Adaptive Speed Control of Brushless DC (BLDC) Motor Based on Interval Type-2 Fuzzy Logic

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Abstract—**To precisely control the speed of BLDC motors at high speed and with very good performance, an accurate motor model is required. As a result, the controller design can play an important role in the effectiveness of the system. The classic controllers such as PID are widely used in the BLDC motor controllers, but they are not appropriate due to non-linear model of the BLDC motor. To enhance the performance and speed of response, many studies were taken to improve the adjusting methods of PID controller gains by using fuzzy logic. Use of fuzzy logic considering approximately interpretation of the observations and determination of the approximate commands, provides a good platform for designing intelligent robust controller. Nowadays type-2 fuzzy logic is used because of more ability to model and reduce uncertainty effects in rule-based fuzzy systems. In this paper, an interval type-2 fuzzy logic-based proportional-integral-derivative controller (IT2FLPIDC) is proposed for speed control of brushless DC (BLDC) motor. The proposed controller performance is compared with the conventional PID and type-1 fuzzy logic-based PID controllers, respectively in MATLAB/Simulink environment. Simulation results show the superior IT2FLPIDC performance than two other ones.**

Keywords-Brushless DC (BLDC) Motor; Invertal Type-2 Fuzzy Logic; Speed Control; Self-tuning PID Controller

I. INTRODUCTION

Due to the disadvantages of conventional motors such as DC brush and single and three phase induction motors, attention to other motors is increased. In the meantime, one of the motors that has attracted a lot of attention is the brushless DC motor (BLDC). In this motor, electronic switches and rotor position detection sensors (e.g. Hall sensors) is used to flow the current to the windings, instead of the use of commutator and brush. BLDC motors in comparison with DC brush motors, because they do not brush, they spent less costly to maintain. In comparison to the induction motors, BLDC motors have higher efficiency and due to lower inertia, are faster dynamic response. In addition, these motors have the ability to control the speed in a wide range. The other features of BLDC motors can be robust performance, lower noise and higher mechanical reliability. The biggest problem of this motor is the high cost of design and development [1-2].

Much research has been done to control BLDC motors. In [3] the direct torque control method is used to control BLDC motor. The advantages of this approach are instantaneous torque control with reduced ripple. In [4] a method is provided to control the current benefits Fourier series coefficients. The use of this procedure is followed the torque ripple reduction. In [5] a switching strategy using PWM technique based on the control of the rotor position is used to reduce torque ripple.

Electric drives with high performance capabilities require precise and fast controllers. Control techniques of BLDC motor include classic control methods (linear and non linear controllers) and intelligent methods (fuzzy systems, etc). Linear controller (PID) due to the simplicity in design and implementation, is common in the industry [6], but because of changes in motor parameters and uncertainties not modeled and also in various operating conditions, PID controllers will not feature high performance in terms of speed and accuracy of response. Nonlinear control methods that have been used in controlling the BLDC drive have better performance than the linear controllers such as PID, but given the complexity of their theory, their implementation were not very comfortable and not common in the industry.

Intelligent control techniques of processes such as fuzzy logic control are a huge success. Especially in the experimental environment, there is a significant need to assess their performance in real-time compared to conventional control methods. Such assessments help make smart process control and provide more complex application in the real world. Conventional controllers cannot provide general solutions to the problems of control. When this process is too complex, conventional control methods cannot efficiently control. To overcome these problems, different modified types of PI and PID controllers such as adaptive PID controller and automatic adjustment are recently developed. As well as non-conventional PID controller using fuzzy logic and is designed and simulated for this purpose. Fuzzy controllers are better than classic controllers; because they can cover a wide range of operating conditions and can also work in noisy and disturbance condition.

Majority of linear and non-linear control solutions are based on accurate mathematical models during the past three decades. Most of these systems are difficult or even

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impossible to be described by old mathematical equations. Hence, the plan may not provide a satisfactory solution.

Behavior of fuzzy logic (FLC) is easily understood by a specialist as the knowledge that is expressed using the language rules. Unlike the traditional theory of linear and nonlinear control, FLC is not based on the mathematical model and is widely used to solve problems in areas with a high degree of nonlinearity.

Fuzzy logic provides a safe level of artificial intelligence for the conventional controllers. The advantages of FLC versus conventional controllers are:

- They are cheap to develop.
- They Covers a wide range of operating conditions.
- They are easily adjustable to natural language terms.
- They have self-regulation as well as non-linear and time variant adjustment.

