

# Adaptive Speed Control System Based on Interval Type-2 Fuzzy Logic

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## ABSTRACT

This paper presents the design and simulation of adaptive control system based on an Interval Type-2 Fuzzy Logic Controller (IT2FLC) with multilevel inverter (MLI) for control of power system, and the command line programming for constructing, editing, and simulating the IT2FLC. The modification was done by considering new membership functions (MFs) for the environment of an Interval Type-2 Fuzzy Logic System (ITFLS). Two other controllers besides the designed IT2FLC, comparing their outputs: a PID Controller and a Type-1 Fuzzy Logic Controller (T1FLC). Various design phases for the fuzzy system, from initial description to final implementation. In this work, the case study is consider for brushless DC (BLDC) motor that is driven by multilevel inverter based on discrete three-phase pulse width modulation (DPWM) generator that forced-commuted the IGBT's three-level converters using three bridges to vectored outputs 12- pulses with three levels. Using DPWM with a three-level inverter solves the problem of harmonic distortions and low electromagnetic interference. The final design system was capable to solve the overshoot problem of BLDC motors and responded better in transient and steady states and was more reliability.

**Keywords:** Interval Type-2 Fuzzy Logic Controller (IT2FLC), discrete pulse width modulation (DPWM), brushless DC (BLDC) motor.

## 1 Introduction

Brushless DC (BLDC) motor is a permanent-magnet synchronous machine with a six-transistor inverter whose on/off switching is determined by the motor's rotor position. It has neither brush nor commutator. With no possible brush/commutation failure, its torque-speed characteristic is similar to that of a permanent-magnet conventional DC motor. The BLDC motor is becoming more popular in high-performance, variable-speed drives; it needs relatively little maintenance and has low inertia, large power-to-volume ratio, is friction-less, and has less noise than does a conventional permanent-magnet DC servo motor of the same output rating. The advantages, however, are costly, and the controller of a BLDC motor is more complex than that of a conventional motor. Also, to satisfactorily operate a BLDC motor, good armature current response is necessary [1-4].

BLDC motors have higher power density than do other motors (e.g., induction motors) because there is no rotor copper loss and no commutation. Their structure is compact and robust. These contribute to their popularity in efficiency-critical applications or where commutation-induced spikes are unwelcome. Commutation necessitates the use of an inverter and a rotor position sensor, which however, can increase drive cost and machine size and reduce reliability and noise immunity [5-8].

Existing current-control techniques include vector control, predictive control, dead-beat control, and direct torque control; each with advantages and limits. Classical controllers are subject to variation in electrical machine parameters such as armature resistance. Intelligent fuzzy logic (FL) has been used often in controller design. The advantage of fuzzy control methods is their non-requirement for precision, unattainable in a dynamic model [9-12].

The control aim of BLDC motors (which have uncertain parameters that affect performance) is to force speed and/or current into following the reference trajectories. The problem can be alleviated through a Proportional Integral (PI) controller, which is simple to implement and common in BLDC motor control. Robust PID/PI controllers for minimum overshoot response of BLDC drives have been introduced into various applications [13-15].

This paper presents the design of Interval Fuzzy Type-2 (IT2FLC). The IT2FLC aims to solve the main problem of overshoot in BLDC motor through quick achievement of the rated speed without any overshoot, and for the motor to respond the same as first-order system response. Section 2 describes the mathematical model of the BLDC motor and its conventional controller problem. Section 3 presents the modelling of a control design that uses the IT2FLC scheme. Section 4 presents a block diagram of the design of the control system and the simulation results. Section 6 offers conclusions.

## 2 Mathematical Model of BLDC Motor

A BLDC motor is a rotating electric machine with a classic 3-phase stator similar to that of an induction motor. Its rotor mounts permanent magnets (see Figure 1). The magnet rotates, whereas the conductors are stationary. This motor equals a reverse-DC commutator motor. DC commutator motors have their current polarity altered by commutator and brushes, whereas BLDC motors do so through power transistors that switches synchronously with rotor position. Often, BLDC motors must therefore incorporate either internal or external position sensors that discern the actual rotor position, or use sensor-less detection [16-18].

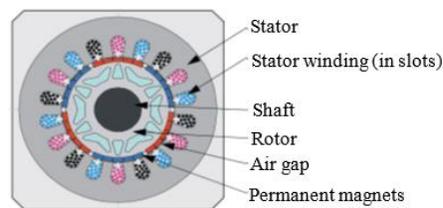


Figure 1: BLDC Motor, cross-sectioned [17]

Figure 2 is a block diagram of a BLDC motor drive. Assuming equal stator resistances of all of the windings and constant self-inductance and mutual inductance, the voltage equation of the three phases can be expressed as in Equation (1) [18], neglecting the magnets, the high-resistivity stainless-steel retaining sleeves, and the rotor-induced currents, and not modelling the damper windings [19-21].

