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Robust IT2FL Controller Design for the Speed Control of a BLDC Motor

Hayder Yousif Abed, Abdulrahim Thiab Humod, Amjad J. Humaidi, Ayad Q. Al-Dujaili

***Abstract*: This work presents the design of intelligent controller for the speed control of a brushless DC motor under uncertainty in motor parameters. The Interval Type 2 Fuzzy Logic (IT2FL) controller has been proposed and designed to achieve the speed control specifications. A comparative study is conducted between IT2FL and PID controllers in terms of tracking performance and robustness characteristics. The effectiveness of both controller structures is verified through simulation within a MATLAB/Simulink environment. The simulated results showed that the IT2FL controller is more efficient than the PID counterpart in terms of tracking and robustness.**

Keywords: Brushless DC motor, IT2FL controller, PID controller

I. INTRODUCTION

Brushless DC (BLDC) motors can be used in several fields and many applications, such as industrial automation electric vehicles and aerospace computers. BLDC motors have some advantages over its brushed DC counterpart. BLDC motors require minimal maintenance due to the disposal of the commutator, have a long operating life because of the lack of friction and electrical loss and have high power density which translates to possible applications that require a high electromagnetic torque-to-weight ratio [1]. Compared with brushed DC motors and induction machines, BLDC motors have lower inertia, thus permitting faster dynamic response to reference commands. They also have high efficiency given their permanent magnets which perform in virtually zero rotor losses [1].

Recently, various modern control solutions are proposed for the speed control of different structures of high-performance motors [2-5]. The BLDC motor is characterized by complex and nonlinear model. As such, a nonlinear type fuzzy logic controller is used to control the speed of a BLDC motor. This intelligent controller has a simple structure and is relatively easy to utilise due to its modest fuzzy rule in rule base. Recently, the intelligent control of BLDC motors has attracted the attention of many researchers. A review of relevant works is presented as follows:

In [6], an adaptive fuzzy PID control was proposed. Fuzzy and PID controllers were combined in accordance with the parameters to enhance control precision. Simulated results confirmed that the adaptive fuzzy PID controller could improve tracking and steady-state performance.

In [7], a fuzzy PID controller is proposed for the speed control of a BLDC motor. The effectiveness of the fuzzy PID and a conventional controller was verified and compared using simulation and experimental results. In [8], a fuzzy-optimised PID controller was designed for a BLDC motor. In this work, the task of a fuzzy logic system was to perform online tuning or adjustment of PID controller terms. The experimental and simulation results showed that the fuzzy based PID controller has better static and dynamic performance compared with the traditional PID controller.

The work presented in [9] designed optimal FL and PID controllers for BLDC motor control. The effectiveness of both controllers was assessed via computer simulation within the MATLAB/Toolbox environment. The FL and PID control-based BLDC motor was implemented in real time, and the experimental results were compared with that of the simulation. In [10], a hybrid neurofuzzy controller was proposed to improve the transient and steady-state characteristics of a speed-controlled BLDC motor. In this control strategy, an integral term was added to modify the control law in an adaptive manner and eliminate the steady-state error. The effectiveness of the suggested controller was verified experimentally to show the improved performance in terms of tracking and steady-state characteristics.

In [11], a novel fuzzy single PID (FSNPID) controller has been designed for the BLDC motor. The genetic algorithm was used to optimise the parameters of a single neuron PID (SNPID) controller, whereas a fuzzy control design was applied for the online update of the SNPID weights. The performance of the proposed FSNPID, conventional FSNPID and SNPID was compared.

II. DYNAMIC MODEL OF BLDC MOTOR

A BLDC motor is a three-phase, star-connected, four-pole, trapezoidal back-EMF type with a three-phase inverter. Fig. 1 shows a basic block diagram of the speed control for a BLDC motor.

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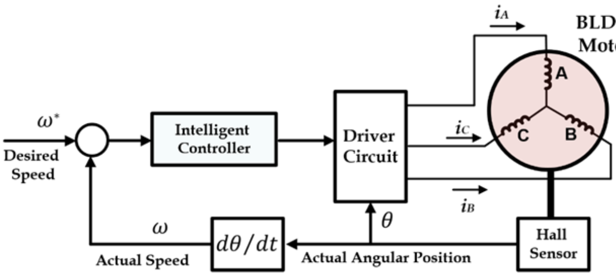

