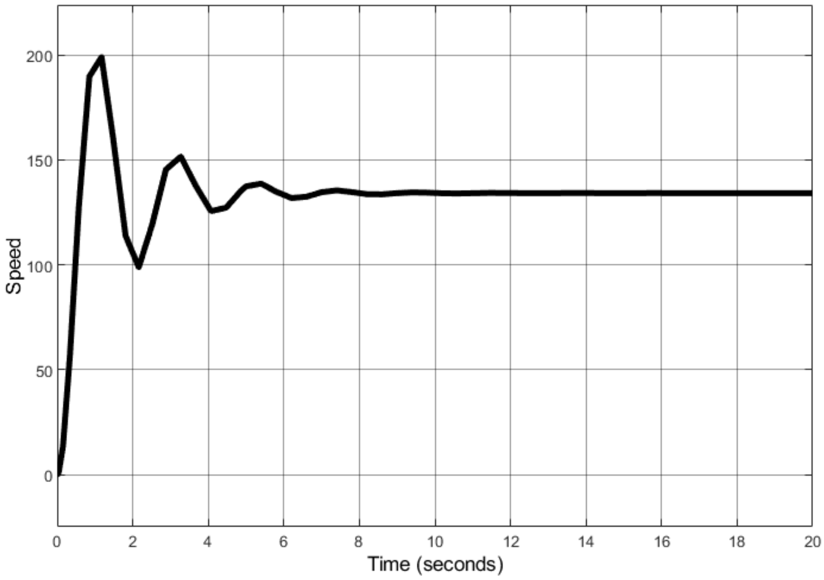

Fig. 10. Response of (speed)for open loop BLDC at no load

The figures show a 20-second test run, with a waveform fluctuating halfway through the period, after which it stabilizes at a certain value. For example, in the voltage signal, we notice an increase in the voltage of approximately 30 volts, which is 50% higher than the specified value, and a decrease to 15 volts, which is 25% higher than the specified value. The other figure represents the current value, with the stabilization current being close to one, while the increase reaches approximately 2.5 and the decrease reaches 0.25. When looking at the torque wave signal, the stabilizing torque can be identified at 0.13, while the increase is more than 0.35, while the decrease is less than 0.05. The figure representing the value of the rotor speed of the motor indicates stability at an amplitude of approximately 130 revolutions, while the increase reaches 200 revolutions and the decrease reaches 100 revolutions. In the second test, when a load is added to the motor, current and torque signals and waves can be plotted, along with speed, to determine the magnitude of the change, as shown in the Fig. 11, Fig. 12, Fig. 13.

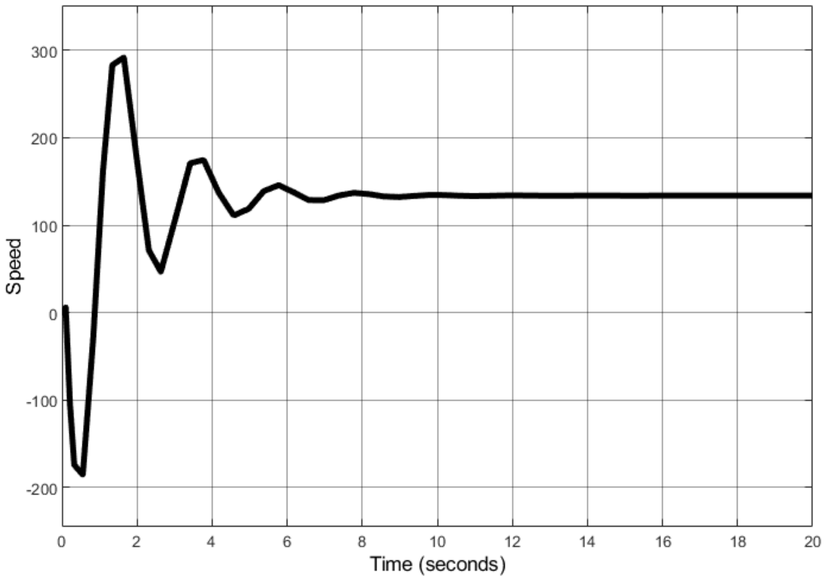

Fig. 11. Response of (speed) for open loop BLDC at constant load

The change in speed can be observed as the speed increases to 300 rpm and decreases to less than 100 rpm, while the load increases to 1.1 Nm, and the current drawn increases to 8 amps.

