MATLAB Simulation For Development of PWM Fuzzy Speed DSP Controller

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Abstract-**This paper presents the development of Pulse Width Modulation (PWM) fuzzy controller for eZ-DSP F2812 using Simulink in MATLAB. The fuzzy controller had been developed in MATLAB environment. The controller is designed to process the input and gives output to control the duty cycle of PWM which control the speed of Brushless DC (BLDC) motor. The fuzzy controller that had been developed in Simulink then is implemented on eZ-DSP F2812 using C language in Code Composer Studio environment. The eZ-DSP F2812 is used as a speed controller for BLDC motor in real-time. The eZ-DSP F2812 does not produce PWM sequence for BLDC winding excitation instead an electronic commutation (EC) driver is used for this purpose, which takes input from eZ-DSP F2812 fuzzy controller. The simulation and real-time implementation results of open loop and closed loop control are presented and compared for its response.**

Keywords-MATLAB Fuzzy;DSP PWM Speed Controller

I. INTRODUCTION

The conventional control theory such as proportional integral (PI) controller which relies on mathematical model has been successfully and widely used in industrial applications due to its simple control structure, easy of design and low cost [1]. The controller is usually applied to the control of a large variety of simple and non-linear processes. However, it has not been as widely used with complex, time varying or nonlinear systems. The main idea of fuzzy control is to build a model of an expert operator who is capable of controlling the plant without thinking in terms of a mathematical model.

Fuzzy logic controllers (FLC) are rapidly becoming an alternative for classical controllers. The reason for this is that a fuzzy controller can closely imitate human control processes [2]. Fuzzy logic technology enables the use of engineering experience and experimental results in designing an embedded system.

Many studies had been done to compare the performance between fuzzy logic and conventional control. H.S El-Sayed, F.M El-Khouly, M.M Khater and A.M. Osheiba[1] concluded that fuzzy logic controller ensures better damping of speed, current and torque oscillations over the whole speed range compared to PI controller. D.D Neema, R.N. Patel and A.S. Thoke[3] reported that the fuzzy controller demonstrate the improved regulation with smaller value of settling time compared to conventional PI controller. G. Sakthivel, T.S. Anandhi and S.P. Natarjan[4] concluded the performance of fuzzy logic controller (FLC) was much superior to conventional PI controller and FLC is able to compensate load changes better than PI controller.Afuzzy controller can be developed by encoding the structured knowledge of the system. This allows faster control algorithms to be developed in less time and at less cost. With the advances of microprocessors and Digital Signal Processor (DSP), fuzzy logic control device are becoming an attractive solution for real time control situations.

This work will focus on developing Takagi-Sugeno type fuzzy logic controller (FLC) to be implemented on eZ-DSP F2812 for real-time speed control of BLDC motor [9].The FLC is designed to process the input and gives output to control the duty cycle of on-chip Pulse Width Modulation (PWM). PWM is a modulation technique that conform the width of pulse, formally the pulse duration, based on modulator signal information. PWM technique is widely used in many electrical devices for controlling the power especially to inertial loads such as motors. PWM is a powerful technique for controlling analog circuits with a microprocessor's digital outputs [5].Many microcontrollers and digital signal processors (DSP) already include on-chip PWM controllers including the eZ-DSP F2812 which makes the implementation easier.All the membership functions and rules of FLC had been developed in MATLAB environment. The FLC then was simulated and tested for open loop and closed loop control using Simulink in MATLAB. Abdallah A.Ahmed, Yuanqing Xia and Bo Liu [7] proposed Takagi-Sugeno type FLC on eZ-DSP F2812 to generate PWM for switch intelligent power module (IPM) to control DC motor fed by IPM converter. The FLC output change the duty cycle of the IPM converter and thereby, the voltage fed to the DC motor regulates its speed. The simulation results using Simulink had been presented in their paper. M.Muruganandam and M.Mahdeswaran[8] proposed Takagi-Sugeno type FLC for various types of DC motor fed by DC-DC converter. In this paper, the fuzzy logic speed control system with PWM was developed and simulated in MATLAB environment and was designed in such a way that it can be implemented in a microcontroller or DSP processor based embedded system.

In this work,the development of FLC on eZ-DSP F2812 is implemented independently in C language using Code Composer Studio (CCS) software. Readily available electronic commutation driver [9] is interfaced with eZ-DSP F2812 to control a geared BLDC motor [9] operation. Subramaniam Vijayan *et al.*[12] implemented Mamdani type FLC to control the speed of switched reluctance motor (SRM) on eZ-DSP F2812 coded in C language using Code Composer Studio (CCS).Yanpeng Dou and Zhang Ze[10] proposed realization of Mamdani type fuzzy self-tuning PID speed controller of permanent magnet synchronous motor (PMSM) on eZ-DSP F2812.They emphasized how to realize this controller using fuzzy search table method in C++ language based on eZ-DSP F2812. Mahlet Legesse[14] implemented Mamdani type Fuzzy-PI speed controller for permanent magnet synchronous motor (PMSM) on eZ-DSP F2812 by generating C code using Real Time Workshop (RTW) embedded coder in MATLAB linked to Code Composer Studio. G. Sakthivel, T.S. Anandhi and S.P. Natarjan[4] proposed an approach for implementation of a Mamdani type FLC for BLDC motor on eZ-DSP F2812 interfacing with Vissim. The implementation of FLC is very straightforward by coding each component of fuzzy inference system in Vissim according to design specifications. Amit Vilas Sant and K.R. Rajagopal [11] implemented hybrid fuzzy PI with switching function speed controller for PMSM on eZ-DSP F2812. N. Senthil Kumar, V.Sadasivam and K.Prema [6] proposed an INTEL 8051 microcontroller based Takagi-Sugeno type FLC for closed loop control of DC drive fed by DC-DC converter.