Fig. 1. Basic block diagram of the sensor less drive of a BLDC motor

The voltage equations of the BLDC motor can be described by the following set of equations [12]:

$$v_a = R_{as}i_a + L_{aa}\frac{d}{dt}(i_a) + L_{ab}\frac{d}{dt}(i_b) + L_{ac}\frac{d}{dt}(i_c) + e_{as} \quad (1)$$

$$v_b = R_{bs}i_b + L_{ba}\frac{d}{dt}(i_a) + L_{bb}\frac{d}{dt}(i_b) + L_{bc}\frac{d}{dt}(i_c) + e_{bs} \quad (2)$$

$$v_c = R_{cs}i_b + L_{ca}\frac{d}{dt}(i_a) + L_{cb}\frac{d}{dt}(i_b) + L_{cc}\frac{d}{dt}(i_c) + e_{bs} \quad (3)$$

where v_a, v_b and v_c are the stator phase voltages; R_a, R_b and R_c are the phase resistances of the stator; i_a, i_b and i_c are the currents of the stator phases; L_{aa}, L_{bb} and L_{cc} are the self-inductances of the stator windings; L_{ab}, L_{bc}, L_{ba}, L_{ac}, L_{ca} and L_{ca} are the mutual inductances amongst the stator windings; E_a, E_b and E_c are the back electromotive forces (emf) of the three phase stator.

The following equation can be obtained given the symmetric structure of the three-stator winding and the equal resistances of the stator windings:

$$L_{aa} = L_{bb} = L_{cc} = L \quad (4)$$

$$L_{ac} = L_{ab} = L_{ba} = L_{bc} = L_{ca} = L_{cb} = M \quad (5)$$

where L and M are the self- and mutual inductances, which are independent of the rotor position, of the stator. For the three-phase star winding motor, the following expression applies:

$$i_a + i_b + i_c = 0 \quad (6)$$

$$Mi_a + Mi_b + Mi_c = 0 \quad (7)$$

The instantaneous induced emfs can be described by

$$e_{ats} = f_{as}(\theta_r)\,\lambda_p\,\omega_m \quad (8)$$

$$e_{bts} = f_{bs}(\theta_r)\,\lambda_p\,\omega_m \quad (9)$$

$$e_{bts} = f_{bs}(\theta_r)\,\lambda_p\,\omega_m \quad (10)$$

where ω_m is the rotor angular speed, and θ_r is the rotor position.

The complete model of the BLDC motor can be written in matrix form using equations. (1), (2) and (3) [12].

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{pmatrix}\frac{d}{dt}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{pmatrix} \quad (11)$$

In consideration of a balanced three-phase motor, all phase resistances were equal and can be designated by (R). Therefore, equation (11) can be written as follows:

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{pmatrix}\frac{d}{dt}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad (12)$$

where the functions $f_{as}(\theta_r)$, $f_{bs}(\theta_r)$ and $f_{cs}(\theta_r)$ have the same shape as e_{ats} , e_{bts} and e_{cts} with ±1 maximum magnitude. Moreover, the induced emfs have rounded edges instead of sharp corners as found in trapezoidal functions, a feature resulting from the time derivative of flux linkages. The flux linkages are fringing and continuous functions, thereby making the flux density functions smooth without sudden edges. The expression of electromagnetic torque can be written as:

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega \quad (13)$$

$$E_p = \lambda_p \omega_m \quad (14)$$

The developed torque is used to overcome the mechanical rotation and load torque as given by:

$$T_e = J\frac{d\omega}{dt} + B_f\,\omega_m + T_L \quad (15)$$

III. TYPE-2 FUZZY LOGIC CONTROLLER

The interval type 2 fuzzy logic controller (IT2FLC) consists of a set of membership functions (MFs) that work with three-dimensional uncertainties. Conversely, the MFs of type 1 fuzzy sets operate with two dimensions. The fuzzy sets of MFs are shown in Fig. 2. These sets can model and handle uncertainties, nonlinearities and linguistic variables related to the fuzzy logic controller (FLC) input and output by modelling them and reducing their effectiveness. Type 1 fuzzy logic controller (T1FLC) fuzzy sets supplement classical fuzzy sets, thus clearly showing preferences of the IT2FLC [13].