In [7] a fuzzy logic controller is used for speed control of BLDC motor that its fuzzy rule number is 5. In [8] a fuzzy controller is also used for a BLDC motor due to weaken armature reaction in the fixed power area and to improve the motor performance. The fuzzy controller can also be used to improve the performance of PID controllers. In [9] a combination of fuzzy control and ID for speed control of BLDC motor is used. The fuzzy controller is used instead of the proportional part of the PID that the fuzzy rules have been determined according to the desired value of the system uplift response. Combined given control performance is far better than the PID controller from view of transient and steady dynamic responses and resistance to load changes. In [10] also an advanced method to improve the performance of PID controller in which the coefficients of PID controller are automatically set using fuzzy rules for different load conditions. The fuzzy control capability can be increased by adapting the control laws, in other words, control laws can be changed according to system conditions. In [11] an adaptive fuzzy controller is used in order to reduce the speed ripple due to cogging torque at low speeds and heavy loads.

In this paper, a type-2 fuzzy logic-based self-tuning PID controller is proposed in order to control the BLDC motor speed. Accurate and rapid speed routing in comparison with conventional PI controllers is one of the characteristics of this method. In the following, the equations of the dynamic motor model are described. Then, the fuzzy algorithm and proposed controller are described, and finally system model is simulated by use of the MATLAB/Simulink software and the effectiveness of the proposed controller is evaluated.

II. DYNAMIC MODEL OF BLDC MOTORS

To improve the performance of a BLDC motor controller, we need to dynamical model the motor. In BLDC motor, the back-emf voltage is trapezoidal, so the two-central theory is not powerful tool in analyzing the dynamic model of the motor. The following equation shows BLDC motor voltage equations in abc reference frame [12]:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (1)$$

where v_a, v_b and v_c are voltage are a, b and c phase voltages, respectively. Also, resistance and self and mutual inductance of a, b and c phases are all equal and respectively equal to R, L and M. i_a, i_b and i_c and also E_a, E_b and E_c indicate current and back-emf voltage of a, b and c phases, respectively. Symbol P indicates derivative operator over time ($p = d/dt$).

Since the stator windings are star and the center of the star has no other connections other than the three primary phases, as a result the following equation applies to the motor phases:

$$i_a + i_b + i_c = 0 \quad (2)$$

Motor electromagnetic torque is obtained from the following equation:

$$T_e = \frac{1}{\omega_m}[E_a i_a + E_b i_b + E_c i_c] \quad (3)$$

where T_e is the electromagnetic torque and wm is the mechanical motor speed. Fig. 1 shows the back-emf voltages and currents of three-phase BLDC motor in which back-emf induced voltage is trapezoidal. As can be seen, back-emf voltage is fixed to 120 degree in each phase. In order to have constant power output and as a result, constant torque output, current should be injected into the motor while the back-emf voltage is constant [13]. In addition, according to equation (3) and since the back-emf voltage is proportional to the velocity; the torque will be proportional to the current:

$$T_e \propto i \quad (4)$$

where i is the current injected into the motor. Thus, we can control the current to be controlled torque. BLDC motor mechanical equation like other rotary machines are as follows:

$$J\frac{d\omega_m}{dt} + B\omega_m = (T_e - T_l) \quad (5)$$

where B and J are indicative of motor inertia and friction coefficient and T_l is load torque. Equations (1) and (5) can be used for dynamic modeling of BLDC motors.

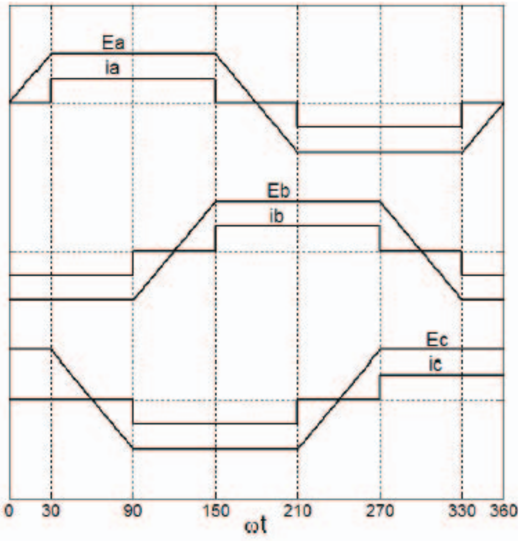

Figure 1. Phase back-emf voltage and current

III. MODELING OF BRUSHLESS DC MOTOR IN MATLAB/SIMULINK

The BLDC motor drive structure under study is shown in Fig. 2. The control unit provides switching pulses for the inverter connected to the motor. Windings are star-shaped along with an inverter feeding the BLDC motor is shown in Fig. 2. At the moment only two switches, one above and one low, are turn on and two phase of the motor are brought up to the circuit, while the third phase is off. Thus, the value of current of the active phases is equal but with opposite directions. This means that the current flows the motor through one of them and leaves the motor through the other active phase.