In this work, one PWM and one digital output from eZ-DSP F2812 will be interface with electronic commutation driver [9] which controls the speed and direction of BLDC motor [9]. The motor Hall Effect sensor pulse signal is connected to eZ-DSP F2812 as a digital input to determine motor velocity for closed loop control. The proposed BLDC motor control is very useful for multiple BLDC motor control. One PWM output from eZ-DSP F2812 can be used to control one BLDC motor. The eZ-DSP F2812 board offers 12 PWM outputs which can be used to control multiple BLDC motor. This control scheme is very useful for mechatronics system such as artificial intelligent electromechanical control valves [13], electrical vehicles (EV) and hybrid vehicles which controls nonlinear and event driven process or systems in automotive, aerospace and power plants.

II. CONTROL SCHEME

Normally six PWM from eZ-DSP F2812 are needed to control a BLDC motor [4]. In this work, available electronic commutation (EC) driver is used to be interfaced with eZ-DSP F2812. Only single PWM is needed from eZ-DSP F2812 to control one BLDC motor. The PWM from eZ-DSP F2812 will be supplied to EC driver. The EC driver will process the input and generates six PWM for BLDC motor control. Signal pulse from Hall Effect sensor of BLDC motor is used for estimating its speed, for which a capture unit on eZ-DSP F2812 is used to read pulses transition on capture input pin.

For closed loop control, the feedback speed is used to compare with reference speed. The difference between reference speed and feedback speed will compute error which will be sending to fuzzy logic controller (FLC) as an input. One more input for FLC is the change in error. The FLC output will changed the PWM duty cycle according to the inputs and send to EC driver. Besides that, the FLC output also will determined the direction of motor whether it is clockwise or counter-clockwise. Single digital output from eZ-DSP F2812 is used for this purpose. Overall closed loop control is shown in Figure 1 below.

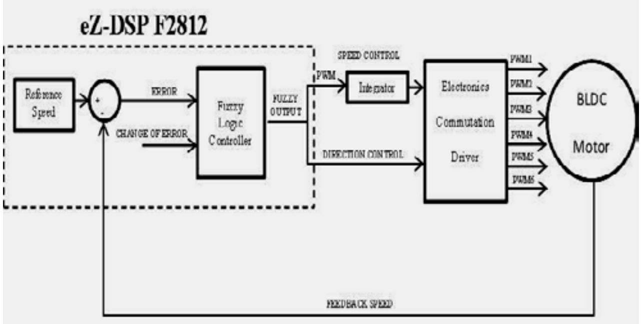


Fig. 1 Closed Loop Control Scheme

The eZ-DSP F2812 from Texas Instrument is used for real time digital control systems. It has 12 PWM outputs with 150MHz clock, up to 128x16k flash, 16 channels of 12-Bit ADC, up to 56 General Purpose I/O (GPIO) pins, timers and counters. It does not have Digital to Analog Converter (DAC) for analog output, which makes it necessary to integrate the PWM output for EC driver. The analog speed input to EC driver is in range of 0-5VDC and digital input for rotation direction is TTL logic 5V.

III. FUZZY LOGIC CONTROLLER (FLC) IN MATLAB

As mentioned in previous section, for speed controller, FLC ensures better damping of speed, current and torque oscillations over the whole speed range compared to PI controller [1]. Besides that, FLC demonstrate the improved regulation with smaller value of settling time compared to conventional PI controller [3] and FLC is able to compensate load changes better than PI controller [4]. Mamdani type FLC was successfully implemented on eZ-DSP F2812 to control BLDC motor [4].