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3.3. Simulation Modeling for Closed Loop System with PIDC Controller of BLDC Motor

In this section the system response can be identified when the traditional control unit is added to the system. By conducting simulation tests, the response curve for current and speed can be drawn and compared to the previous case, as in the Fig. 14.

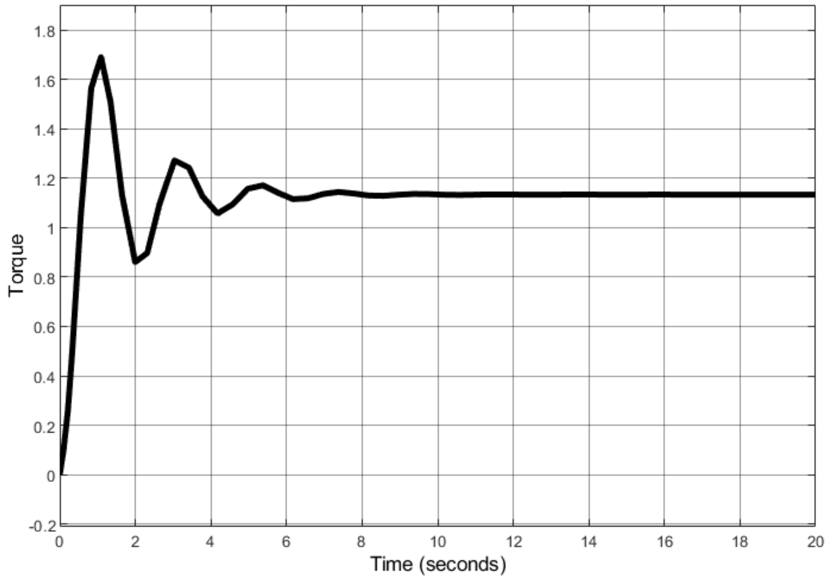

Fig. 12. Response of (torque) for open loop BLDC at constant load

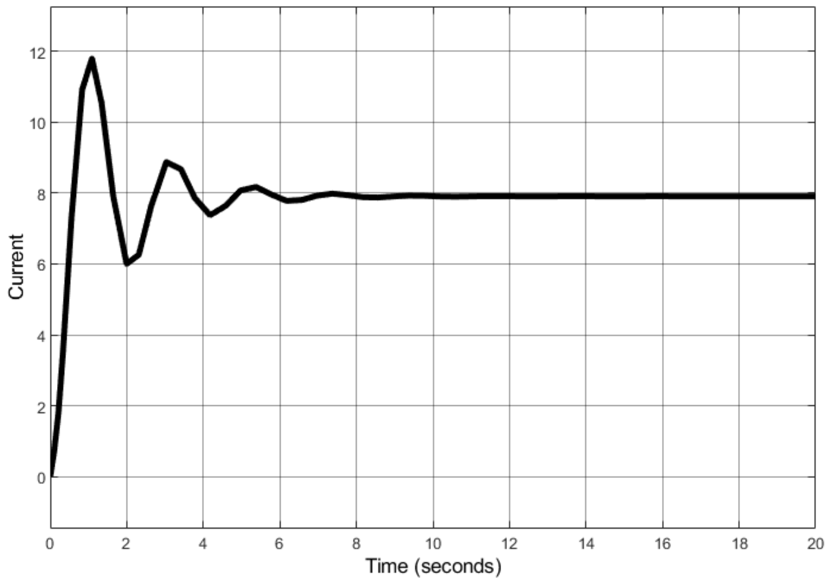

Fig. 13. Response of (current) for open loop BLDC at constant load

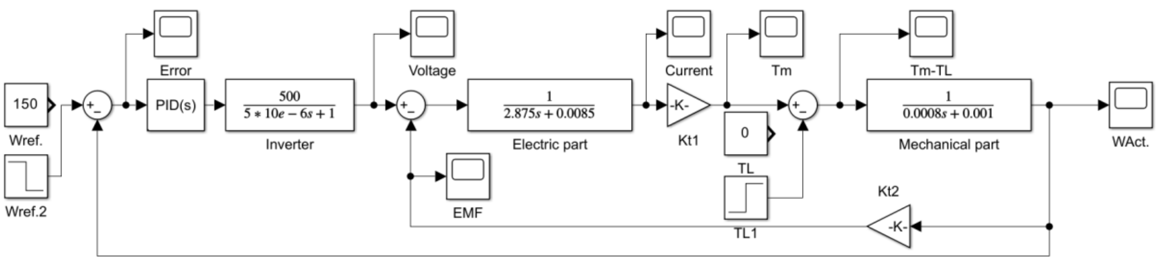

Fig. 14. Modeling of closed loop system with PIDC for BLDC at load

3.4. Response for Closed Loop System with PIDC Controller of BLDC Motor

The system behavior for the closed loop system with PIDC for BLDC at load test cases can be identified using the simulation models in the previous paragraph by drawing the reference voltage waves followed by the actual voltage value, current, and torques as shown in the Fig. 15, Fig. 16, Fig. 17.

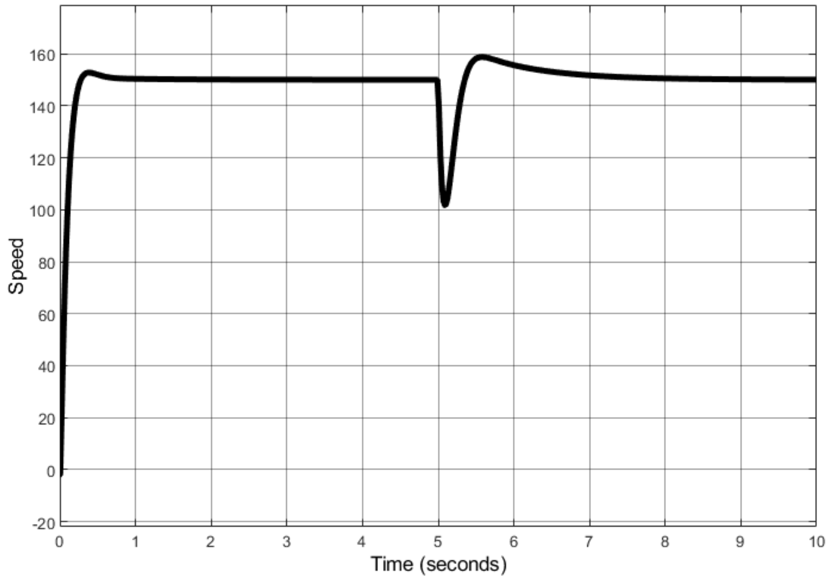

