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An FPGA-Based Comparative Analysis of Control Techniques for Gimbals and Fins of Missiles

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ABSTRACT

In this study, implementation of incremental fuzzy control (IFC) method on field programmable gate array (FPGA) is investigated for gimbals and fins of missiles that include brushless direct current (BLDC) motors and its comparison with conventional proportional-integral (PI) control method are analyzed. BLDC motors are widely used in two important parts of guided missiles due to their high performance. Firstly, gimbals usually consist of seeker cameras, whose axis controls are provided by BLDC motors. These motors provide two axis seeker camera motions, so that the missiles can trace the target. Secondly, missiles can be guided to intended direction by BLDC motors that are used in the control system of fins. According to these important roles, controlling of BLDC motors is very important for defense industry. Therefore, performance of FPGA-based conventional PI and proposed IFC methods on BLDC motors are analyzed in detailed in terms of both simulation and experimental study. Simulation results are obtained by using MATLAB/Simulink program. Also, an FPGA-based test bench is used for experimental studies. Results obtained from simulation and experimental set up are compared and it is proved that the implementation of proposed IFC method improves the BLDC motor performance used in missiles compared to the conventional PI control method.

***Index Terms*—**BLDC motor control, FPGA, gimbal and fin control, Incremental Fuzzy Control

I. INTRODUCTION

Motion control systems are important parts of defense industry, including guided missiles [1]. Therefore, brushless direct current (BLDC) motors are the most preferred motors for motion control systems due to high efficiency, electromagnetic interference (EMI) compatibility, and good mechanic reliability [2]. However, control of BLDC motors is complicated in terms of electronic circuit, control algorithms, and digital computations [3].

There are too many controller types for BLDC motors. Most used of them is conventional proportional-integral (PI) controllers because of their ease of design and basic structure. Therefore, more than 90% of the controller methods include PI controller [4]. PI control method is basic, consistent, highly trustworthy, and capable of simple adjustment for linear systems. However, constant PI parameters are not good solution for non-linear systems.

Fuzzy logic (FL) has become a popular method in many controller designs. Due to the constant K_p and K_i parameters of the conventional PI controller, FL is developed to tune the constant values. Fuzzy-tuned PI control method is a better method for controlling complicated and non-linear systems. This method can give better rising time, fast dynamic response, robustness, and efficient control, thanks to fuzzy tuning [5]. There are a lot of subclasses of fuzzy tuning method, namely incremental fuzzy control (IFC) [6], fuzzy gain scheduling (FGS) [7], fuzzy set-point weight tuning (FSWT) [8], fuzzy self-tuning (FST) [9] etc. In this paper, IFC method is used as a current controller.

IFC-based controllers have been applied to a wide range of engineering problems, which have particularly non-linear dynamics. It has recently been applied as the main controller for renewable energy systems [10] such as drive problems of photovoltaic (PV) systems [11]. The results of the incremental fuzzy-controlled DC-DC boost converter confirm that the proposed maximum power point tracking (MPPT) control strategy performs well in reference voltage variations

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and reference voltage tracking in [12]. In [13], proposed controller, which incorporates the advantages of both fuzzy and PI control, can effectively develop the permanent magnet synchronous motor (PMSM) drive for a solar water pumping system. Also, an efficient fuzzy-based variable step incremental conductance MPPT method for grid-connected PV systems is presented in [14]. Considering the above-mentioned literature studies, in this study, proposed IFC method is applied instead of conventional PI in order to make PI parameters more resistant to changes caused by external factors.

There are different processors to implement the controller such as digital signal processor (DSP) and field programmable gate array (FPGA) [15]. Complex control algorithms for position and current control can be implemented on DSPs. However, DSPs cannot be operated with high frequency for current feedback and position control at the same time. In addition, limited capacity is another disadvantage of these types of processors [16].

FPGA-based control is one of the most preferred methods [17]. Properties of FPGAs, such as programmability, easy design cycle, marketable, efficiency, and sufficient density, increase the usage of FPGAs [18]. BLDC motor controllers which are implemented on FPGA are less complicated and more reliable than the DSP and more flexible than microcontroller-based controllers [19]. In addition, FPGA provides higher performance and flexibility from software by filling the gap between software and hardware [20]. Considering these advantages, FPGA-based IFC method is designed to be implemented for gimbals and fins of missiles.

In this paper, the proposed IFC method and its operation principle is given in section II. Hardware design is also given in section III. Simulation and experimental results are presented in sections IV and V, respectively. Finally, conclusion is given in section VI.

II. INCREMENTAL FUZZY CONTROL METHOD

There are many control methods for controlling BLDC motors in missiles. In this study, IFC method which is one of them is investigated and applied as a current controller. Conventional PI controllers are used for several industrial control processes in view of their basic structure and wide range of operating conditions [21]. Its steady state and transient response performance in time-invariant systems show that the parameters K_p and K_i are always constant during the process. When dynamics variations or environmental conditions occur, PI controller is inefficient and unstable due to the constant controller parameters which give uncertain behavior. Instead of this conventional method, a method which is combination of PI and FL can be preferred for dynamic variations [22]. FL has been recognized to be very convenient in the designing control systems and successfully applied in many consumer products and engineering areas since 1974 [23].

In this study, proposed IFC method is used for tuning the parameters and improving the performance of conventional PI control. This method of tuning is improved according to the error and change of the error of the system. The control rules are generated interested on the influence of the PI parameters. The general IFC method block diagram is given in Fig. 1.

The mechanism for adjusting the K_p and K_i coefficients by the IFC method is given in (1) and (2), respectively.

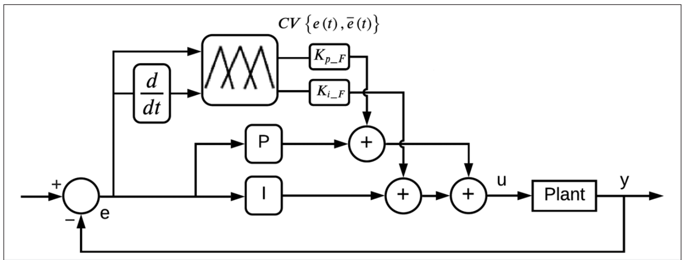

Fig. 1. Control block diagram of IFC method.

$$P = P + CV\{e(t), e'(t)\} * K_{p\_F} \quad (1)$$

$$I = I + CV\{e(t), e'(t)\} * K_{i\_F} \quad (2)$$

where $CV\{e(t), e'(t)\}$ is output of fuzzy inference system.