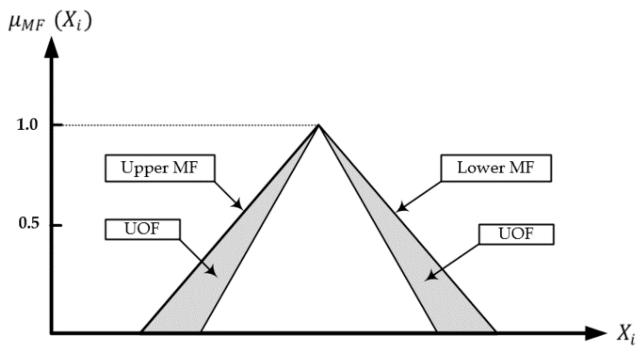

Fig. 2. Interval fuzzy type 2 membership function structure

The mathematical equation of a system is the most important requirement for designing traditional control systems. Two types of equations describe the system dynamics: the differential equations associated with continuous time systems and the difference equations associated with discrete time systems. Developing a model for a physical system is difficult due to complexity and nonlinearity. A traditional controller design is complicated due to the high complexity of the derived model.

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As a result, achieving the required dynamics of the system necessitates certain assumptions (e.g. system linearity).
Many advantages of the T2FLC logic controllers over those of the T1FLC are found in the literature, including the following [14]–[17]:

- T2FLCs have a wide range of operation, and they are more robust than T1FLCs. Another advantage is the resistance of the former to noise and the plant load changes.
- The footprint of uncertainty (FOU) of the T2FLC can handle and model numerical uncertainties, nonlinearities and linguistic variables that accompany the input and output of the universe of discourse (UOD) for an FLC.
- The uncertainty of type 2 fuzzy sets can take the same UOD as the type 1 fuzzy sets but with fewer labels.

The mathematical concepts of the T2FLC are described in accordance with the following definitions [14]:
Definition 1. If $\tilde{A}$ denotes type 2 fuzzy sets which are characterised by MF $u_{\tilde{A}}(x.u)$, where $x \subset X$, X is the universe of discourse (UOD), and $u \in J_x \subseteq [0.1]$, then
$\tilde{A} = \{((x.u).\mu_{\tilde{A}}(x.u))| x \in X . u \in J_x \subseteq [0.1]\}$,
where $0 \leq u_{\tilde{A}}(x.u) \leq 1$. This equation can be expressed as

$$\tilde{A} = \int_{x \in X} \int_{u \in J_x} \frac{\mu_{\tilde{A}}(x.u)}{(x.u)} J_x \subseteq [0.1] \quad (17)$$

where $\int \int$ represents the union over all admissible u and x.
Definition 2. A two-dimensional system whose axes are u and $u_{\tilde{A}}(x.u)$ is known as the vertical slice of $u_{\tilde{A}}(x.u)$ as represented by
$\mu_{\tilde{A}}(x = x_1.u) = \mu_{\tilde{A}} = \int_{u \in J_x} \frac{\mu_{\tilde{A}}(x.u)}{(x.u)} J_{x1} \subseteq [0.1]$,
where $0 \leq f_{x1}(u) \leq 1$; and $\mu_{\tilde{A}}(x)$ are defined as the secondary MF and secondary set, respectively. The primary MF of x_1 is designated by J_{x1} and is the domain of the secondary membership, where $J_{x1} \subseteq [0.1]$ for all x_1 in X.
Definition 3. The amplitude of the secondary MF is defined as the second degree or the secondary grade.
Definition 4. The bounded area of the uncertainty for the type 2 fuzzy set $\tilde{A}$ is called the FOU. It defines the union of all primary MFs and can be described by:
$FOU(\tilde{A}) = U_{x \in X} J_x$
Definition 5. The upper and lower MFs of $\tilde{A}$ are two type 1 fuzzy sets, where the boundaries of $FOU(\tilde{A})$ for type 2 fuzzy sets $\tilde{A}$ are the lower and upper bounds of the type 1 fuzzy sets. The lower MF is described by $\underline{\tilde{\mu}}_{\tilde{A}}(x)\ x \in X$, whereas the upper MF is defined by $\overline{\tilde{\mu}}_{\tilde{A}}(x)\ x \in X$, which means
$\overline{\tilde{\mu}}_{\tilde{A}}(x) = \overline{FOU(\tilde{A})}$
$\underline{\tilde{\mu}}_{\tilde{A}}(x) = \underline{FOU(\tilde{A})}$

As the domain of the secondary MFs have been limited within the range [0, 1], the lower and upper MFs often exist. The structure of the interval type 2 fuzzy logic membership of the MFs with secondary MFs are shown in Fig. 3.