Fig. 15. Speed response of closed loop system with PIDC for BLDC at variable load

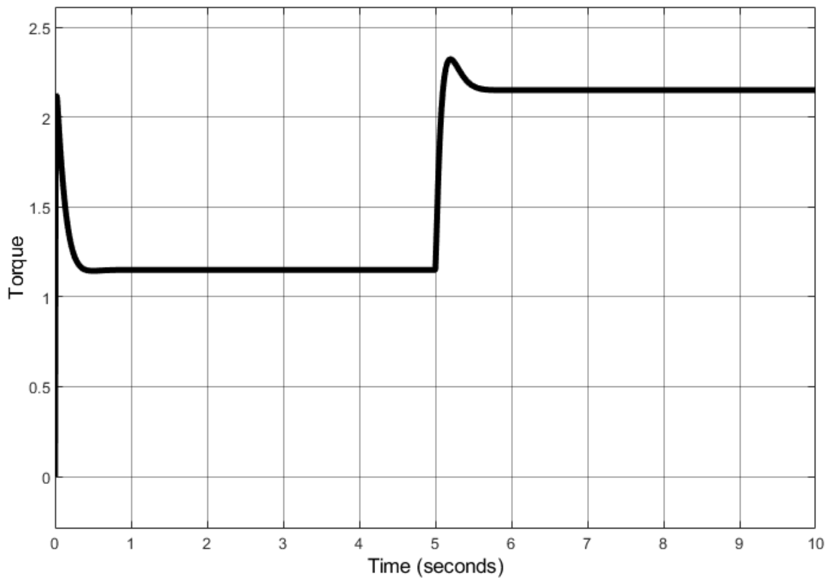

Fig. 16. Torque response of closed loop system with PIDC for BLDC at variable load

3.5. Modeling for Closed Loop with Fuzzy Logic Control (FLC) of BLDC Motor

In this part there are two test by using the modeling in Fig. 14, and in Fig. 15, that show the test at no load and at constant load load and the Fig. 16 show the subsystem of FLC model. Fuzzy logic is represented in simulations by input and output variables, which can be represented in Fig. 17 under the heading (Fuzzy Logic Designer). After determining the number of variables in the input and output of the fuzzy logic simulation model (membership function editor)., the type of variables and the change limits for each type (-1,1) can be determined, as can be seen in Fig. 18 include (NB, NS, Z, PS and PB). The rules of fuzzy logic are represented in the simulation by the change in the appropriate input and output limits of the variables in all possible input and output states as can be seen in Fig. 19.