In FL systems, input of the system should be converted into the corresponding fuzzy representations. The proposed IFC method has two inputs called error and change of error. All errors and change of errors have different fuzzy representation according to their numeric value.

Since IFC is a rule-based method, the relationship between inputs and outputs can basically be defined in if-then format as follows:

If error is large negative and change of error is large negative, then output is small positive.

If error is small negative and change of error is large negative, then output is big positive.

If error is small negative and change of error is small negative, then output is small negative.

…

When the outputs are defined for all error and change of error cases, fuzzy rule table is obtained as in Table I. Fuzzy outputs are generated according to fuzzy rule table by using classes of error and change of error. Then, the fuzzy outputs can be converted into their relevant numerical outputs as given in Table I. These output values represent the degree of fuzzy tuning effect on PI control method.

TABLE I. FUZZY RULE TABLE AND NUMERIC VALUES OF FUZZY OUTPUT

Fuzzy Output	Definition	Numeric Value
VBP	Very big positive	8
BP	Big positive	6
MP	Medium positive	4
SP	Small positive	2
Z	Zero	0
SN	Small negative	−2
MN	Medium negative	−4
BN	Big negative	−6
VBN	Very big negative	−8

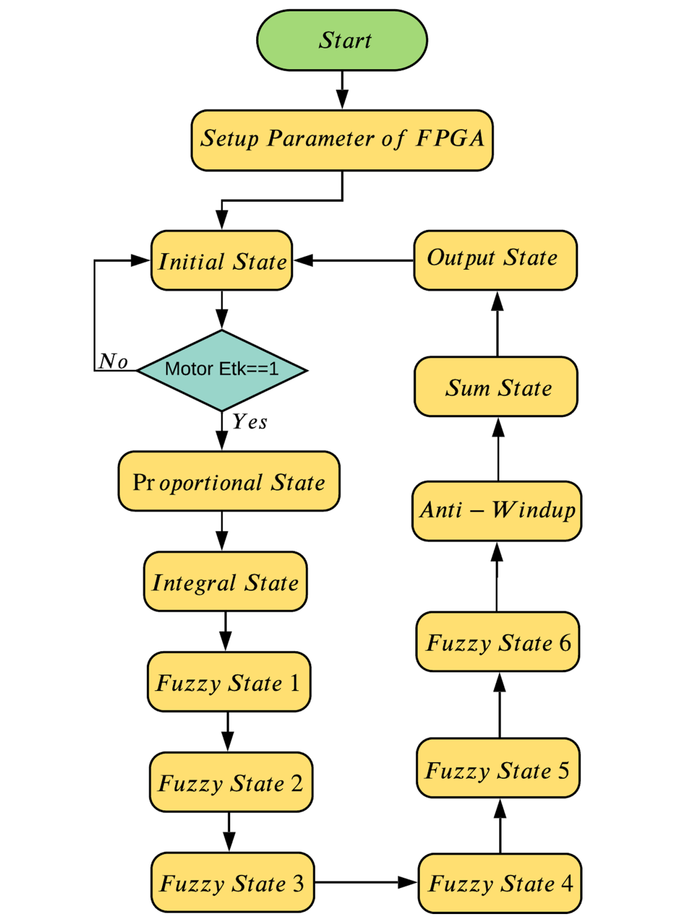

Fig. 2. Flowchart of the proposed IFC method implemented in FPGA-based electronic board.

Flowchart of the proposed IFC method implemented in FPGA-based electronic board is shown in Fig. 2 and these states are detailed as given below:

Proportional State: It is the coefficient by which the system is adjusted proportionally according to the current error.

Integral State: The integral term evaluates the action as the sum of the errors that occurred during the time it was running, not just the current error.

Fuzzy State 1: It is the process by which the derivative of the current error is obtained.

Fuzzy State 2: The process by which current error and derivative current error classes are defined as in Table I.

Fuzzy State 3: It is the process in which fuzzy outputs are defined according to the rule table given in Table I.

Fuzzy State 4: Expresses the process by which the integral of the fuzzy output is calculated for the fuzzy integral error.

Fuzzy State 5: The process by which fuzzy proportional and integral error calculations are applied.

Fuzzy State 6: This is the stage where coefficients obtained from the fuzzy outputs are summed with the conventional PI control coefficients.

Anti-windup State: It is defined as the process in which upper and lower limits are determined for the output and active in case these limits are exceeded.

Sum Stage: It is the stage where the proportional and integral terms are summed in the IFC method.

Output Stage: This is the stage where the value obtained from the sum stage is applied to the plant as in Fig. 1.

III. HARDWARE DESIGN

Controlling BLDC motors used in missiles is not an easy process. Besides, there is a need for a complex electronic card that can run many processes at the same time. The electronic board which is used to control BLDC motor includes six main circuit modules. All of these modules are related to each other. Also, this electronic board must be operated properly under tough environmental conditions such as excessive vibration, high acceleration, over speed, cold and hot weather condition, etc. Fig. 3 shows the control block diagram of a missile.

Power Converter Module*:* Around 28 V_{dc} is required to operate properly all functions of the electronic board. All required voltages for analog digital converter (ADCs), FPGA, current sensors, buffers, gate drivers, hall sensors, and encoders are generated by using the 28 V input voltage of the electronic board.

Position Measurement Module: Two digital data signals named data A and data B come from the incremental encoder to the FPGA board. Data A and data B digital data signals are read by using buffers and FPGA. Buffers strengthen data signals and regulate voltage levels to become suitable for FPGA. FPGA increases or decreases the value of position register according to data A and data B pulses. So, the position of motor can be stored on this position register. FPGA-based position measurement structure is given in Fig. 4 (a).