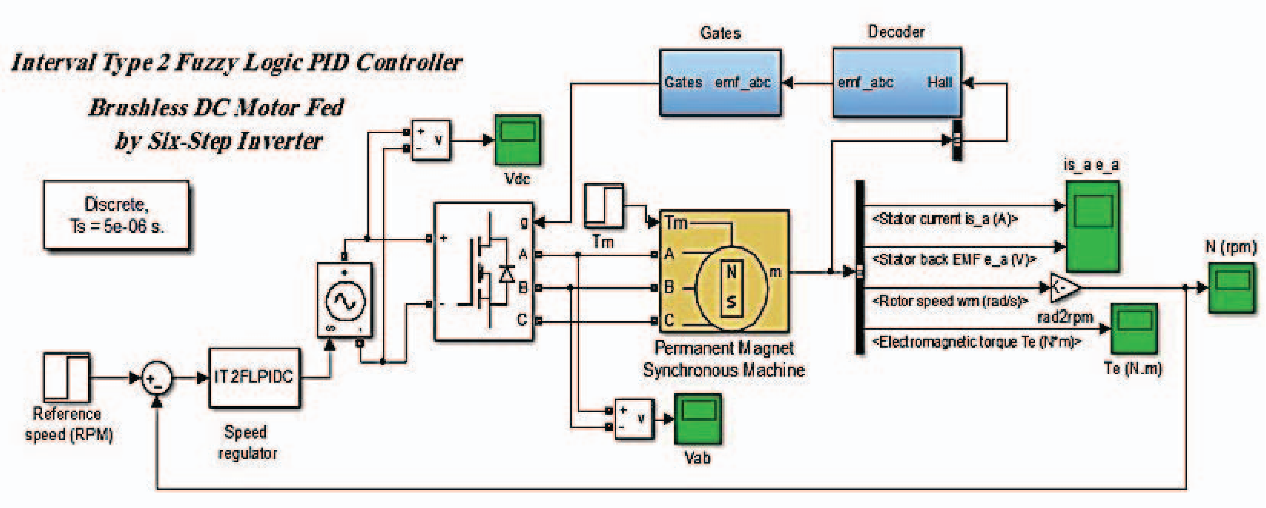

Figure 2. Simulation schematic of BLDC motor controlled by IT2FLPID Controller in SIMULINK/MATLAB

IV. STRUCTURE OF SPEED CONROL SYSTEM OF BLDC

The complete block diagram of speed control of BLDC motor is shown in Fig. 3. This control structure consists of two control loops. The inner loop synchronizes the inverter gates signals with the electromotive forces. The outer loop controls the motor's speed by varying the DC bus voltage. The inverter which is connected to the dc supply feeds controlled power to the motor. The magnitude and frequency of the inverter output voltage depends on the switching signals generated by the hysteresis controller.

V. REVIEW ON INTERVAL TYPE-2 FUZZY LOGIC SYSTEM

The concept of fuzzy sets type-2 by was bring up by "Zadeh" as an extension of typical fuzzy sets so called fuzzy systems type-1.

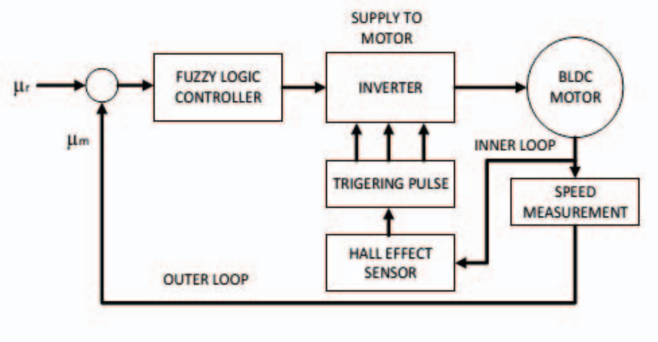

Figure 3. Block Diagram of speed control of BLDC Motor

In a type-2 fuzzy set, the degree of membership for each point is a normal fuzzy number, which can change in range

[0,1]. Such sets are suitable for cases in which their membership functions are uncertain. For example, uncertainties may be in the form of membership functions or some parameters of membership have an uncertainty, such as a Gaussian function with the uncertain mean or variance has the specified shape and uncertain parameters.