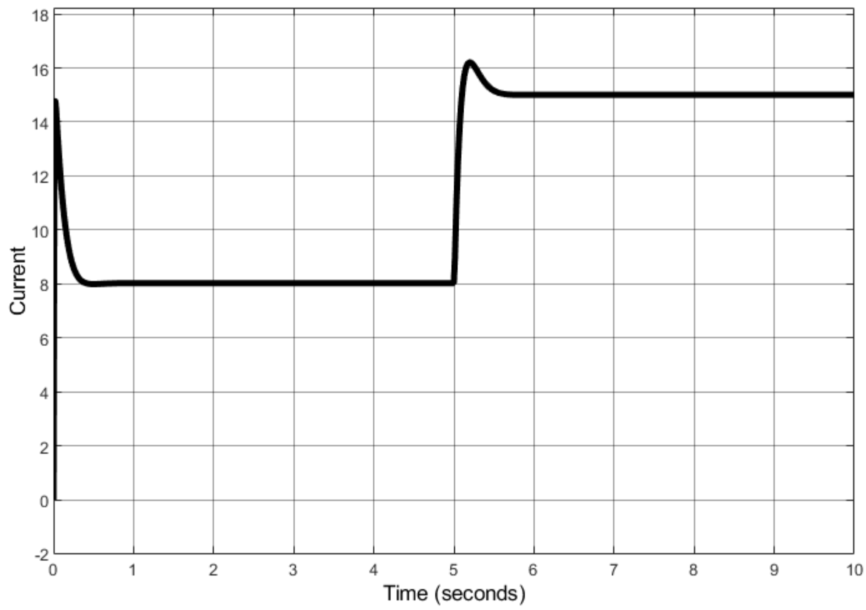

Fig. 17. Current response of closed loop system with PIDC for BLDC at variable load