Hall Sensor Module: Three digital data signals hall 1, hall 2, and hall 3 come to electronic board from hall sensors. These digital data signals are read by using comparator IC and FPGA. Comparator IC compares the 15 V_{dc} hall signals with 5 V. If voltage levels of hall signals are over 5 V_{dc}, then the comparator generates 3.3 V_{dc} output signals. Otherwise, the voltage levels of hall signals are under 5 V_{dc}, then the comparator generates 0 V output. FPGA determines which metal oxide semiconductor field effect transistor (MOSFET) will be activated according to these hall sensor signals. FPGA-based hall sensor read structure is given in Fig. 4 (b).

Current Measurement Module*:* As the current passing through phases of the BLDC motor also passes through the current sensor (ACS709LLFTR), phase current can be measured. These current feedbacks are used as an input of motor control module. Current sensor gives an analog voltage feedback according to current and this feedback is converted to digital signal by using 2 mega sample per second (MSPS) ADC (AD7944BCPZ). These converted digital data are read by FPGA with Serial Peripheral Interface (SPI) protocol. FPGA-based current measurement structure is also given in Fig. 4 (c).

Motor Driver Module: The phase current can be measured because the current passing through the phases of the motor

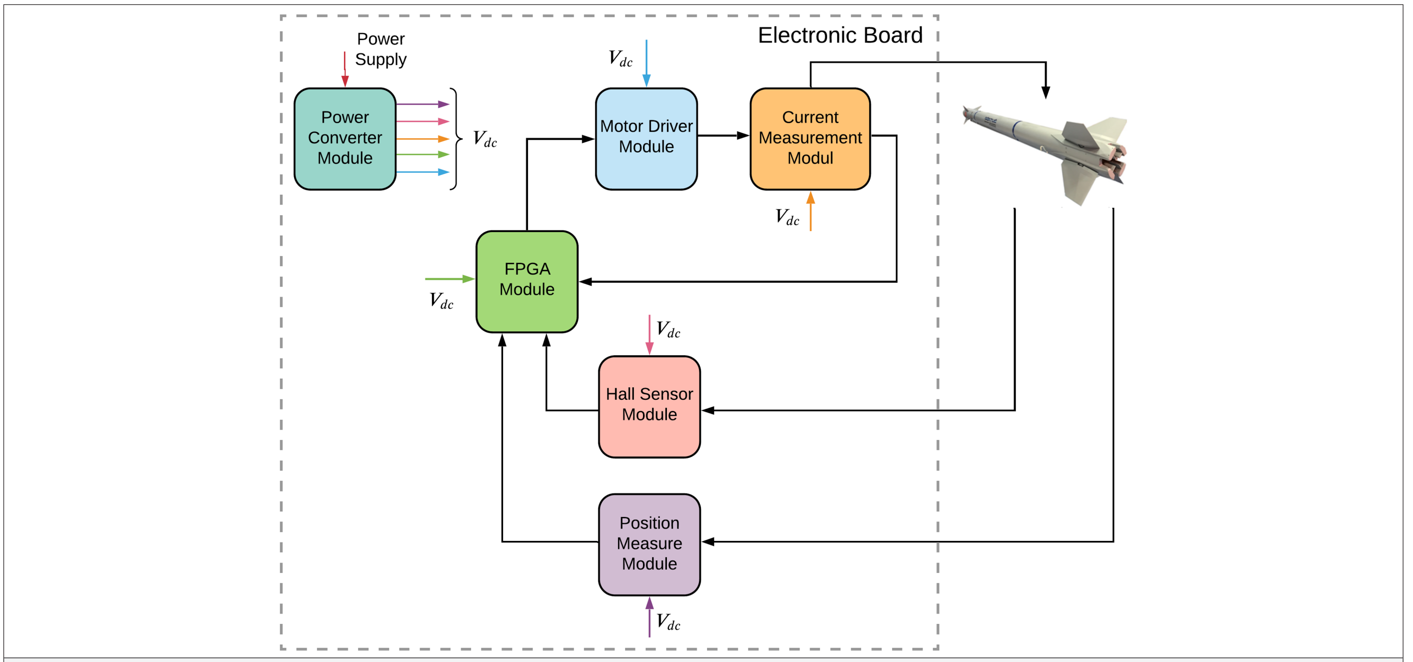

Fig. 3. Control block diagram of a missile.

passes through the current sensor (ACS709LLFTR). These current feedbacks are used as an input of motor control module. Current sensor gives an analogue voltage feedback according to current and this feedback is converted to digital signal by using 2 MSPS ADC (AD7944BCPZ). These converted digital data are read by FPGA with SPI protocol. FPGA-based BLDC motor drive circuit structure is given in Fig. 5.

FPGA drives the gate driver integrated circuits according to the six-step commutation technique. In this technique, FPGA reads six different hall sensor data combinations which come from motor and activates two MOSFETs of driver circuit. One of these MOSFETs is high-side MOSFET of one phase. The other one is low-side MOSFET of another phase. So current goes through one phase and comes back on another phase.

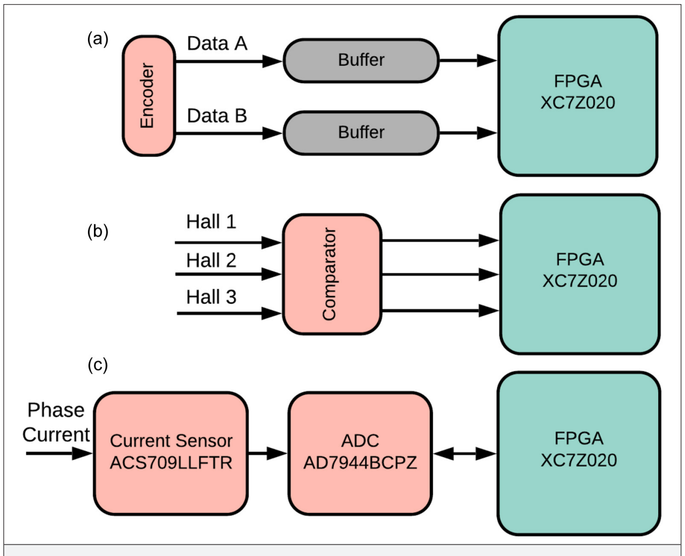

Fig. 4. a) FPGA-based position measurement structure; b) hall sensor read structure; c) current measurement structure.