Indeed, the type-2 fuzzy systems allow us to model the effects of uncertainty in the rule-based fuzzy systems and to minimize the impact of uncertainty, but unfortunately since type-2 fuzzy sets are more complicated in the understanding and application than the type-1fuzzy sets, use of them is less spread than type-1 fuzzy sets. These complexities are achieved because of the three-dimensional nature and direct dependence of its equations to the development principle "Zadeh" and thereupon its computational complexity.

In type-1 fuzzy systems, at least there are four uncertainty origins are:

1. The meanings of words have been used in the antecedent and conclusion of the rules can be uncertain. In other words, vocabularies have different concepts for different people.

2. Conclusion sets may be a graph of the values, especially when knowledge is derived from a group of experts who all are not completely agreed.

3. The measured quantities that stimulate fuzzy system (input vector of fuzzy system) may be noisy and therefore unreliable.

4. The information and data used to set the parameters of a fuzzy system may be noisy.

All above uncertainties face us with a fuzzy system and uncertain membership functions. Type-1 fuzzy sets are not able to directly model above uncertainties; because their membership functions are completely non-fuzzy. Since type-2 fuzzy sets have fuzzy membership functions; they are able to model the above uncertainties. Therefore, the modeling of these uncertainties will also reduce their impact.

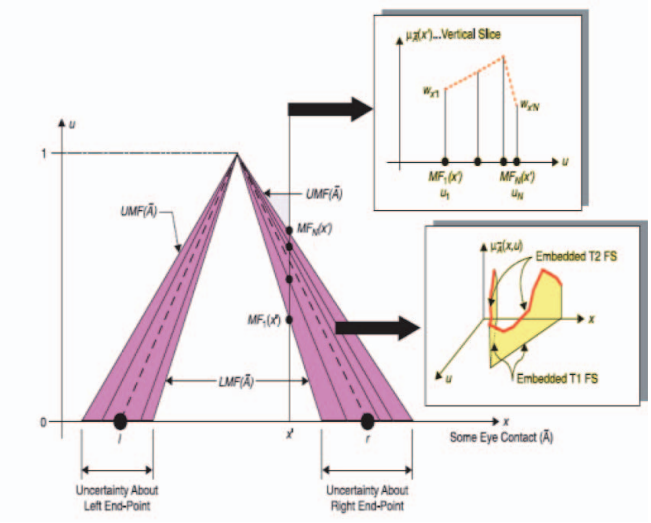

Figure 4. A type-2 fuzzy set including discrete domain, vertical cut, embedded sets

A. *Interval type-2 fuzzy logic controller*

In Fig. 5, the overall structure of a type-2 fuzzy system is shown. A type-2 fuzzy system consists of fuzzifier, rules, inference, and output processing.

In fact, a fuzzy system is a mapping between a non-fuzzy input and a non-fuzzy output. In a type-2 fuzzy system the output process includes two stages. At first, the mapping of a type-2 fuzzy set to a type-1 fuzzy set so called the type reduction or order-1 reduction. Then, the defuzzification stage of set is set to lower order. Methods of reducing the order in type-2 fuzzy systems are actually the same method developed for the defuzzification in type-1fuzzy systems. The reducing order consists of the center of gravity, the center of set and height [14]. More on the concept of type-2 fuzzy systems can be studied in [15-16].

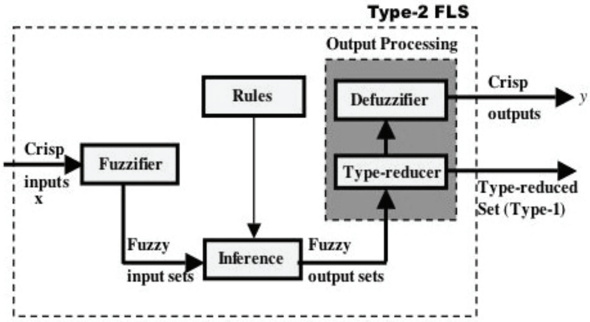

Figure 5. Interval type-2 fuzzy logic controller

VI. SELF-TUNING ADAPTIVE PID CONTROLLER

In this part, the design of two feedback controls is proposed and conventional PID and fuzzy-based self-tuning PID controllers are recommended to control the speed of a BLDC motor.