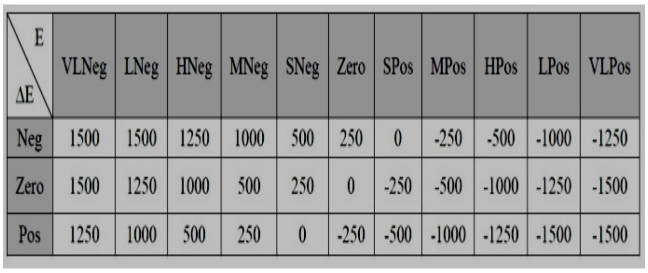
In this work, two inputs Takagi-Sugeno type FLC was developed in MATLAB to be implemented on eZ-DSP F2812 for BLDC motor control. One input is used for error and the other input is used for change in error. In this work, the motor variable considered is the speed. The speed is the control object of FLC. For closed loop control, the definitions for error and change in error are given as:

$$Error = ReferenceSpeed - ActualSpeed$$

$$ChangeofError = CurrentError - PreviousError$$

In closed loop control, mixed of trapezoidal and triangular membership functions are used for both inputs meanwhile for open loop control, all membership functions were triangular. For error input, 11 linguistic variables were used while for change of error input, 3 linguistic variables were used. Table 1 shows the rule table of the fuzzy logic controller.

TABLE I FUZZY RULES



E ΔE	VLNeg	LNeg	HNeg	MNeg	SNeg	Zero	SPos	MPos	HPos	LPos	VLPos
Neg	1500	1500	1250	1000	500	250	0	-250	-500	-1000	-1250
Zero	1500	1250	1000	500	250	0	-250	-500	-1000	-1250	-1500
Pos	1250	1000	500	250	0	-250	-500	-1000	-1250	-1500	-1500

The results of all the rules that have fired are “defuzzified” to an output value by using Takagi-Sugeno defuzzification method:

$$Output = \frac{\sum_i^{33} \propto_i c_i}{\sum_i^{33} \propto_i} \qquad (1)$$

Where i is the index for fired rules and there are total 11x3=33 rules, α is the rule firing strength and c is the degree of membership of the output. Graphical representations of the membership functions are shown in figures below.

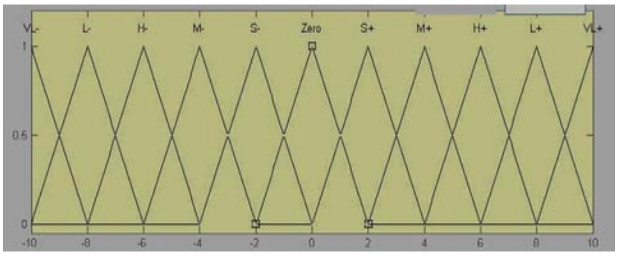


Fig. 2 Open Loop Membership Function of Error Input Variable

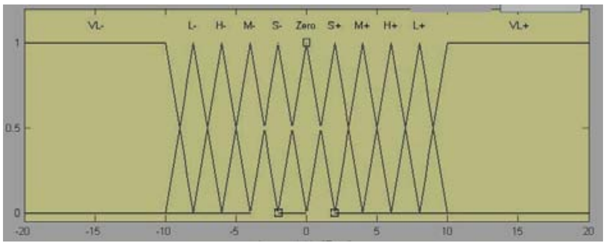


Fig. 3 Closed Loop Membership Function of Error Input Variable

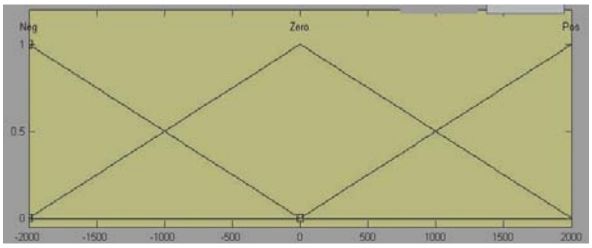


Fig. 4 Membership Function of Change of Error Input Variable

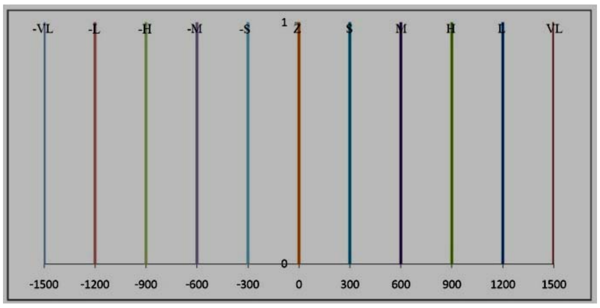


Fig. 5 Membership Function of Ouput Variable

IV. SIMULATION SETUP OF PWM FUZZY SPEED CONTROLLER

Simulation of PWM fuzzy speed controller was implemented in Simulink. In the simulation, the output from Fuzzy Logic Controller block is connected to Controlled PWM Voltage block. From there, the voltage is supplied to Universal Bridge block which act as PWM inverter to control the speed of BLDC motor. Step input block is used to give torque load to the BLDC motor. Simulation system of open and closed loop control are shown in the Figure 6 and Figure 7 below.