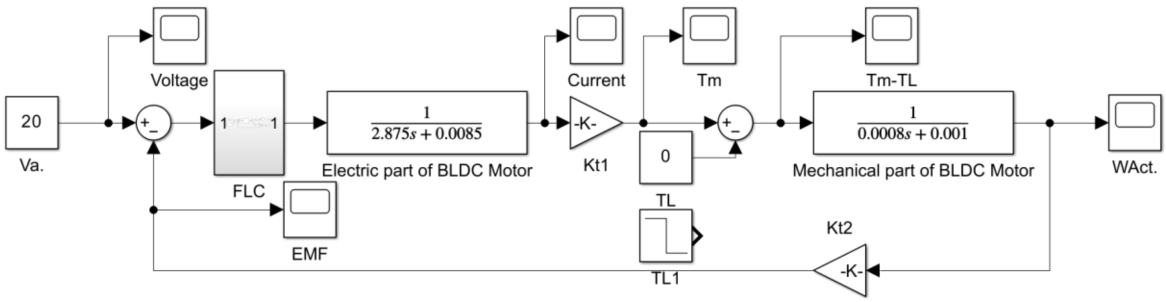

Fig. 18. Modeling for closed loop with FLC controller of BLDC motor at no load

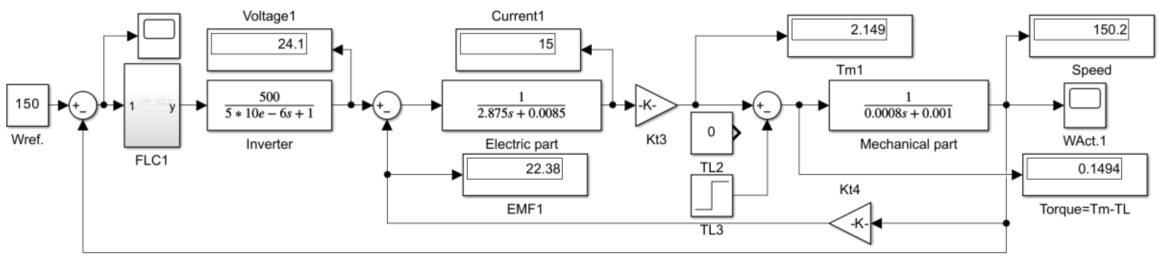

Fig. 19. Modeling for closed loop with FLC controller of BLDC motor at load

3.6. Response for Closed Loop System with FLC Controller of BLDC Motor with Load

The first test of this section by using the simulation model in Fig. 14 and the response can be show in Fig. 20, Fig. 21, Fig. 22, Fig. 23. The second test of this section by using the simulation model in Fig. 15 and the response can be show in Fig. 24, Fig. 25, Fig. 26, Fig. 27, Fig. 28, Fig. 29.

Through simulation results for both the closed-loop system using the traditional controller and the expert controller, the level of improvement in system performance can be identified according to criteria that include response speed, specifically the settling time, the rise time, and the Overshoot (%), undershoot % (over- and under-exceeding rates) of the set value, which can be written in a Table 1.