FPGA Module: FPGA (XC7Z020) manages other modules. Current and position feedbacks are read with the help of FPGA. Current control algorithms are implemented on FPGA. Position control algorithm is implemented on soft core microprocessor named PicoBlaze. PicoBlaze has a fully soft core, embedded 8-bit reduced instruction set computer (RISC) architecture optimized for Xilinx FPGA architectures. Configuration and programming of the soft core processor are implemented with Vivado Design Suite. FPGA and microprocessor are integrated on the same FPGA chip. Besides, very high speed integrated circuit hardware description language (VHDL) is used to design and model the proposed system architecture.

Due to easy implementation, robustness, and no steady-state error of PI control method, in the following sections, the performance of PI and proposed IFC control methods are analyzed by simulation and experimental results.

IV. SIMULATION STUDIES

The performance of the conventional PI and proposed IFC control methods is analyzed through simulation, and comparative evaluation is presented in this section. Simulation studies are performed by the MATLAB/Simulink program. Simulink has flexible control blocks with excellent possibilities to model the control system, realistically. Therefore, all the blocks used in the simulation include only the Simulink and Simscape toolboxes.

Fig. 6 shows the command vs feedback graphics for current (A), speed (rpm), and position (deg) on conventional PI controller. Feedback data usually can trace command data. But rarely the feedback cannot trace the command and there are some unexpected feedbacks.

The IFC method is begun with the position command that is given to system as an input. Then, speed command is produced by using

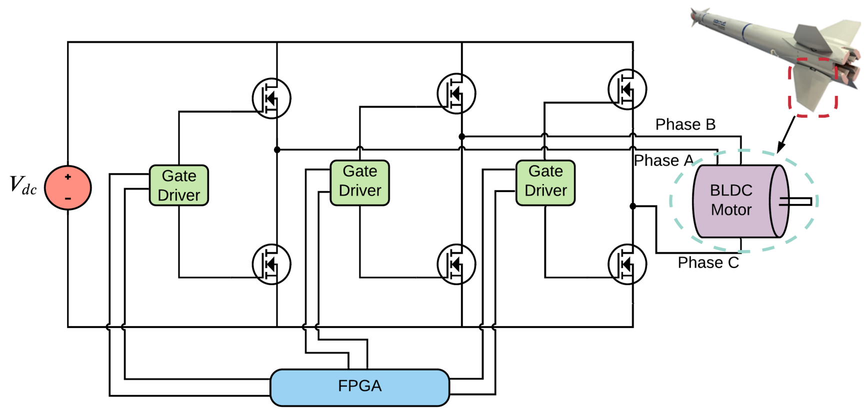

Fig. 5. Structure of BLDC motor driver circuit.

position error. After that, current command is obtained by using speed error. Then, current error is calculated by using current feedback and current command and this current error is used as an input of the IFC method. Fuzzy process tunes the parameters of PI controller according to change of current error and current error. Output of this controller is used in pulse width modulation (PWM) generator module. Finally, gates of MOSFETs are driven according to PWM signal and hall sensor data. By this way, expected current flows through the opened MOSFETs.

Fig. 7 shows the feedback vs command graphics for current, speed, and position on proposed IFC method. Feedback data almost always

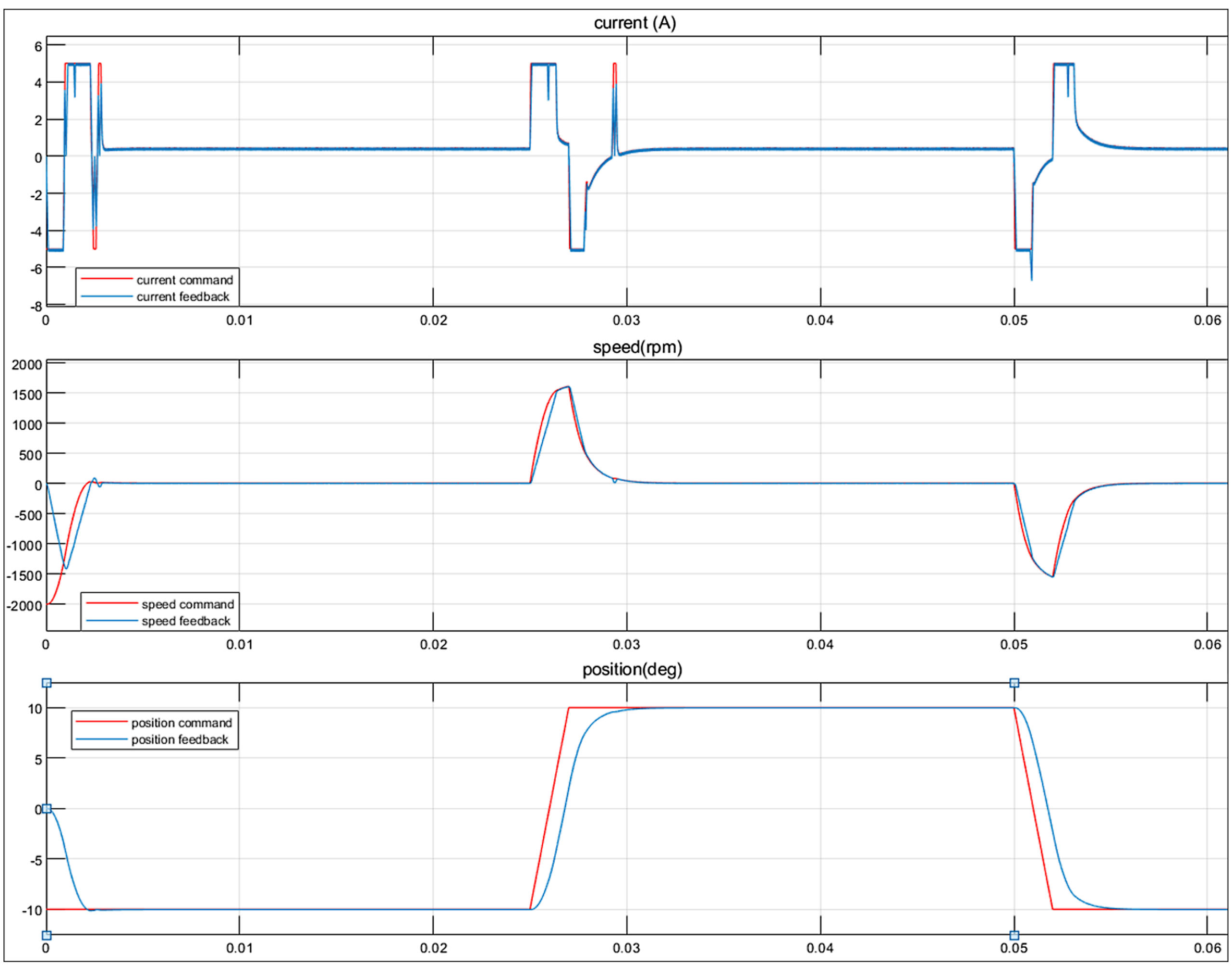

Fig. 6. Current, speed, and position waveforms of conventional PI method.