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} + \begin{bmatrix} L_s - M & 0 & 0 \\ 0 & L_s - M & 0 \\ 0 & 0 & L_s - M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

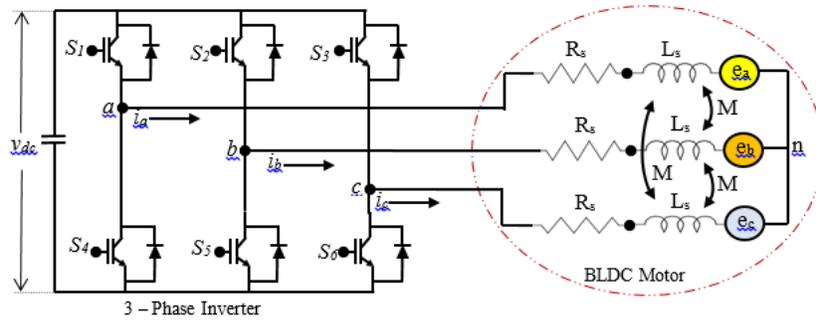


Figure 2: BLDC motor drive [20]

Here  $v_a$ ,  $v_b$ , and  $v_c$  denote the phase voltages,  $R_s$  the stator resistance,  $i_a$ ,  $i_b$ , and  $i_c$  the phase currents,  $L_s$  the stator inductance,  $M$  the mutual inductance, and  $L=L_s-M$ . The back-EMFs of the phase are  $e_a$ ,  $e_b$ , and  $e_c$ . The mechanical angular velocity is  $\omega_m$ . Figure 3 shows that injecting a square-wave phase current into the part that has the magnitude of the back-EMFs fixed will reduce the torque ripple and stabilise control. The work presented in this paper substituted an MIFT2 controller for the current and speed controllers of a BLDC motor to obtain the deadbeat response desired in high-performance applications.

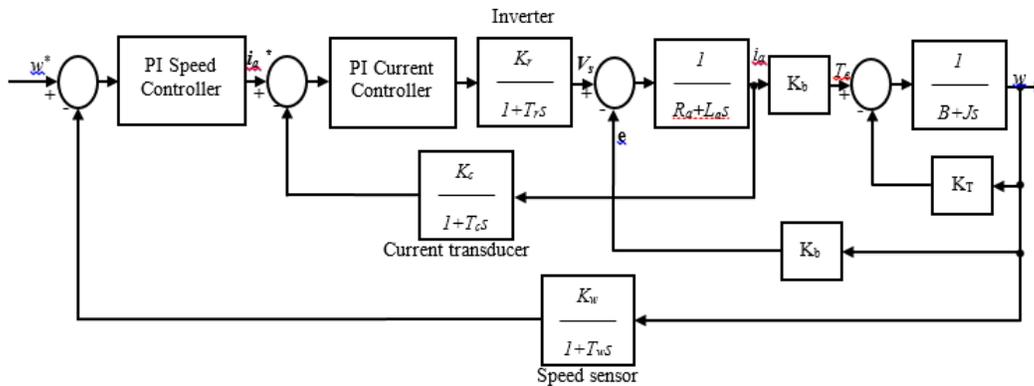


Figure 3: classical controller diagram for BLDC motor [23]

The plant transfer function varies with the operating conditions. In all the old techniques, maintaining the desired performance requires appropriate changes to the controller parameters. Figure 3 is the block diagram of a BLDC motor drive system with a conventional controller. The system uses two controllers: one in the inner loop (for current control), another in the outer loop (for speed control). Both controllers are replaced by one intelligent controller that does not require tuning - which increases response accuracy and overcomes the problem of in-operation-tuning of the controller parameters [22-27].

### 3 Modelling and Design Of IT2FLC System

Figure 5 shows the structure of IT2 direct reasoning with IT2 fuzzy inputs. An Fuzzy Inference System (FIS) is a rule-based system that uses FL instead of Boolean logic. Its basic structure has four components (see Figure 4) [28-30].

Characterising a T-2 fuzzy set is not as easy as characterising a T-1 fuzzy set. A T-2 fuzzy set, denoted by  $\tilde{A}$ , is characterised by a T-2 MF  $\mu_{\tilde{A}}(s, u)$  where  $x \in X$  and  $u \in J_x \subseteq [0,1]$ , i.e.,:

$$A^- = \{((x,u), \mu_{A^-}(x,u)) \mid \forall u \in J_x \subseteq [0,1]\} \quad (2)$$

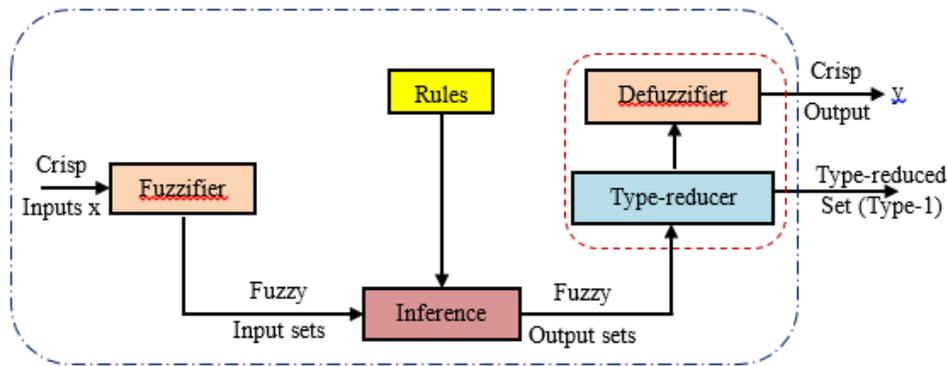


Figure 4: Structure of IT-2 FIS

The domain of a secondary MF is called the primary membership of  $x$ , where  $J_x \subseteq [0,1] \forall u \in X$ . If  $X$  and  $J_x$  are both discrete, then Equation (3) can be expressed as