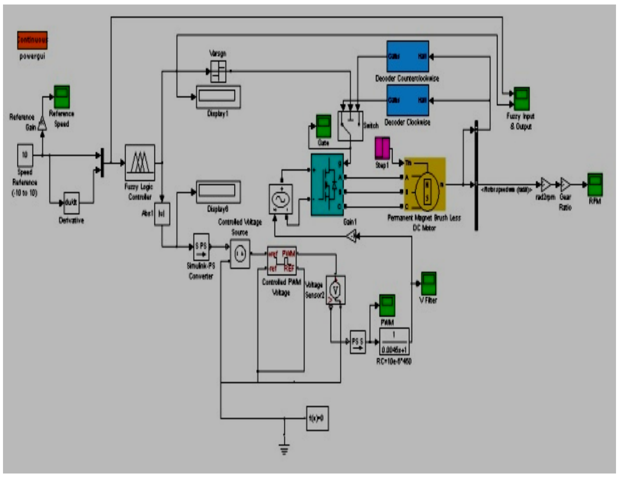


Fig. 6 Open Loop Control of Proposed System

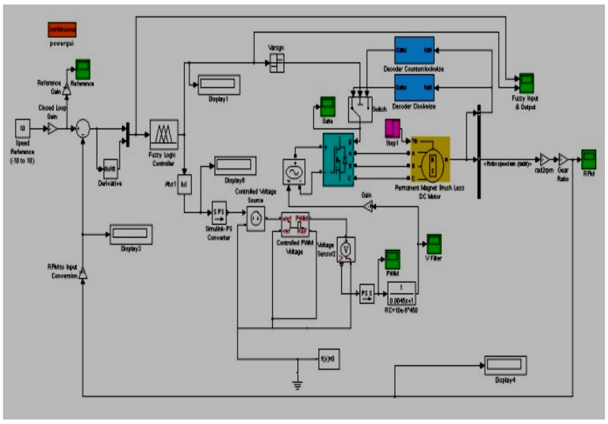


Fig. 7 Closed Loop Control of Proposed System

V. DSP HARDWARE SETUP

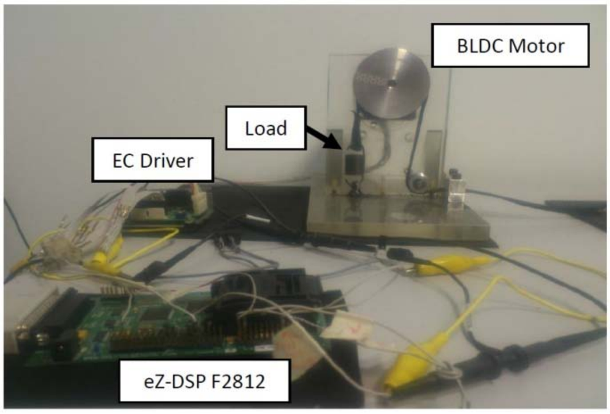


Fig.8 DSP Hardware Setup

Figure 8 above shows the hardware setup for the real time speed controller implementation. The electronic commutation (EC) driver is connected to geared BLDC 30W motor with the gear ratio 10:1. Pulse signals of 30 pulses per revolution from the Hall Effect sensor are output in synchronism with the motor drive. Pin 2 from EC driver provides output signals from the Hall Effect sensor and is connected to eZ-DSP F2812 for speed measurement. The motor maximum speed is 300 rpm at rated 5V analog signal input at Pin 5 of EC driver. The Pin 5 is connected with 3V PWM output from eZ-DSP F2812 via integrator circuit and expected maximum speed is 180 rpm. Pin 9 of EC driver is used for direction control. Figure 9 below shows the input and output signals connection of EC driver.

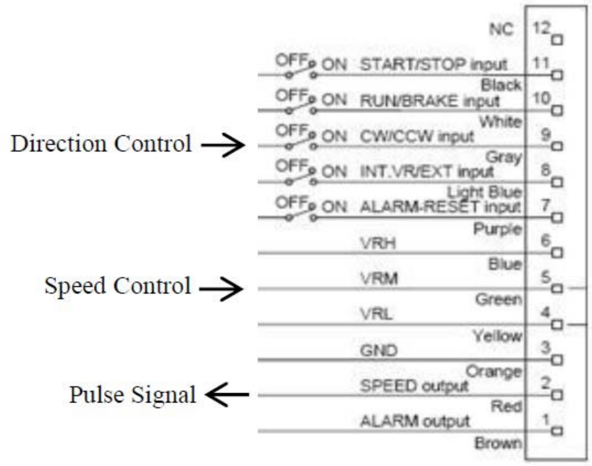


Fig. 9 Electronic Commutation Driver Connection

A. *PWM Speed Integrator*

The PWM output from the eZ-DSP F2812 is in digital form with duty cycle processed by the fuzzy controller. The EC driver speed input requires analog output. The integrator filter shown in Figure 10 is used for charge storage rather than ac signal filtering. The low pass integrator with $C = 10\mu f$ and $R = 1.5k\Omega$ simulation results are shown in figure. Filter time constant $T = RC = 15msec$ is greater than PWM pulse period is 1msec; means that the capacitor remain charged during the PWM pulses and act as an integrator. Integrator response is:

$$speed\ out = PWM * \left[1 - e^{-\frac{2msec*n}{RC}}\right] \qquad (2)$$

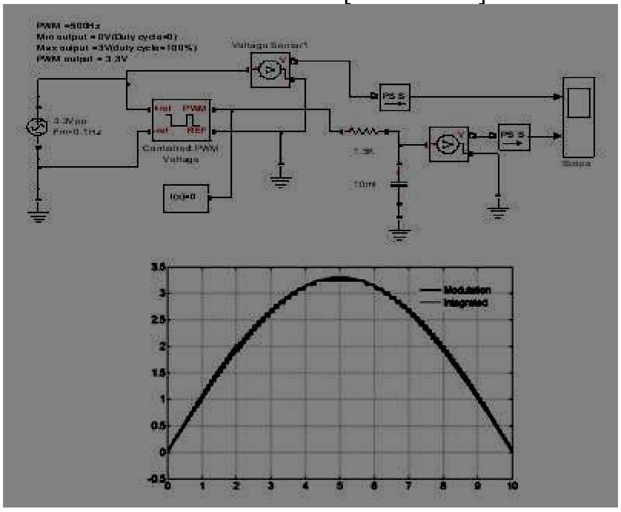


Fig.10MATLAB simulation (top) and PWM speed integrator output (bottom)

B. *FLC Implementation on eZ-DSP F2812*

Fuzzy Logic Controller (FLC) implementation on eZ-DSP F2812 is implemented following the membership functions and rules that had been developed in MATLAB in previous section. In the work describe here, fuzzy function is called upon to act on the two fuzzy input and generate Takagi-Sugeno based [18] gravity defuzzification output (refer Equation 1)

$$ManVar = \frac{\sum_i^{33} \propto_i c_i}{\sum_i^{33} \propto_i} \qquad (3)$$

Where i is the index for fired rules and there are total 11x3=33 rules, α is the rule firing strength and c is the degree of membership of the output.

The inputs of FLC for closed loop speed control are the error and change of error meanwhile for open loop control, one input can be used for reference speed. As proposed earlier in this paper, for closed loop control, error is computed by comparing the reference speed with the feedback/actual speed. Change of error is computed by deducting the current error with previous error

The output ManVar is checked for sign and stored in variable

```
‘varsgn’ = sign(ManVar)
```

This will be output to EC driver via register-port `GPIOB1`.

```
GpioDataRegs.GPBDAT.bit.GPIOB1 = varsgn
```

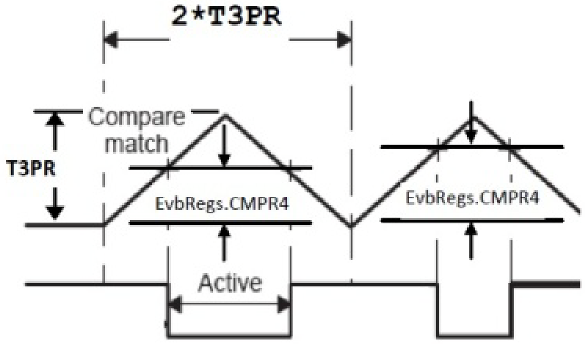


Fig.11 EvbRegs.CMPR4 effect on PWM duty cycle

To change the duty cycle of the PWM as per fuzzy output, the register `‘EvbRegs.CMPR4 = T3PR’`as shown in Figure 11 has to be modify as

```
EvbRegs.CMPR4=EvbRegs.T3PR–abs(ManVar)*25
```

Where scaling T3PR/1500 = 25 sweep the complete PWM duty cycle from 0-100%. Here it is worth to mentioned that PWM duty cycle computation is same for both the direction the sign `‘varsgn’` of the manipulated variable ManVar determine the motor direction on pin GPIOB1.

C. *Motor Dead Band*

Dead band is required to stop the motor completely before switching the directions. The dead band selected is shown in Figure 12, can be programmed with if-else statement and is 25/1500 = 1.6 % of complete range available for motor speed control.

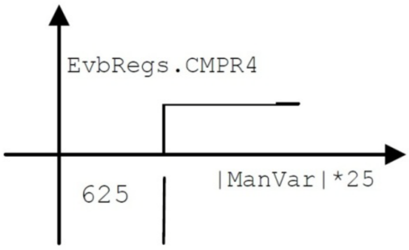


Fig.12 Dead band for motor before change of direction

If 25*(|ManVar| > 25) the motor is forced to run with PWM7 compare action control register set to active high

```
EvbRegs.ACTRB.bit.CMP7ACT =0x0002;
EvbRegs.CMPR4 = EvbRegs.T3PR –
abs(ManVar)*25
```

Else the the motor is stopped in the dead band with forced active low on CMP7ACT register as

```
EvbRegs.ACTRB.bit.CMP7ACT =0x0000;
```

A small delay (10000ticks ~= 5msec) is to be used in for-loop to avoid abrupt motion.