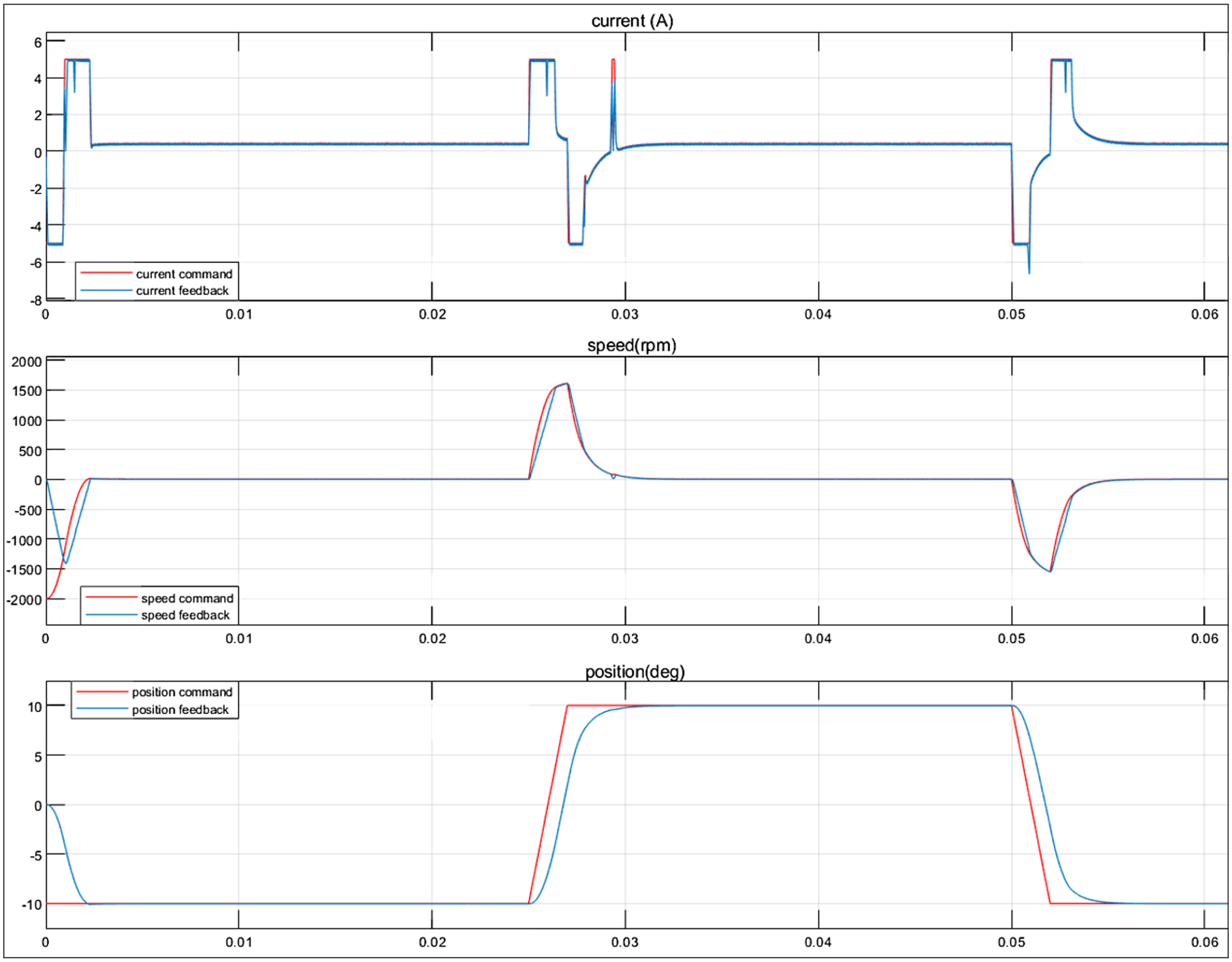

Fig. 7. Current, speed, and position waveforms of IFC method.

can trace commands. Generally, controller is successful, stable, and efficient.

Fig. 8 (a) and (b) show the current control performance of the conventional PI and proposed IFC methods, respectively. During the simulation, reference current is changed from −5 A to 5 A. In Fig. 8 (a), feedback current cannot fully follow the reference current in transient state in conventional PI control method. However, as can be seen from Fig. 8 (b), since the proposed IFC algorithm continuously minimizes the error function with adjustable K_p and K_i parameters, feedback current follows the reference current with a small error (max. 0.4%) during the current variations in the transient state. Fig. 8 (c) and (d) show the speed control performance of the conventional PI and proposed IFC methods, respectively. During the simulation, the reference speed is changed from −2000 rpm to 0 rpm. In Fig. 8 (c), feedback speed has an oscillation during the transient state in conventional PI control method. Therefore, the response time is longer than the proposed method. However, as can be seen from the Fig. 8 (d), feedback speed follows the reference speed with a small error in transient and steady states. Fig. 8 (e) and (f) show the position control performance of the conventional PI and proposed IFC methods, respectively. As can be seen in both figures, conventional PI and proposed IFC methods have the same performance in position control.