$$A^- = \left. \begin{aligned} & \sum_{x \in X} \frac{\left[ \sum_{u \in J_x} f_x(u)/u \right]}{x} = \sum_{i=1}^N \frac{\left[ \sum_{u \in J_{x_i}} f_{x_i}(u)/u \right]}{x_i} \\ & = \frac{\left[ \sum_{k=1}^{M_1} f_{x_1}(u_{1k})/u_{1k} \right]}{x_1} + \dots + \frac{\left[ \sum_{k=1}^{M_N} f_{x_N}(u_{Nk})/u_{Nk} \right]}{x_N} \end{aligned} \right\} \quad (3)$$

Uncertainty  $A^-$  in the primary memberships of a T-2 fuzzy set consists of a bounded region (FOU):

$$FOU(A^-) = \bigcup_{x \in X} J_x \quad (4)$$

The concept of FOU, associated with the concepts of lower and upper MFs, allows easy characterising of T-2 fuzzy sets. FOU models uncertainties in the shape and position of a T-1 fuzzy set. T-2 Gaussian MF is obtained by blurring a T-1 Gaussian MF with mean  $m_k$  and standard deviation  $\sigma_k$ . Consider the case of a Gaussian primary MF with a fixed mean  $m_k$  and an uncertain standard deviation that takes on values in  $[\sigma_{k1}, \sigma_{k2}]$ , i.e.,

$$\mu_A(x) = \exp \left[ -\frac{1}{2} \left( \frac{x - m_k}{\sigma_k} \right)^2 \right]; \quad \sigma_k \in [\sigma_{k1}, \sigma_{k2}] \quad (5)$$

Different membership curves for each of the two  $\sigma_k$  ( $\sigma_{k1}, \sigma_{k2}$ ) values can be calculated. The uniform shading for the FOU again denotes interval sets for secondary MFs and represents the entire T-2 fuzzy set  $\mu_A(x, u)$  interval. The FOU can be described in terms of upper and lower MFs. The modified MFs are bounds for the FOU of an IT2 fuzzy set  $A^-$ . The upper MF is associated with the upper bound of the FOU ( $A^-$ ) and is denoted  $\overline{\mu_{A^-}}(x), \forall x \in X$ .

$$\overline{\mu_{A^-}}(x) \equiv \overline{FOU(A^-)} \quad \forall x \in X \quad \text{and} \quad \underline{\mu_{A^-}}(x) \equiv \underline{FOU(A^-)} \quad \forall x \in X \quad (6)$$

Because the domain of a secondary MF has been constrained in (1.0) to be contained in [0, 1], the lower and the upper MFs always exist. Note that  $J_x$  is an interval set:

$$J_x = \{(x, u) : u \in [\underline{\mu}_{A^-}(x), \overline{\mu}_{A^-}(x)]\} \tag{7}$$

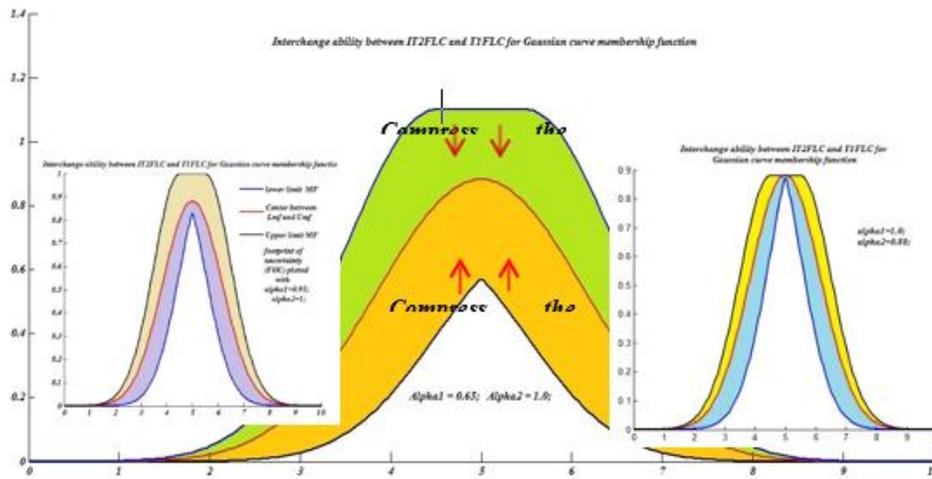


Figure 5: modified MF that used with IT2FLC

This work used as a tuning start point the embedded IT2-FIS located in the middle of each FOU. Once the MIT2-FSs had been converted to IT2-FIS, the MF parameters were tuned in Matlab, to calculate and plot the upper and the lower limits of the change. Figure 5 presents the limits of the modified MF that used with IT2FLC in this work (see Figure 5).