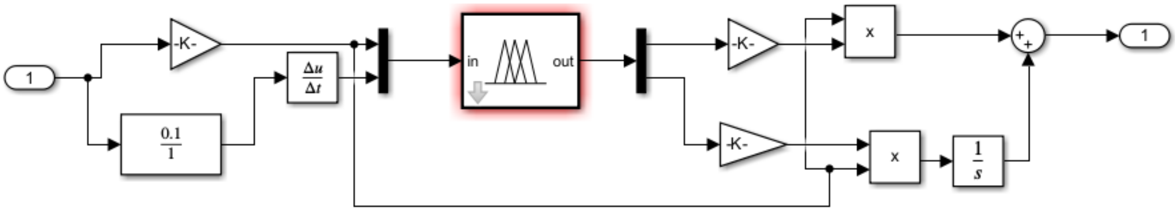

Fig. 20. Model of FLC controller

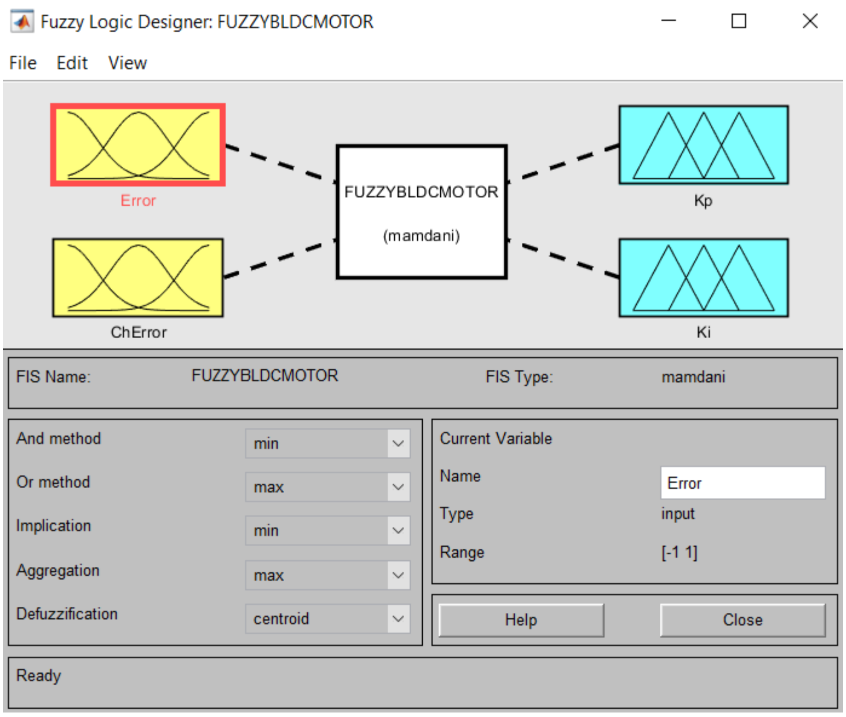

Fig. 21. Model of fuzzy logic designer for FLC controller

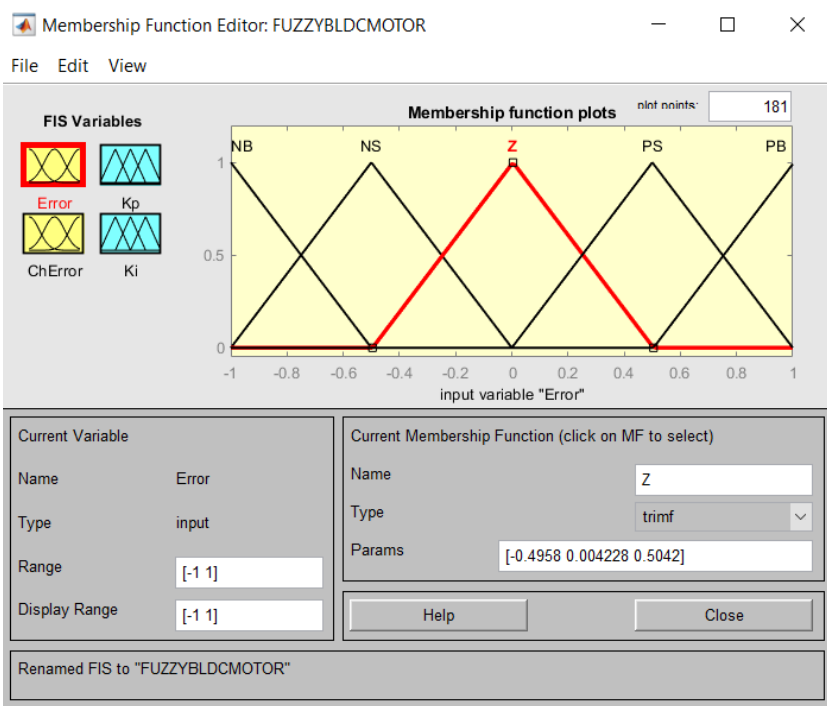

Fig. 22. Model of membership function editor for FLC controller

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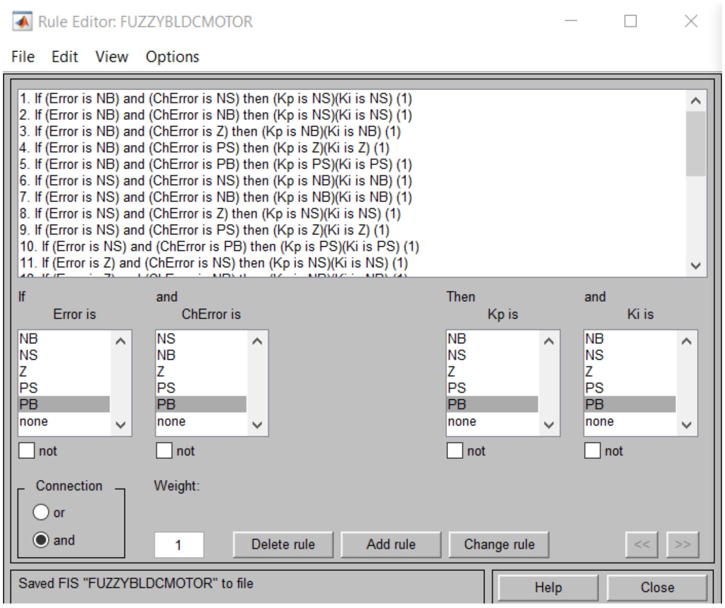

Fig. 23. Model of rule editor for FLC controller

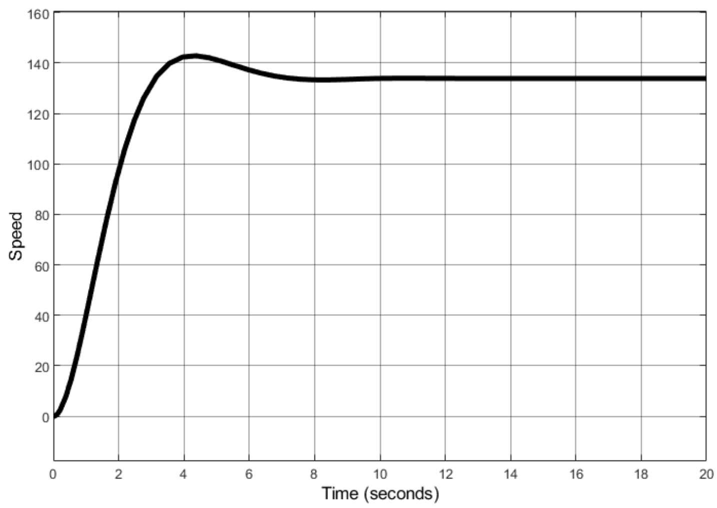

Fig. 24. Speed response for closed loop with FLC controller of BLDC motor at no load