The conventional PI control and proposed IFC methods were analyzed by giving same position command on simulation. Simulation circuit for IFC was generated by adding the fuzzy block to PI control circuit. That is the only difference between the two control method simulations. When the graphs of results are analyzed, it can be observed that undesired command and feedbacks of conventional PI control are more than the IFC method. Especially, when focused between 0.002 and 0.003 seconds on conventional PI and proposed IFC simulation result graphics, unwanted oscillation on current, speed, and position graphics of conventional PI controller can be seen easily. But there is any unexpected situation such as this oscillation on all graphics of proposed IFC method. According to these results of simulation, IFC is more stable and reliable than conventional PI control method.

V. EXPERIMENTAL STUDIES

In this section, experimental results of the conventional PI and proposed IFC methods are analyzed under various conditions and comparative evaluation is presented. The parameters used in experiment are given in Table II.

The laboratory set up that is used for experimental studies are also given in Fig. 9. The laboratory set up consists of the following

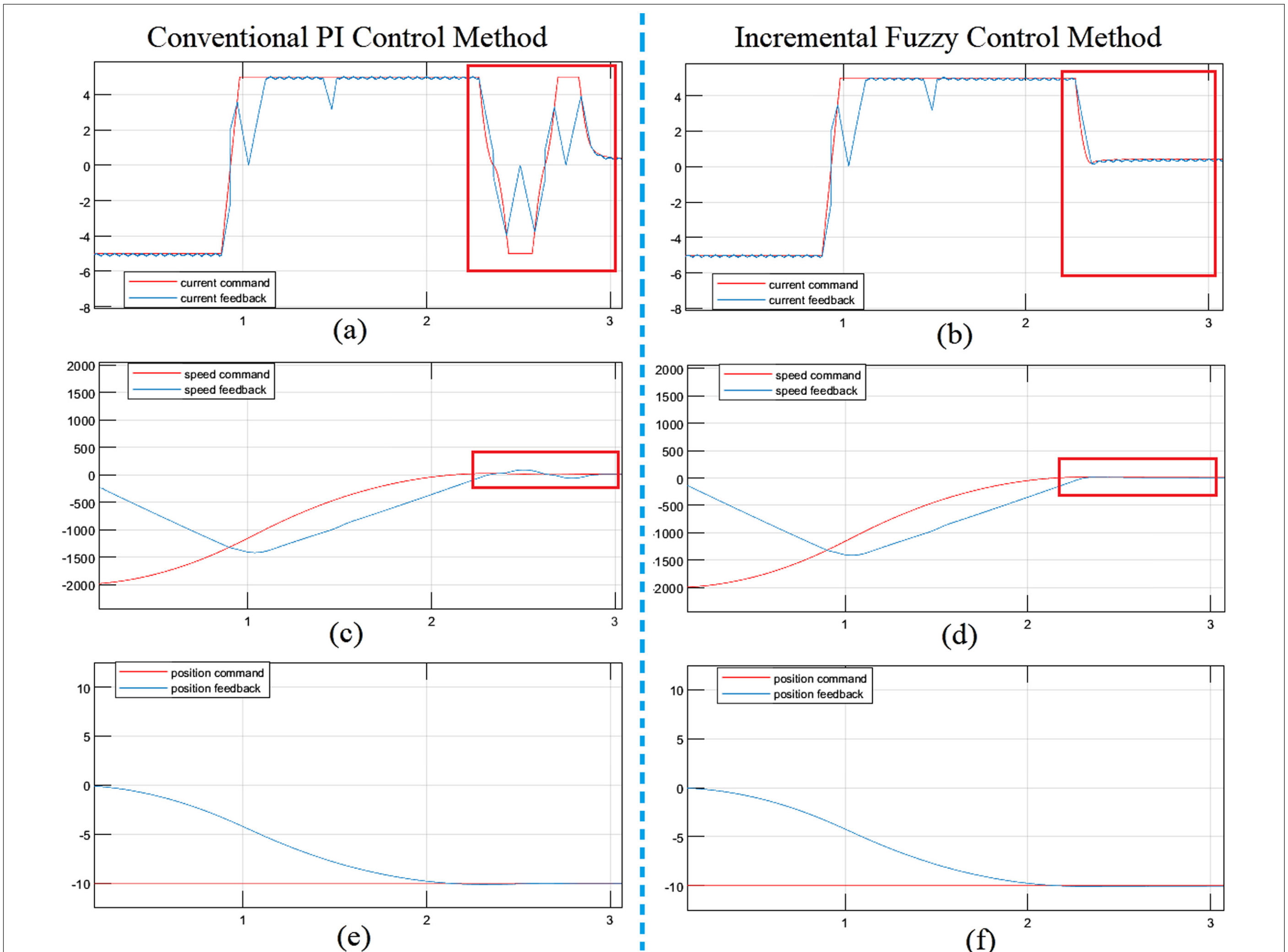

Fig. 8. Current, speed, and position waveforms of the conventional PI and IFC methods for transient state: (a) current control with conventional PI control method, (b) current control with IFC method, (c) speed control with conventional PI control method, (d) speed control with IFC method, (e) position control with conventional PI control method, and (f) position control with IFC method.

elements: 1) PC; 2) cables for electronic board connection with PC; 3) electronic board; 4) cables for electronic board connection with BLDC motor; 5) BLDC motor, hall sensor and encoder; 6) power supply for BLDC bus voltage; and 7) power supply for electronic board.

TABLE II. PARAMETER SPECIFICATIONS USED IN EXPERIMENT

Parameter	Symbol	Value
Motor bus voltage	V	140 [V]
Switching frequency	f_s	20 [kHz]
MOSFET	*IRFSL4127*	
Gate driver	*FAN7391*	
FPGA	*XC7Z020*	
ADC	*AD7944BCPZ*	
Current sensor	*ACS709LLFTR*	

FPGA, field programmable gate array.

PC (1) sends the position and current commands to electronic board (3). Also, data which came from board are collected by using PC. One of the cables (2) provides the power transmission from power supplies to electronic board and the communication between electronic board and PC. Other cable (4) connects the motor (5) and electronic board to each other. One of the power supplies (6) gives to electronic board 140 V_{dc} to use as bus voltage. Other power supply (7) provides that electronic board work properly with 28 V_{dc}. In this paper, experimental studies are performed separately for the conventional PI and proposed IFC method.