D. Speed Sensitivity

The voltage after integrator ranges from 0V to ~3.3V. This voltage controls the speed of the BLDC motor. The speed of BLDC motor with respect to the voltage after integrator is given by:

$$Speed = \frac{210}{3.33}\ x\ (Voltage\ after\ integrator) \qquad (4)$$

VI. RESULTS AND DISCUSSION

The development of PWM speed fuzzy controller was simulated in Simulink. The FLC output controls the duty cycle of PWM. The PWM then supplied to the BLDC motor to control its speed. From the simulation, it has been proved that the PWM’s duty cycle can be controlled by FLC. Figure 13 shows the comparison between closed loop and open loop speed response before and after the load applied at reference speed of 105 rpm(50%PWM duty cycle). Figure 14 shows the comparison between closed loop and open loop speed response before and after the load applied at reference speed of 210 rpm(100% PWM duty cycle). The 2 Nm load is applied to the BLDC motor after t=0.6s. The figures show that after load applied at t=0.6 s, speed of both cases decreased. Closed loop speed control shows the FLC tried to maintain the speed according to reference speed after the load applied meanwhile for open loop control, the FLC is not responding to the applied load. Table 2 below shows the comparison of open loop and closed loop speed response together with the speed drop percentage for both cases. For PWM generated, it can be seen from Figure 15, the FLC of closed loop control change the PWM duty cycle after applying the load while for open loop, it is not. The duty cycle remain the same before and after load applied for open loop control. It is worth to mention when the reference speed is maximum (100% PWM duty cycle), the PWM response of open loop and closed loop will remain the same before and after load applied, same goes to the speed response as seen in Figure 14 and 16. These results proved the proposed PWM fuzzy speed controller is functioning and can be implemented on eZ-DSP F2812.

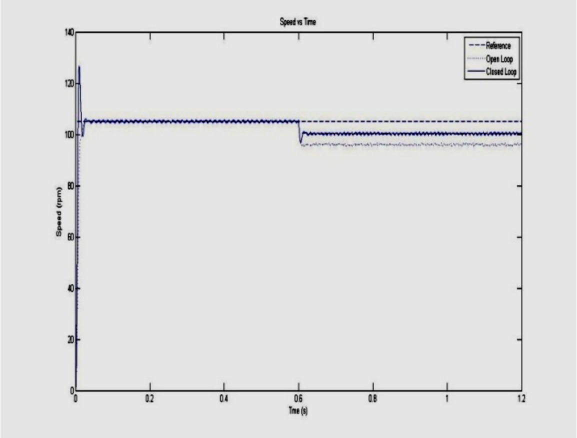


Fig. 13 Simulation Speed Response at Reference Speed of 105 rpm

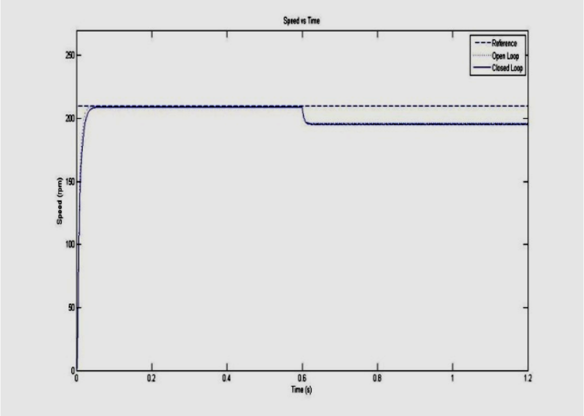


Fig. 14 Simulation speed Response at Reference Speed of 210 rpm

TABLEII SPEED RESPONSE FOR OPEN LOOP AND CLOSED LOOP SIMULATION RESULTS

Reference Speed	Open Loop Speed Response			Closed Loop Speed Response		
	Without Load	With Load	Speed Drop (%)	Without Load	With Load	Speed Drop (%)
105 rpm	105 rpm	95 rpm	9.52 %	105 rpm	103 rpm	1.90%
210 rpm	210 rpm	190 rpm	9.52%	210 rpm	190 rpm	9.52%