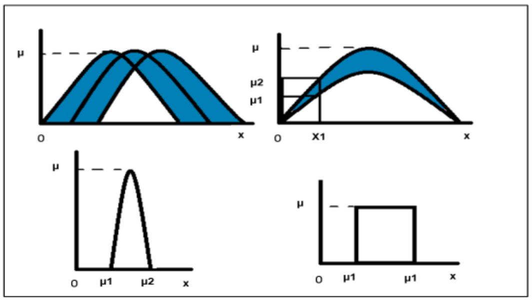

Fig. 3. Interval fuzzy type 2 MF structure with its secondary MFs

IV. SIMULATION RESULTS

The effectiveness of the PID controller and T2FLC for the speed control of a BLDC motor was verified through simulation within a MATLAB/Simulink environment. The Simulink modelling of the PID-based speed control is shown in Fig. 4. The BLDC motor parameters used throughout the simulation are listed in Table 1.

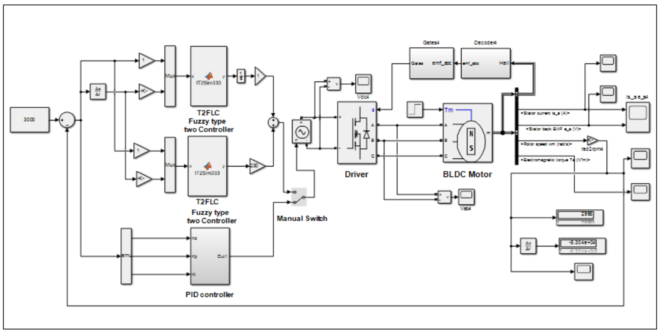

Fig. 4. BLDC motor with PID controller

Fig. 5 shows the speed profile of a BLDC motor based on the PID and IT2FL controllers. In this figure, the IT2FL controller achieved better dynamic performance than the PID controller. Fig. 6 depicts the behaviour of currents generated by both controllers. The current due to the IT2FL controller had less excursion levels compared with that generated by the PID controller.

Table- I: Parameters of the BLDC motor

Motor Parameters	Values
Number of poles	8
Number of phases	3
Stator Resistance	0.7 Ω
Stator Inductance	0.5×10^{-3} H
Rated power of motor	92 Watt
Rated speed of motor	3000 RPM
Rated torque of motor	0.22 N.m
Rotor inertia of motor	0.0075 $\times 10^{-3}$ Kg.m^2

Fig. 7 illustrates the behaviour of the developed torque for the PID and IT2FL controllers. In this figure, the torque generated by the IT2FL controller was less than that developed by the PID controller in the steady state. Thus, the power absorbed by the IT2FL controller was less than that using the PID controller.

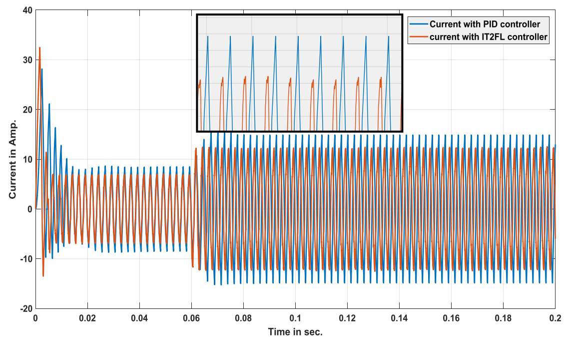

Fig. 5. Phase A current from using the PID and IT2FL controllers.

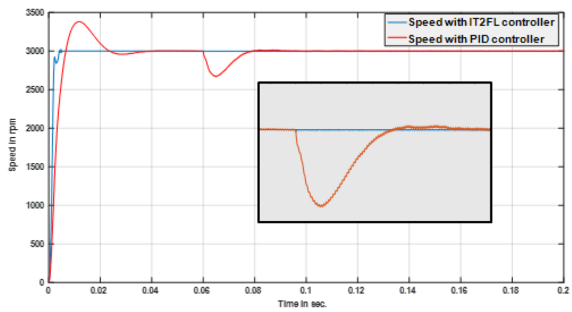

Fig. 6. Motor speed from using the PID and IT2FL controllers

The disturbance rejection capability was examined by exerting a load change of height of 0.2 N.m within a period of 0.06–0.08 s, as shown in Fig. 8. The response due to the ITFL controller under load application indicated no change, whereas a maximum dip of value of 310 rpm was observed at the speed response using the PID controller under this load change. Therefore, the IT2FL controller demonstrated better disturbance rejection capability compared with the PID controller.

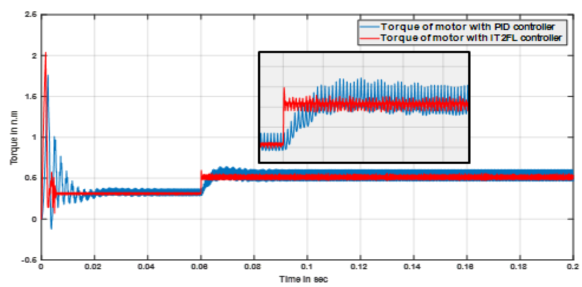

Fig. 7. Electrical torques of the motor from using the PID and
IT2FL controllers.