A. Experimental Result for Conventional PI Control Method

For the conventional PI control method, position control tests are applied to test the robustness of the conventional PI control method for different frequencies. Two different position commands are applied to two BLDC motors using an electronic card. One of these commands is the 65° to 65°, 1 Hz, square wave position command shown in Fig. 10. According to the position feedback data, BLDC motor can follow this command with conventional PI control method. –

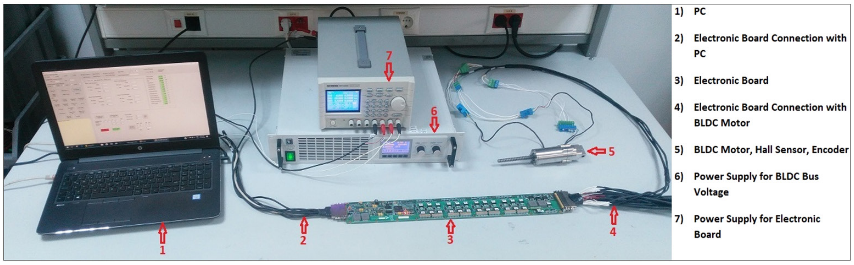

Fig. 9. Experimental test set up.

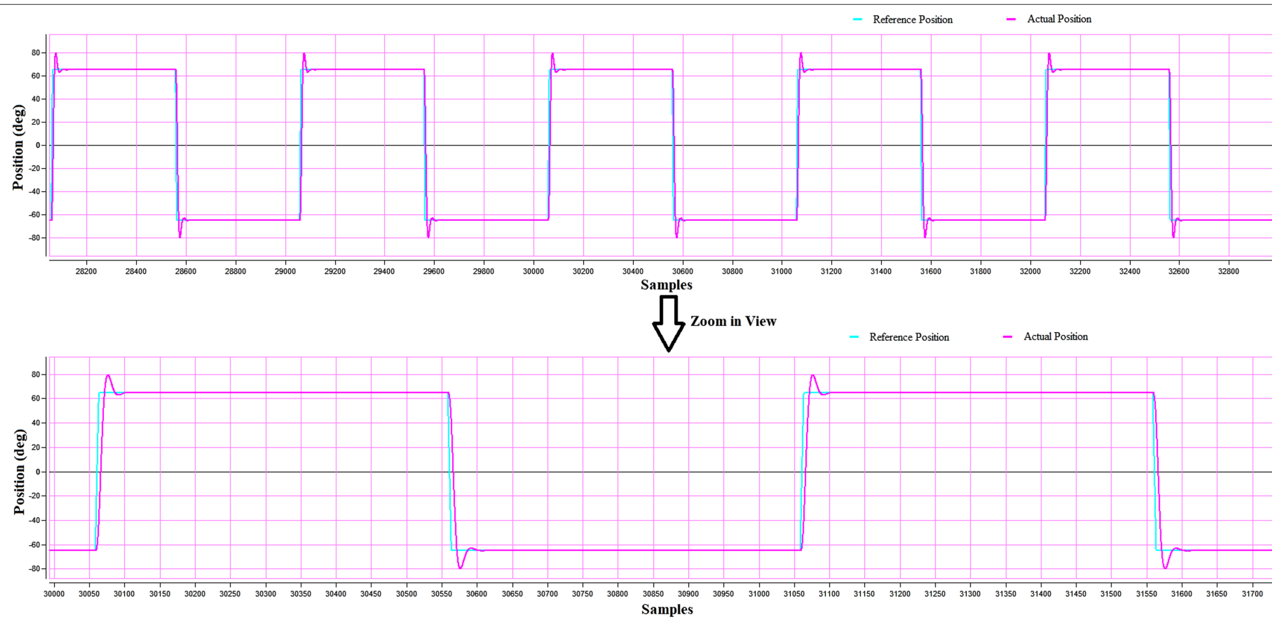

Fig. 10. Experimental test results for conventional PI control on position control for 1 Hz.

The other command is 10 Hz, square wave from 65° to −65° degrees shown in Fig. 11. According to the position feedback data, BLDC motor can also follow this command with conventional PI control method. In addition, 1000 mA, 100 Hz, square wave is applied to the system to perform the current control test as shown in Fig. 12. As a result, the BLDC motor cannot always properly track its reference command with the conventional PI control and there is too much noise in steady state. Measurements and data table of conventional PI control method for current control test are given in Table III and Table IV, respectively.

B. Experimental Results for Proposed IFC Method

The first experimental test for the proposed IFC method is position control test. Two different position commands were applied two BLDC motor by using electronic board. One of these commands is 65° to −65°, 1 Hz, square wave position command which is shown on Fig. 13. According to the position feedback data, BLDC motor can trace this command with proposed IFC method.

The other command is faster than the first position command and is a 10 Hz, square wave from 65° to −65° shown in Fig. 14. According to the position feedback data, BLDC motor can also follow this command with proposed IFC method.

The last experimental test for the proposed IFC method, 1000 mA, 100 Hz, square wave is applied to the system to perform the current control test as shown in Fig. 15. As can be seen in figure, BLDC motor always can track the current command with proposed IFC method. Also, there is no noise in steady state. Measurements and data table of proposed IFC method for current control test are given in Table V and Table VI, respectively.

There are also experimental studies to compare the conventional PI and proposed IFC methods in this paper. FPGA-based electronic board was used for these experimental studies. Current and position command are sent to electronic board through Ethernet communication interface by using PC which is connected to the electronic board. Also, current and position feedback are sent to PC by using this Ethernet interface. Proposed IFC method is obviously better than conventional PI control method. In order to increase the performance of IFC, recommended future works are listed below:

- Classification of the inputs of IFC method can be more generic. Border which depends on command can be used instead of constant border for classes.
- Steady-state error for negative command was higher than conventional PI controller on the experimental current tests. Some improvements can be found to reduce this error.
- Experimental tests were applied to unloaded BLDC motor. The implementation of experimental studies on the loaded motor is one of the main objectives of the next study.