Unlike conventional control, which is based on a plant’s mathematical model, FLC usually embeds the intuition and experience of a human operator and sometimes those of designers and researchers. When controlling a plant, a skilled human operator’s aim is to manipulate the process input (i.e., controller output) based on  $e$  and  $\Delta e$ , as fast as possible and with the least error. The variable of a fuzzy controller is  $u(t)$ . The MFs of the input and output variables must be considered once the fuzzy controller inputs and outputs are chosen. This paper defines all MFs for conventional fuzzy controller inputs ( $e$  and  $\Delta e$ ), and the controller output, on a common normalised domain [-1, 1]. Symmetric triangles (except the two MFs at the extreme ends) were used, with an equal base and 50% overlap with the neighbouring MFs. This choice is the most natural and unbiased for MFs. Figure 6 shows the seven MFs: MN (Most Negative), NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero Error), PS (Positive Small), MP (Most Positive), PM (Positive Medium), and PB (Positive Big).

The rule base was designed next. If the inputs had 9 MFs, the corresponding rules are  $9^2=81$ . The MF was calculated and plotted for two types of fuzzy controller (type-1, interval type-2). The area under the curve of the IT2FLC MF was wide during transient period but narrow at the envelope end - the modification eliminated the overshoot from the speed response (which also became more stable at steady state).

For T-1 fuzzy controller input voltage, the control law is:

$$u = \frac{\sum_{j=1}^M f_j u_j}{\sum_{j=1}^M f_j}; \tag{8}$$

where:  $f_j(x) = \mu_{A_{j1}}(x_1) * \dots * \mu_{A_{jn}}(x_n)$

For T2-FLC input voltage,

$$U(F_1, \dots, F_M) = \int_{f_1} \dots \int_{f_M} \tau_{j=1}^M \mu_{F_j}(f_j) \left/ \frac{\sum_{j=1}^M f_j u_j}{\sum_{j=1}^M f_j} \right.; \tag{9}$$

For traditional IT2-FLC input voltage,

$$U(F_1, \dots, F_M) = \int_{f^1 \in [f^1, \bar{f}^1]} \dots \int_{f^M \in [f^M, \bar{f}^M]} 1 \left/ \frac{\sum_{j=1}^M f_j u_j}{\sum_{j=1}^M f_j} \right.; \tag{10}$$

And for IT2-FLC, according to the modified MF:

$$U(F_1, \dots, F_M) = \int_{f^1 \in [f^1, \bar{f}^1]} \dots \int_{f^M \in [f^M, \bar{f}^M]} 1 \left/ \frac{\sum_{x=1}^M f_x J_x}{\sum_{x=1}^M f_x} \right.; \tag{11}$$

where:  $J_x = \{(x, u) : u \in [\mu_{A^-}(x), \mu_{A^+}(x)]\}$

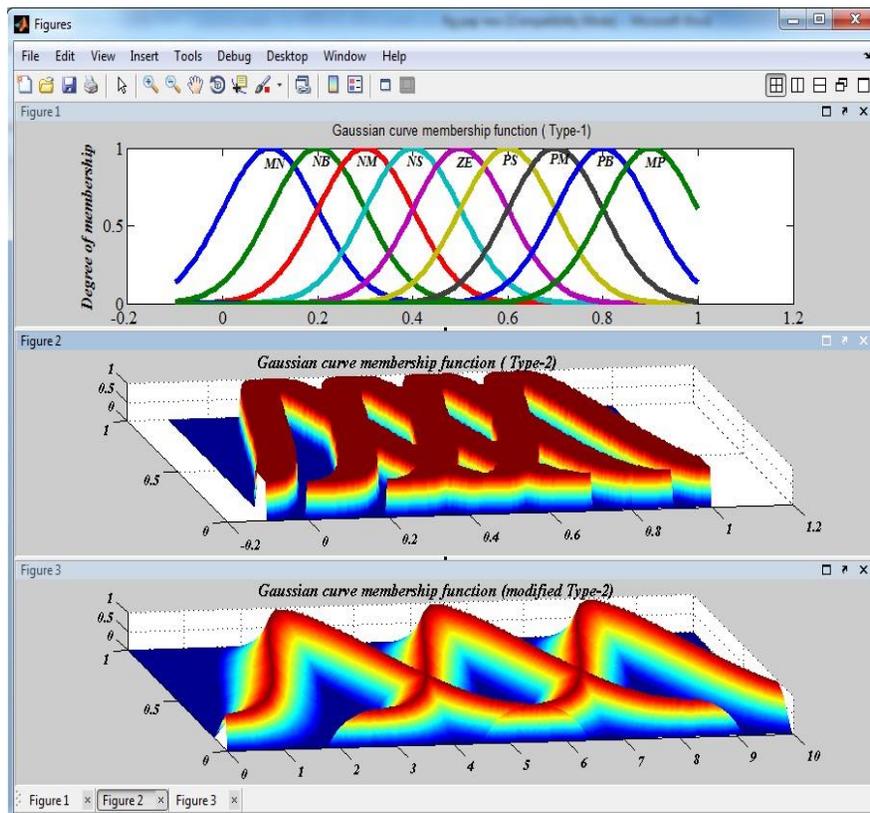


Figure 6: Gaussian curve MFs of various fuzzy controller types

## 4 Design Simulation and Analysis

The simulation of the system design was done by using Matlab / Simulink Ver. 2013a, this simulation starts with described and simulation for the three-phase multilevel inverter (MLI) that is fed to the BLDC motor is shown in Figure 7. This model represents modeling a 50 kW, 380 V, 50 Hz, three-phase, three-level inverter. The IGBT inverter uses the discrete three-phase pulse width modulation (DPWM) technique (8 kHz carrier frequency) to convert DC power from a  $\pm V_{dc}$  source to V AC, 50 Hz. The inverter feeds a 50 kW resistive load through a three-phase transformer. L-C filters are used at the converter output to filter out harmonic frequencies generated mainly around multiples of 8 kHz switching frequency. The 12-inverter pulses required by the inverter are generated by the discrete three-phase PWM generator. The system operates in open loop at a constant modulation index. The inverter is built with individual IGBTs and diodes.