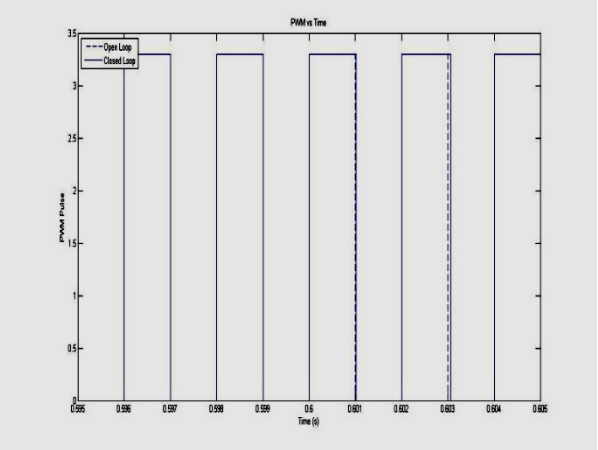


Fig. 15 Simulation PWM Response at Reference Speed 105 rpm

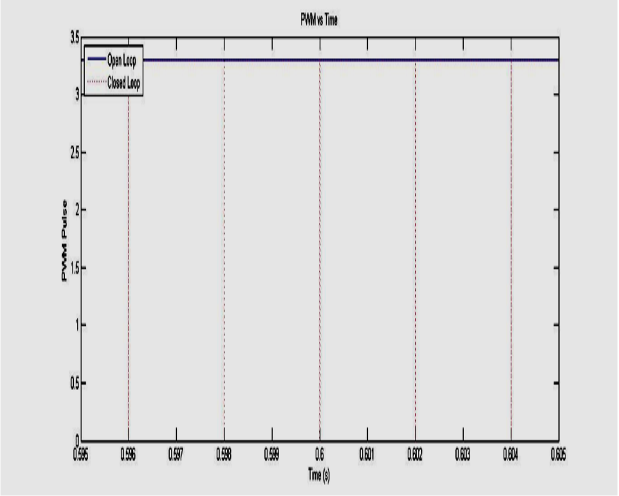


Fig. 16 Simulation PWM Response at Reference Speed 210 rpm

The results of real-time implementation are shown in the Figure 17, 18, 19 and 20 below. Channel 1 of the oscilloscope shows the voltage after integrator and Channel 2 shows PWM output from fuzzy ManVar (refer Equation (3)). The speed control remains the same for both direction and only the 'varsgn' sign bit is used to change the direction of the motor. The reference speeds used are ~105 rpm (50% PWM duty cycle) and ~210 rpm (100% PWM duty cycle). Closed loop control is used for real-time implementation. It can be seen in the figures, the frequency of PWM is 500 Hz as calculated in previous section. Figure 17 and 18 shows the PWM and voltage response without any load applied. The voltage after integrator are 1.67 V and 3.32 V while the PWM duty cycles are 50% and 100% respectively as seen in the figures. Meanwhile in Figure 19, when the load is applied, the FLC tried to increase the voltage after integrator and PWM duty cycle which are 1.71 V and 52.6% because of error computed by comparing reference speed with the actual speed. As mentioned before in simulation results, when reference speed is maximum (100% PWM duty cycle), the voltage after integrator and PWM response will remain almost the same before and after the load applied as shown in Figure 20. Table 3 below shows the voltage after integrator and PWM duty cycle response with and without load condition for real-time implementation. The speed for every case was calculated using Equation (4).

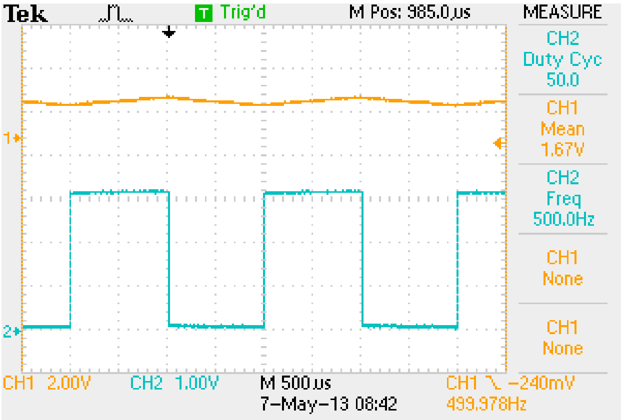


Fig. 17 Real Time PWM and Voltage Response at reference speed of 105 rpm without load

$$Speed = \frac{210}{3.33} x(Voltage\ after\ integrator)$$

$$Speed = \frac{210}{3.33} x(1.67) = \sim 105.32\ rpm$$

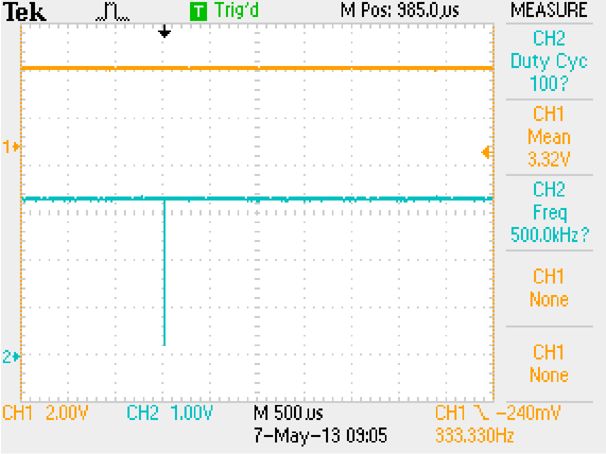


Fig. 18 Real Time PWM and Voltage Response at reference speed of 210 rpm without load

$$Speed = \frac{210}{3.33} x(Voltage\ after\ integrator)$$

$$Speed = \frac{210}{3.33} x(3.32) = \sim 209.37\ rpm$$

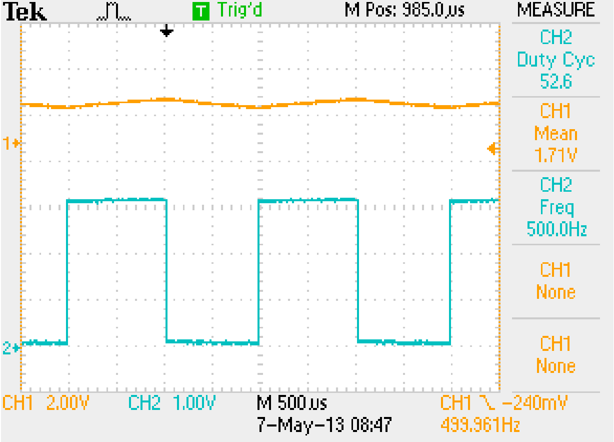


Fig. 19 Real Time PWM and Voltage Response at reference speed of 105 rpm with load