A. PID controller: proportional-integral-derivative (PID) controller is intended as standard control structures of classical control theory. Certain functions of the system are improved by the values of k_p = 16.61, k_i = 0.013and k_d = 0.01 .

B. Fuzzy-based self-tuning PID controller: this controller converts the fuzzy inference systems (FISs) to the parameters k_p, k_i and k_d in accordance with the error (e) and error derivative (δe) implemented in Fig. 6 [17].

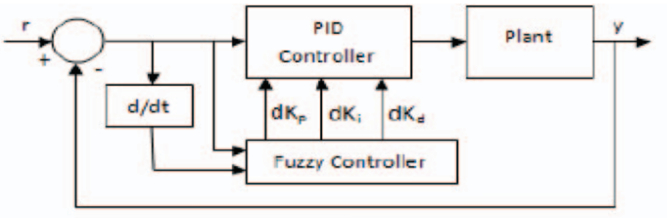

Figure 6. A structure of fuzzy-based self-tuning PID controller

In fuzzy-based self-tuning PID controller, rules based on BLDC motor characteristics and in accordance with the PID controller are designed. Parameters k_p, k_i and k_d shall be determined by fuzzy regulators. The fuzzy tuner has two inputs i.e. error (e) and error derivative (δ_e), and three output i.e. k_p, k_i and k_d.

Fig. 7 shows the proposed control structure. According to Fig. 7, the structure of the type-2 fuzzy logic-based self-tuning PID controller is used.

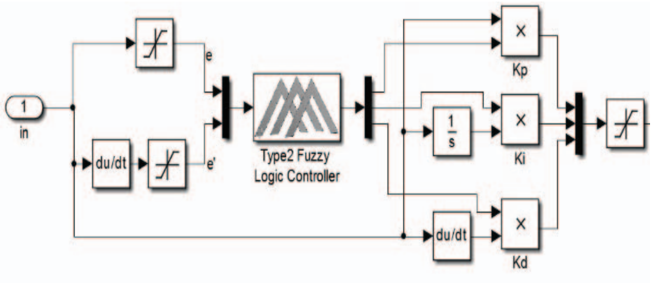

Figure 7. Structure of IT2FL PID Controller block

The gaussian membership function is used for all variables shown in Figs. 8-9. The fuzzy variables are defined for the rule base as: e, ec = {the error, the variation of error, {NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big)}, [-1,1], μ}. k_p, k_i, k_d ={the control parameters, {ZE (Zero), VS (Very Small), S (Small), M (Medium), B (Big), VB (Very Big), VVB (Very Very Big), [0,2], μ}.

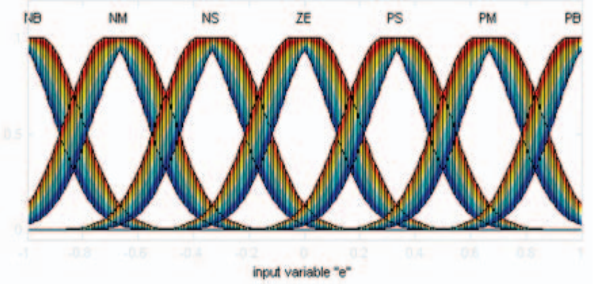

Figure 8. The membership functions for the inputs e and ec

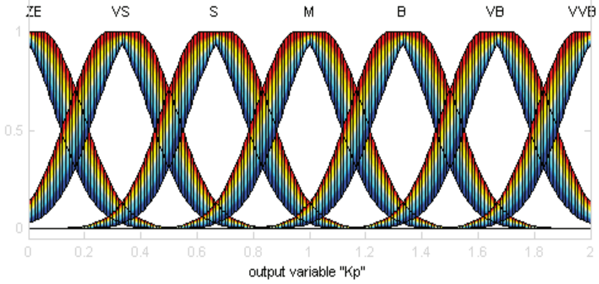

Figure 9. The membership functions for the outputs kp, ki and kd

The fuzzy inference rules between inputs (e, ec) and outputs (k_p, k_i, k_d) are summarized in Tables I, II and III.