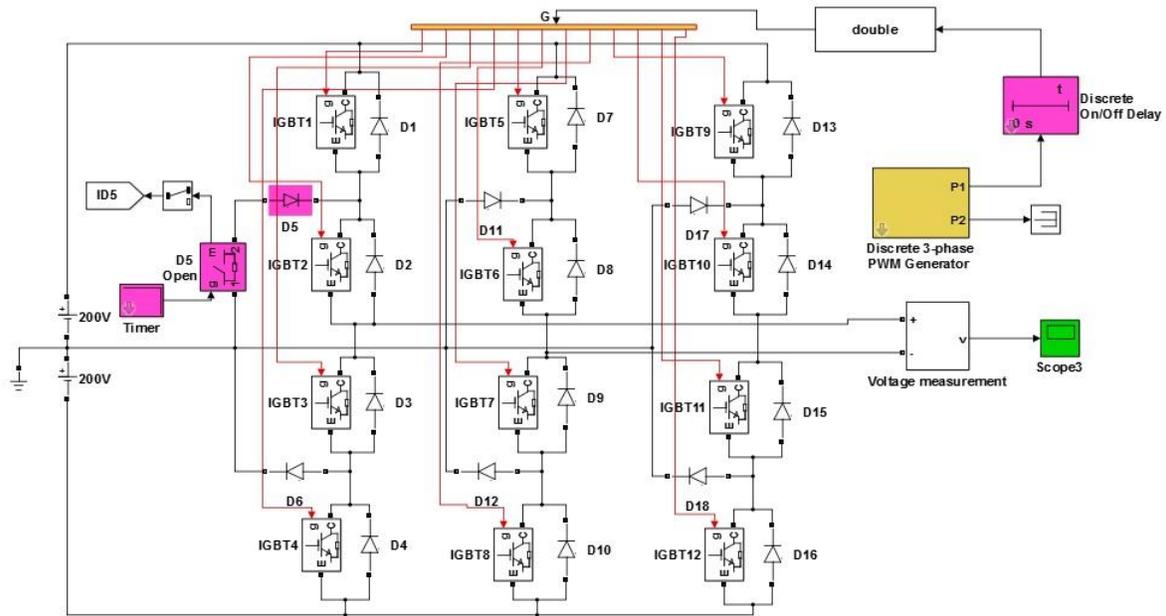


Figure 7: Three-phase three-level inverter with DPWM

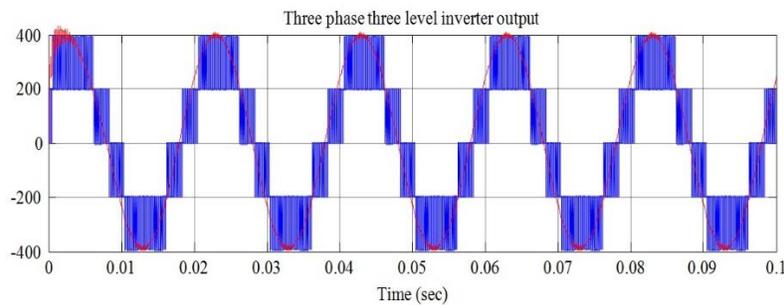
In a three-level voltage-sourced converter (VSC) using ideal switches, the two pairs of pulses sent to each arm could be complementary. For example, for phase A, IGBT1 is complementary of IGBT3 and IGBT2 is complementary of IGBT4. However, in practical VSCs, the turnoff of semiconductor switches is delayed because of the storage effect. Therefore, a time delay of a few microseconds (storage time + safety margin) is required to allow complete extinction of the IGBT that is switched off before switching on the other IGBT.

The proposed model of multilevel technique synthesizes the AC output terminal voltage with low harmonic distortion, thus reducing the filter requirements. In particular, MLIs are emerging as a visible alternative for high-power, medium-voltage applications. One of the significant advantages of multilevel configuration is the harmonic reduction in the output waveform without increasing the switching frequency or decreasing the inverter power output. In this simulation used same numerical values for system design to make compression, table 1 presents the numerical values.