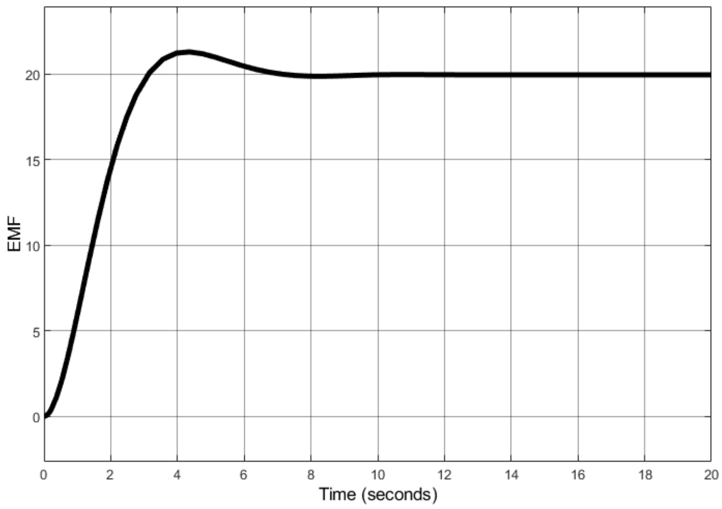

Fig. 25. EMF response for closed loop with FLC controller of BLDC motor at no load

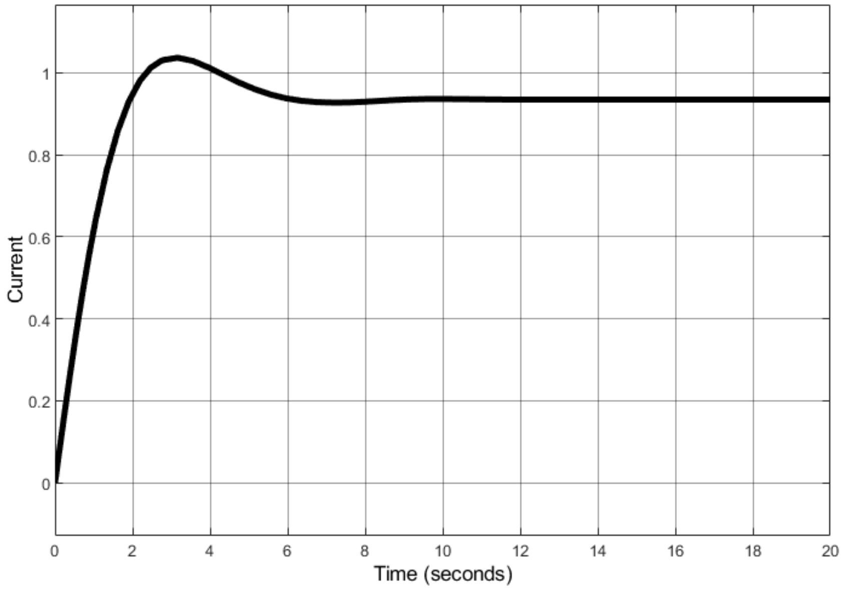

Fig. 26. Current response for closed loop with FLC controller of BLDC motor at no load