TABLE I. THE FUZZY RULE TABLE FOR ΔKP

e	ec						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	VVB	VBB	VBB	VBB	VBB	VBB	VBB
NM	VB	B	B	B	B	B	VB
NS	M	M	VB	VB	VB	M	M
ZE	ZE	S	M	M	M	S	M
PS	M	M	VB	VB	VB	M	M
PM	VB	B	B	B	B	B	VB
PB	VVB	VBB	VBB	VBB	VBB	VBB	VBB

TABLE II. THE FUZZY RULE TABLE FOR ΔKI

e	ec						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NM	VS	ZE	ZE	ZE	ZE	ZE	VS
NS	B	M	VS	ZE	VS	M	B
ZE	VBB	B	VB	ZE	VB	B	VBB
PS	B	M	VS	ZE	VS	M	B
PM	VS	ZE	ZE	ZE	ZE	ZE	VS
PB	ZE	ZE	ZE	ZE	ZE	ZE	ZE

TABLE III. THE FUZZY RULE TABLE FORΔKD

e	ec						
	NB	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	ZE	ZE	ZE	ZE	ZE	ZE	ZE
NM	M	S	VS	VS	VS	S	M
NS	VB	M	M	M	M	M	VB
ZE	VBB	VBB	B	VB	B	VBB	VBB
PS	VB	M	M	M	M	M	VB
PM	M	S	VS	VS	VS	S	M
PB	ZE	ZE	ZE	ZE	ZE	ZE	ZE

VII. SIMULATION RESULT

The simulated results of the rotor speed control of the BLDC motor based on three controllers: conventional PID, T1FPID and IT2FLPID controllers are shown in Figs. 10-12. The speed deviation of BLDC at several speeds with the above controllers is shown in Fig. 10. The load deviation of BLDC motor and speed response of BLDC at 2000 rpm with the above controllers is also shown in Fig. 11. From simulation results it is found that the IT2FLDC has superior performance than T1FPIDC and conventional PID controller. In addition, the ability of torque control of IT2FLDC controller is shown in Fig. 12 completing its superiority in comparison to two other ones.

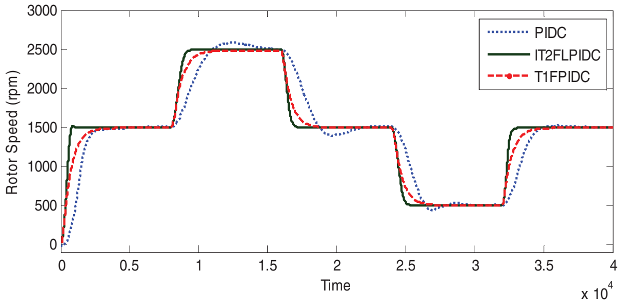

Figure 10. Speed Deviation of BLDC Motor

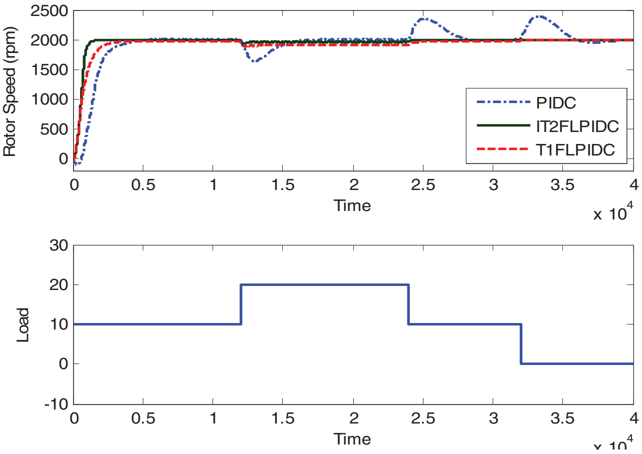

Figure 11. Load Deviation of BLDC Motor

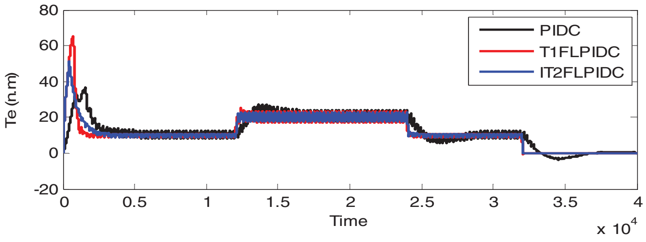

Figure 12. Torque Deviation of BLDC Motor

VIII. CONCLUSION

In this paper, the speed control of the BLDC motor is studied and simulated in MATLAB/Simulink. In order to overcome uncertainties and variant working condition, the adjustment of PID gains through fuzzy logic is proposed. In this study, three controller types are considered and compared: conventional PID, type-1 and type-2 fuzzy-based self-tuning PID controllers. The simulation results show that type-2 fuzzy PID controller has superior performance and response than two other ones.

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