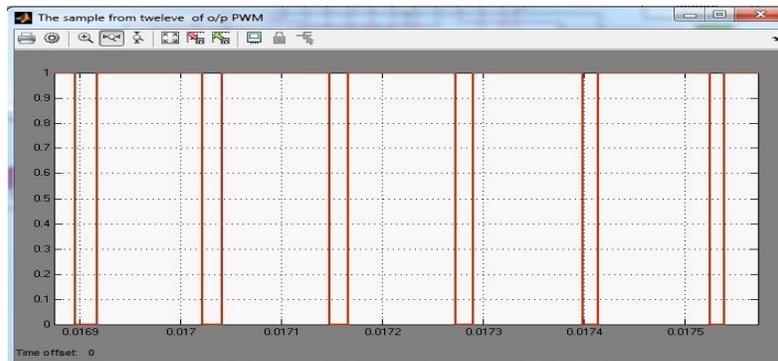
**Table 1. The numerical values for system design.**

parameter	value	parameter	value
<b>Stator phase resistance Rs (ohm):</b>	2.8750	Torque Constant (N.m / A_peak)	1.4
<b>Stator phase inductance Ls (H) :</b>	8.5e-3	Back EMF flat area (degrees)	120
<b>Flux linkage established by magnets (V.s)</b>	0.175	Inertia, viscous damping, pole pairs, static friction [ J(kg.m <sup>2</sup> ) F(N.m.s) p() Tf(N.m)]:	[ 0.8, 1e-3 1e-3, 4]
<b>Voltage Constant (V_peak L-L / krpm)</b>	146.6	Initial conditions [ wm(rad/s) thetam(deg) ia,ib(A) ]	[0,0,0,0]
The parameters of PI controller are: Proportional K <sub>p</sub> = 25, Integral k <sub>i</sub> =0.13.			

The output voltage waveform of an MLI is composed of the number of levels of voltages, typically obtained from capacitor voltage sources starting from three levels, the number of levels can increase until the output is a pure sinusoidal. The output of the simulation for system design for MLI model described in Figure 7 and used with BLDC motor is shown in Figure 8. The output of this inverter based on DPWM with 12 pulses sequences, Figure 9 explains the sample from the sequences used for operation MLI Otherwise, a short circuit could result on the DC bus.



**Figure 8: Output of three-phase three-level inverter with DPWM.**



**Figure 9: The sample from output of the DPWM**

To examine the feasibility and validity of the proposed controller, IT2FLC was applied to the speed control of a BLDC motor. The simulation was applied with three types of controllers and compared between them according to the settling times, rising time and Max. Overshoots of the responses. Performance indices for the controller feasibility were absolute error and root mean square error:

$$AE(k) = |y(k) - y_d(k)| \tag{12}$$

$$RMS(k) = \sqrt{(y(k) - y_d(k))} \tag{13}$$

Where:  $y(k)$  represents the output of the plant while  $y_d(k)$  represents the desired output.

➤ *Simulation of the classical controller*

Figure 3 shows the control system having two loops: current control loop, which controls motor torque, and speed control loop, which adjusts motor speed. The model can be used in various researches, but identifying most parameters of the current controller and speed controller needs fuzzy controller Type 1 or Type 2. Figure 9 gives the structure and simulation of a classical controller (PI) and fuzzy controller Type 1. The BLDC motor was modelled and analysed on Matlab/Simulink.

The inverter gate signals are produced by decoding the motor Hall Effect signal. The inverter three-phase outputs are applied to the PMSM-block stator windings. The load torque applied to the shaft of the machine is set to 0 and then (at  $t=0.1s$ ) stepped to its nominal value (11Nm). The inner loop synchronises the inverter gate signals and electromotive force ( $emf$ ). The outer loop controls the motor speed through variation in the DC bus voltage. With this design and taking the best results among trials with many parameter sets, the final PI parameter values post tuning were  $K_i=0.13$  and  $K_p=25$ . Figure 9 gives the simulation results of the classical controller, whose most advantageous responses were quick settling and a good steady-state error of 0.99% o/p  $w_m=2982$  (see Figure 9).

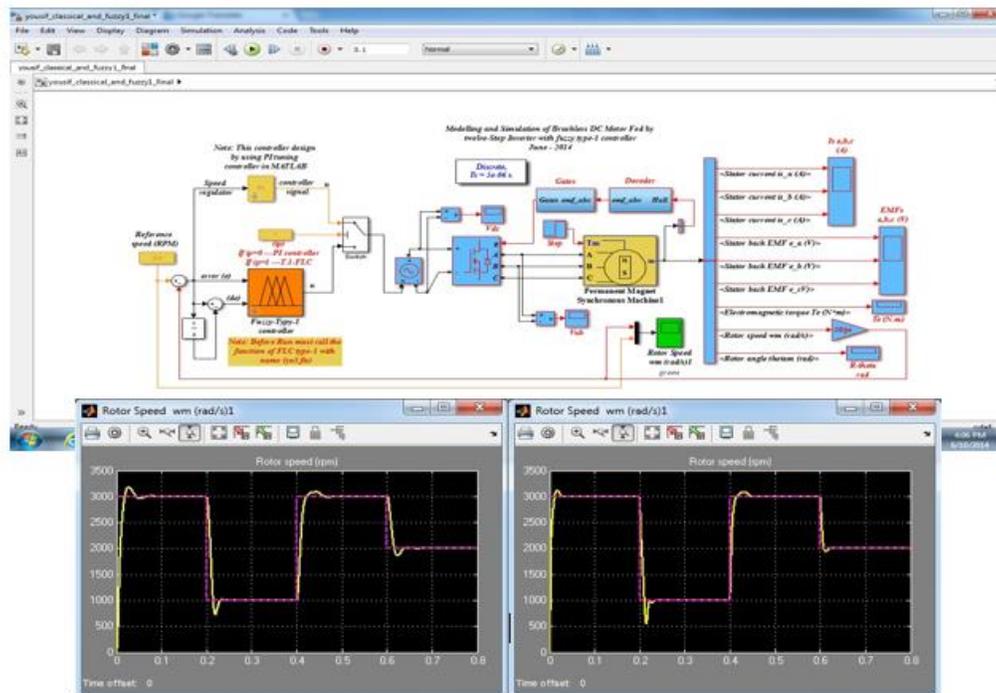


Figure 10: Simulation of classical and Fuzzy type-1controller of BLDC motor

For simplicity and accuracy, the analysis of the BLDC motor assumed an unsaturated BLDC motor, equal stator resistances, constant self-inductance, and constant mutual inductance, ideal semiconductor devices of the inverter, negligible iron losses, and equal back-EMF waveforms for all of the phases. The assumptions were based on the