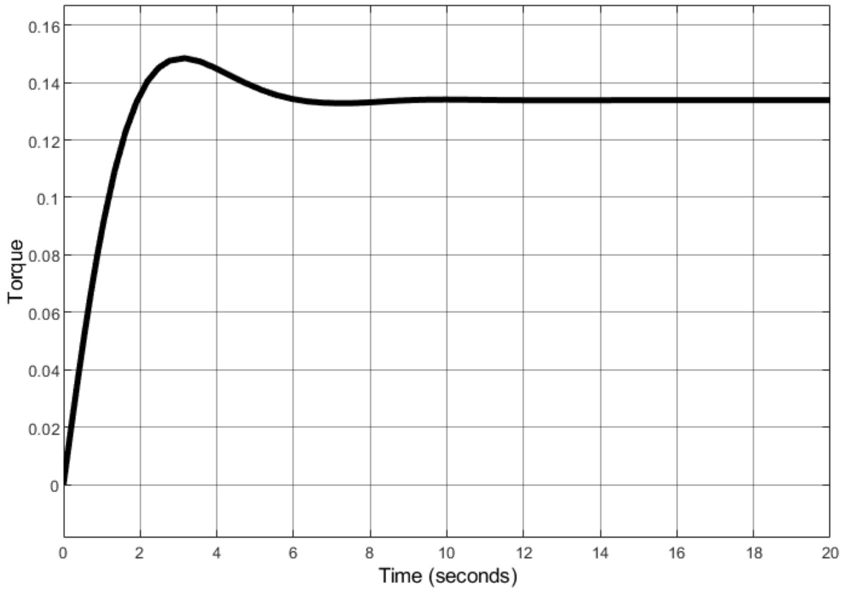

Fig. 27. Torque response for closed loop with FLC controller of BLDC motor at no load

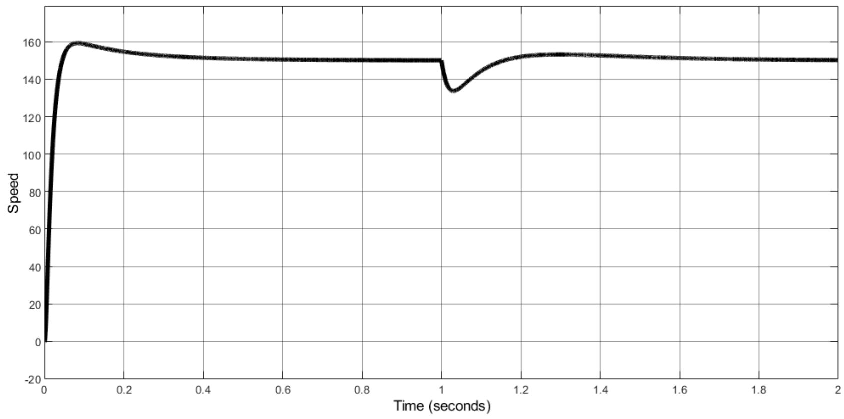

Fig. 28. Speed response for FLC controller of BLDC motor at variable load

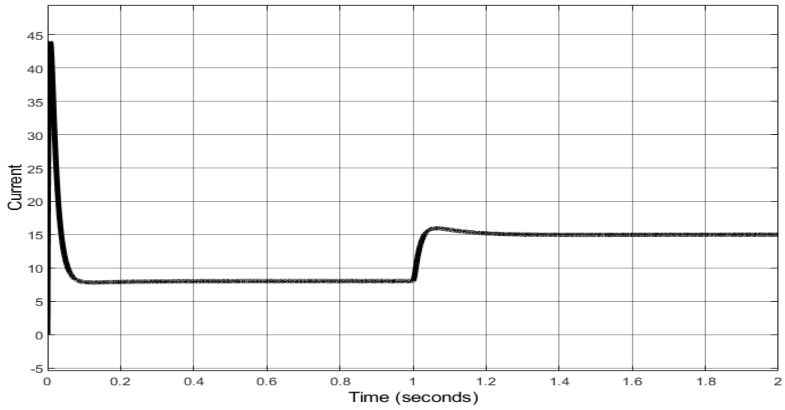

Fig. 29. Current response for FLC controller of BLDC motor at variable load

Table 1. System performance for conventional controller and the expert controller

Type of Control Units	Traditional Controller (PID Controller)	Expert System (Fuzzy Logic Controller)
Rise Time (Tr)	205.406 msec	71.780msec
Settling Time	3.05 msec	5.505 msec
Overshoot (%)	18.452%	6.989%
Under Shoot (%)	6.633%	1.987%

4. Conclusion

In this study, a simulation model is proposed for development through implementation and operation tests. The model includes open- and closed-loop systems, under no-load, constant-load, and variable-load conditions, to represent linear and nonlinear systems. By analyzing the simulation results, the system behavior for all proposed test cases was determined. This research contributes to the tuning of gain constants by introducing and designing a conventional proportional-integral-derivative (PID) controller. Another contribution to the tuning of gain constants is the introduction and design of an expert fuzzy logic controller (FLC). Through simulation, the use of a prototype, and the proposed model based on the system results, the effectiveness of the proposed system was experimentally verified. The conventional controller can be used to control rotational speed, torque, and rotor position in linear systems, while the expert controller is suitable for nonlinear systems. Future applications that can leverage the results of this study include electric vehicles and robotics, among others.

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