$$Speed = \frac{210}{3.33} x(Voltage\ after\ integrator)$$

$$Speed = \frac{210}{3.33} x(1.71) = \sim 107.84\ rpm$$

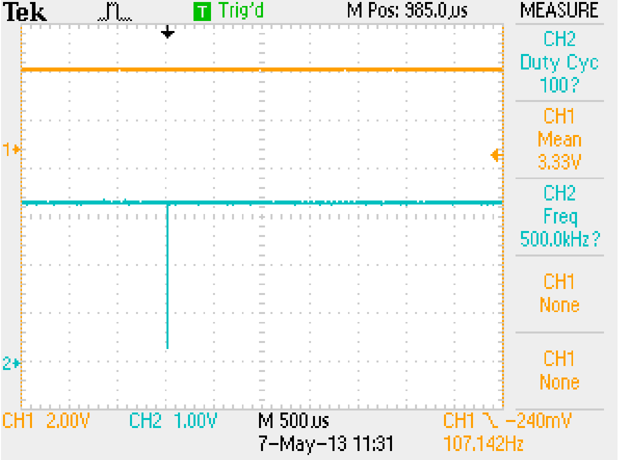


Fig. 20 Real Time PWM and Voltage Response at reference speed of 210 rpm with load

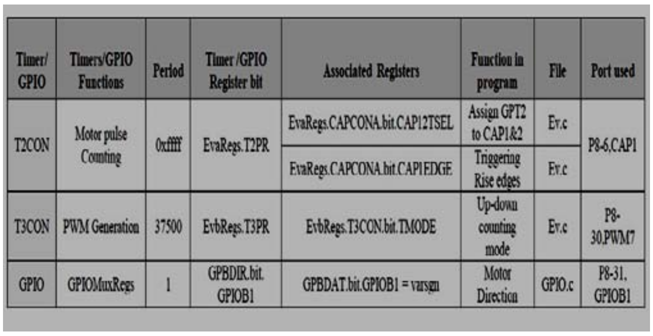
$$Speed = \frac{210}{3.33} x(Voltage\ after\ integrator)$$
$$= \frac{210}{3.33} x(3.33) = \sim 210\ rpm$$

TABLE III REAL-TIME IMPLEMENTATION RESULTS

Reference Speed	Voltage After Integrator		PWM Duty Cycle	
	Without Load	With Load	Without Load	With Load
105 rpm (50% duty cycle)	1.67V	1.71V	50%	52.6%
210 rpm (100% duty cycle	3.32V	3.33V	100%	100%

A summary of the all registers changed and modified from the original C281xC/C++ Header Files and Peripherals Examples – SPRC097 [16], required for the work presented here in this work is shown in Table 4. Also presented in the Table 2 is the register bit and their function in the program. The ports information is provided for connectivity of eZ-DSP F2812 with EC driver and devices.

TABLE IV SUMMARY OF REGISTERS MODIFIED AND CHANGED



Timer/ GPIO	Timers/GPIO Functions	Period	Timer /GPIO Register bit	Associated Registers	Function in program	File	Port used
T2CON	Motor pulse Counting	0xffff	EvaRegs.T2PR	EvaRegs.CAPCONA.bit.CAP12TSEL	Assign GPT2 to CAP1&2	Ev.c	P8-6,CAP1
				EvaRegs.CAPCONA.bit.CAP1EDGE	Triggering Rise edges	Ev.c	
T3CON	PWM Generation	37500	EvbRegs.T3PR	EvbRegs.T3CON.bit.TMODE	Up-down counting mode	Ev.c	P8-30,PWM7
GPIO	GPIOMuxRegs	1	GPBDIR.bit. GPIOB1	GPBDAT.bit.GPIOB1 = varsgn	Motor Direction	GPIO.c	P8-31, GPIOB1

VII. CONCLUSION

In this work, the PWM fuzzy speed controller had been simulated in MATLAB and its real-time implementation had been accomplished using eZ-DSP F2812. The real time implementation had been developed independently in C language by using Code Composer Studio software. Commercially available BLDC motor driver was used in conjunction with eZ-DSP F2812 which housed the high end control algorithm. Due to limitation of memory and computation speed on BLDC driver's microcontrollers it is advisable to combine the EC driver and eZ-DSP F2812 for reliable and robust control system. In this work the BLDC motor application is considered for mechatronic system, robotic, electric vehicles (EV) and valves control system where the control response is much slower but the control algorithms requires fast processing speed for solutions of complex algorithms such as artificial intelligence, adaptive, robust and optimal controls.

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