#### *Simulation of Fuzzy (IT2FLC, T1FLC) controller for the BLDC motor*

Figure 10 is the block diagram for T1FLC and IT2FLC with two inputs ( $e_1, e_2$ ) and one output ( $u$ ). The error signal is calculated by subtracting the reference speed from the actual rotor speed; the same for all other types of FLC:

$$e_1(k) = w_r(k) - w_m(k) \quad (15)$$

with  $e_1$  being the error,  $w_r$  the reference speed, and  $w_m$  the actual motor speed. The change in error ( $e_2(k)$ ) is calculated by Eqn. (16), with  $e_1(k-1)$  being the preceding error value.

$$e_2(k) = e_1(k) - e_1(k-1) \quad (16)$$

The FLC system defines two normalisation parameters ( $e_{1N}, e_{2N}$ , for input) and one de-normalisation parameter ( $u_N$ , for output). In normalisation, the input values are scaled between (-1, +1). In de-normalisation, the output value of the fuzzy controller is converted to a value that depends on the terminal control element. The fuzzy values obtained from the fuzzy inference mechanism have to be defuzzified into a crisp output value ( $u$ ). A Gaussian fuzzy MF is thus defined for each input value and each output value by the nine clusters.

The Modified Matlab Fuzzy Toolbox depended on T-2 Fuzzy Logic Toolbox. The IT2FLC was simulated in Matlab GUI, which enabled calculation and design of the main FIS structure of the T-1 fuzzy controller. The FIS model was also calculated and designed through the Generalised Fuzzy System (GFS) algorithm. Describe the design and simulation of the two controller types (classical, T1FLC).

The first window introduces the idea behind the IT2FLC controller and allows the simulation windows of all the designs to be called. The next window allows each of the controller types to be called. The third window runs the classical controller; it enables analysis of the BLDC motor mathematical model and tuning of the PID controller.

The fourth window allows running of T1FLC and IT2FLC processes. The fifth window presents the MIT2FLC design. The modified MF is advantageous mainly through its adjustable parameters; also, it is not severely limited (allowing the controller to achieve the desired response without any overshoots). The wide-ranging MF base overcomes the initial-operation (during transient response) problem of the BLDC motor.

The second button in the fifth GUI (see Figure 10) allows converting the TIFLC to IT2FLC before modifying it into MIT2FLC. The window enables calling of Type-1 rules and then changing them into IT2FLC by calculating the upper and the lower FOU for each MF. The third button enables plotting of the surface error of the new design.