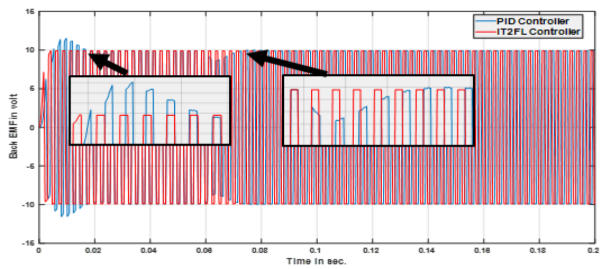

Fig. 8 Back EMF of the motor based on PID controller and IT2FL controller

The robustness characteristics were verified by changing the value of the armature resistance in discrete form within a range of 0.7–0.63 Ω. Fig. 9 and 10 show the group of speed responses due to the discrete variation of stator resistance using the PID and IT2FL controllers, respectively. Compared with the PID controller, the IT2FL controller could keep the change of the speed profile under a parameter variation within a low range. Robustness can be numerically evaluated by calculating the variance between the maximum deviation of speed and the normal speed. The numerical evaluation of the transient parameters for both controllers are listed in Table 2. The dynamic performance of the IT2FL controller was better than that of the PID controller as illustrates in Table 2. Table (3) presents the numerical assessment and comparison of both controllers in terms of robustness. The IT2FL controller was more efficient than the PID controller in terms of robustness characteristics under parameter uncertainty (see Table 3).

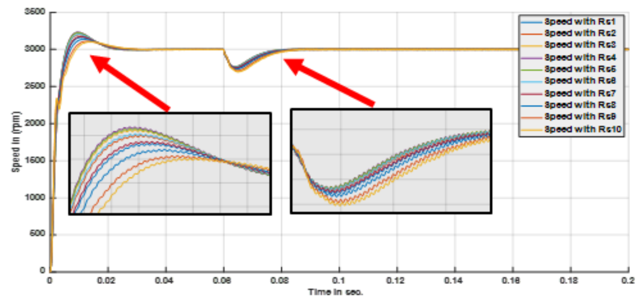

Fig. 9. Speed response of the BLDC motor using a PID controller under parameter uncertainty.

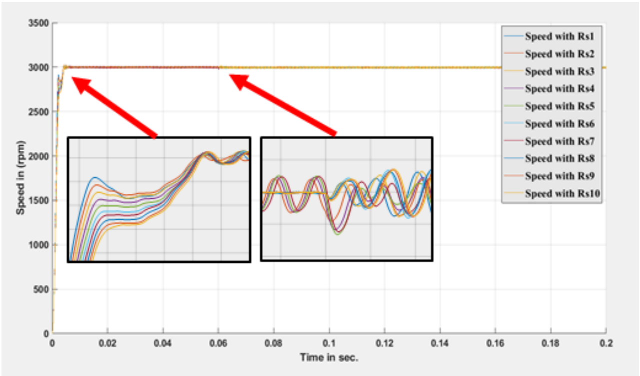

Fig. 10. Speed response of the BLDC motor using an IT2FL controller under parameter uncertainty.

Table- II: Performance comparison between IT2FL and PID controllers

Transient Characteristics	**Types of Controllers**	
	PID Controller	**IT2FL Controller**
Rising Time (T_r) Sec	3.34×10^{-3}	3.12×10^{-3}
Maximum Overshoot (M_p) rpm	277	23
Steady-state error (E_{ss}) rad/sec.	4.3797	1.6193
Settling Time (T_s) Sec.	12.9×10^{-3}	3.2×10^{-3}

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Table- III: Numerical evaluation of robustness for PID and IT2FL controllers

	Types of Controllers	
	PID Controller	IT2FL Controller
Percentage of variances	2.9 %	2.1 %

V. CONCLUSION

This work presents design of IT2FL controller for speed control of BLDC motor in the presence of uncertainty in motor parameters. A performance comparison between IT2FL and PID controllers has been made in terms of tracking and robustness. The effectiveness of the conventional and intelligent controllers was verified within the MATLAB/Simulink software format. The simulated results confirmed that the IT2FL controller outperforms the performance of PID controller in terms of load rejection capability, robustness characteristics and dynamic performance.

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