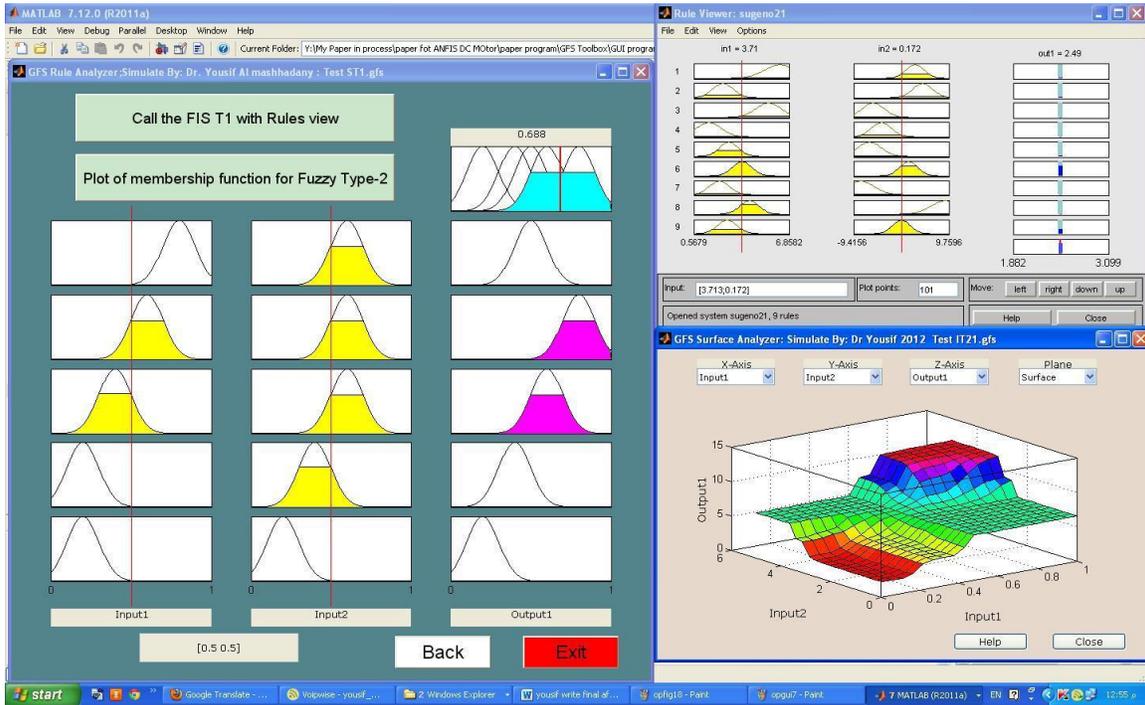


Figure 11: The GFS, the rule analyzer, the viewer

The fourth button reveals the final design of the IT2FLC, whose simulation block diagram (used to select the switching technique for the two controllers in the same plant) is as of Figure 11. Figure 12 gives the design outputs: four outputs for the two controllers, each subjected to the same simulation conditions of the BLDC motor. The IT2FLC showed better response than did the other controllers; its overshoot value was the smallest (overcoming the problem of overshooting), and the settling time was optimal.

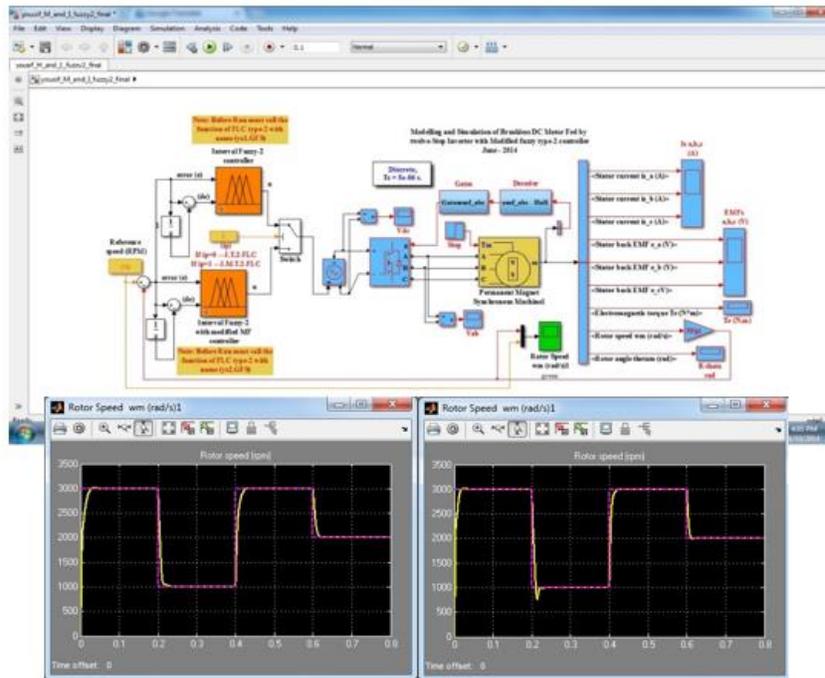
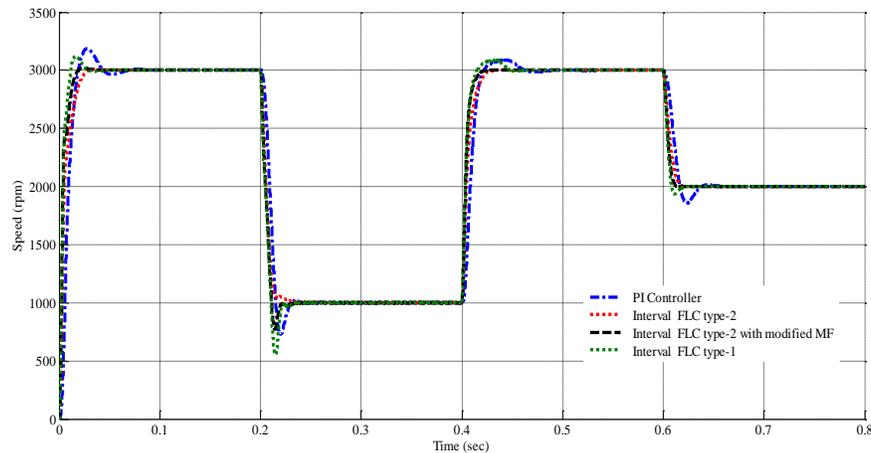


Figure 12: Final simulation of the IT2FLC and IT2FLC with modified MF function



**Figure 13: Comparison of the controller outputs of the BLDC motor**

## 5 Conclusions

The time series results show the ability of adaptive control system as direct control for a power system through an interval type-2 fuzzy controller. They also compared the results of the three controller types. The design and implementation performed first by using tuning classical controller (PI), than the IT1FLS Toolbox is potentially important for research on interval type-2 fuzzy logic, as the proposed Toolbox design model for the IT2 fuzzy controller is for solving complex problems in various applications. Our future work is to improve the IT2FLS Toolbox with the power-system-toolbox-based GUI for all types of controllers. For now,

- *The IT2FLS has shown high performance that outperforms all of the other controllers in terms of speed response and minimum overshoot.*
- *The GUI designed here has shown high functionality and ease of use (the easiest method by far) for the simulation of the IT2FLC for a BLDC motor.*
- *Future work is planned for a full toolbox that is able to simulate any machine controller.*

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