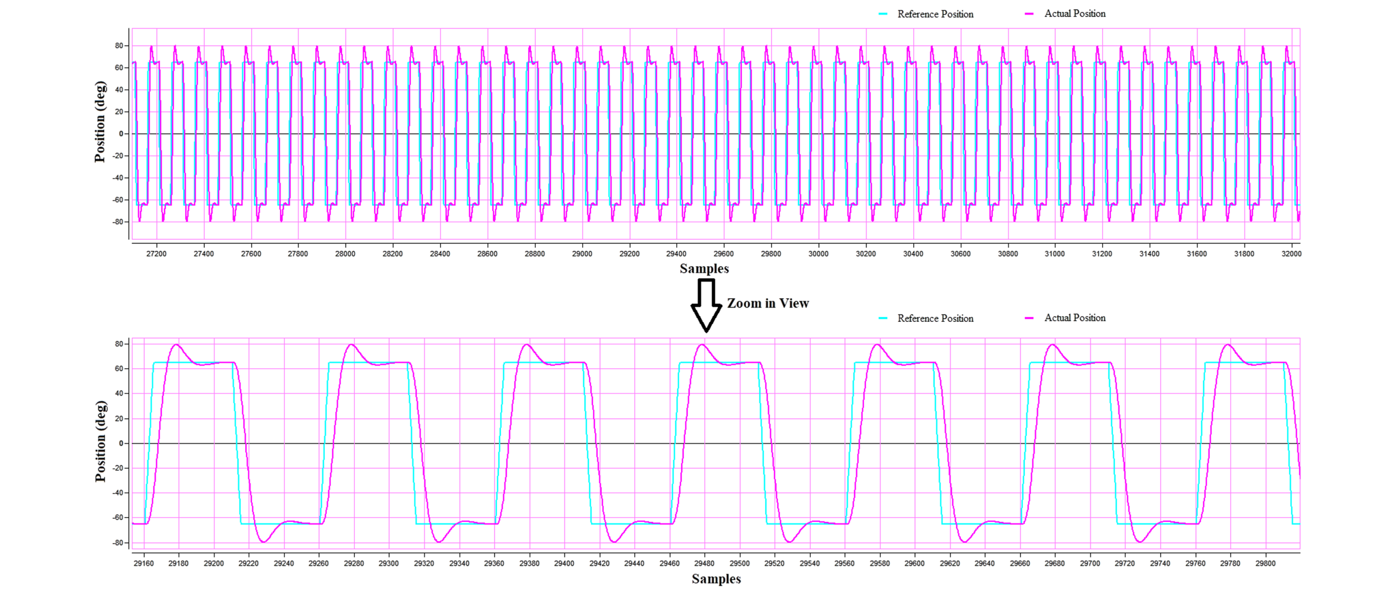

Fig. 11. Experimental test results for conventional PI control on position control for 10 Hz.

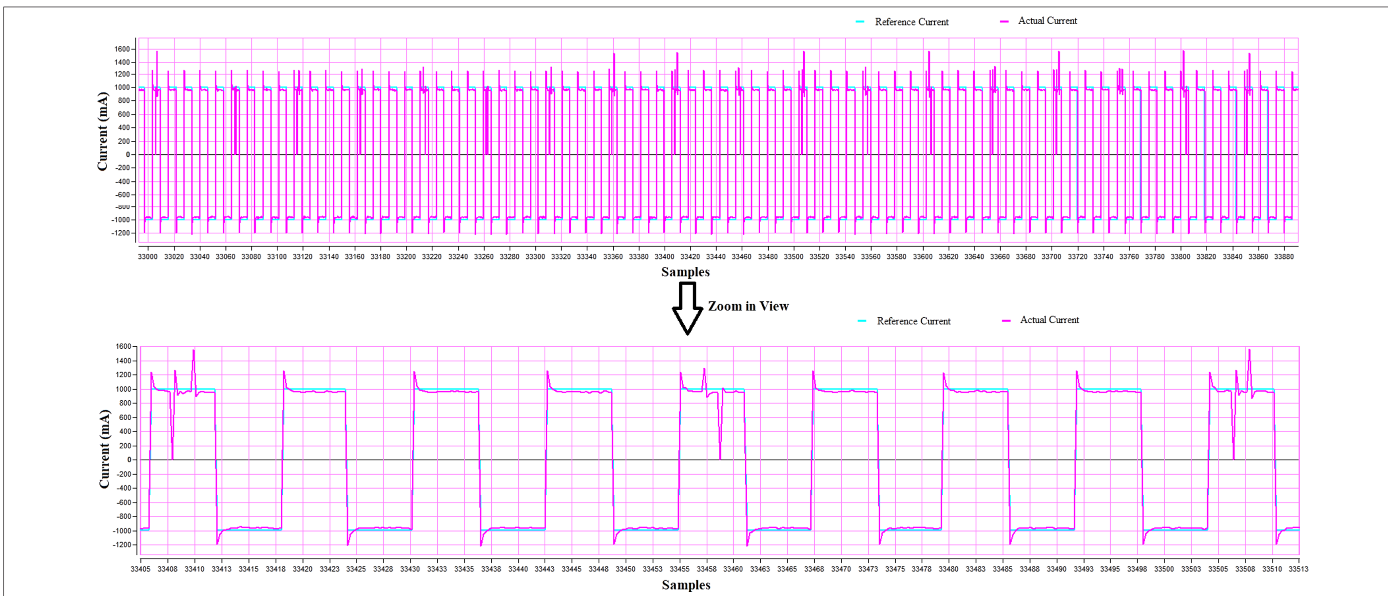

Fig. 12. Experimental test results for conventional PI control on current control test for 100 Hz.

TABLE III. MEASUREMENTS OF CURRENT CONTROL TEST FOR CONVECTIONAL PI CONTROL METHOD

Measurements (PI Control Method)	Value
Rise time	~0.2 ms
Settling time	~2 ms
Overshoot	25%
Steady-state error (positive command)	−4%
Steady-state error (negative command)	−4%

PI, proportional-integral control.

TABLE IV. DATA TABLE OF CONVENTIONAL PI CONTROL METHOD FOR CURRENT CONTROL TEST

Time (ms)	Current Command (mA)	Current Feedback (mA)
33 454.8200	−997.3839	−970.1330
33 455.8000	997.3839	970.1330
33 456.0500	997.3839	975.5832
33 458.5200	997.3839	953.7825
33 460.9900	997.3839	964.6828
33 461.2300	−997.3839	−1215.3910

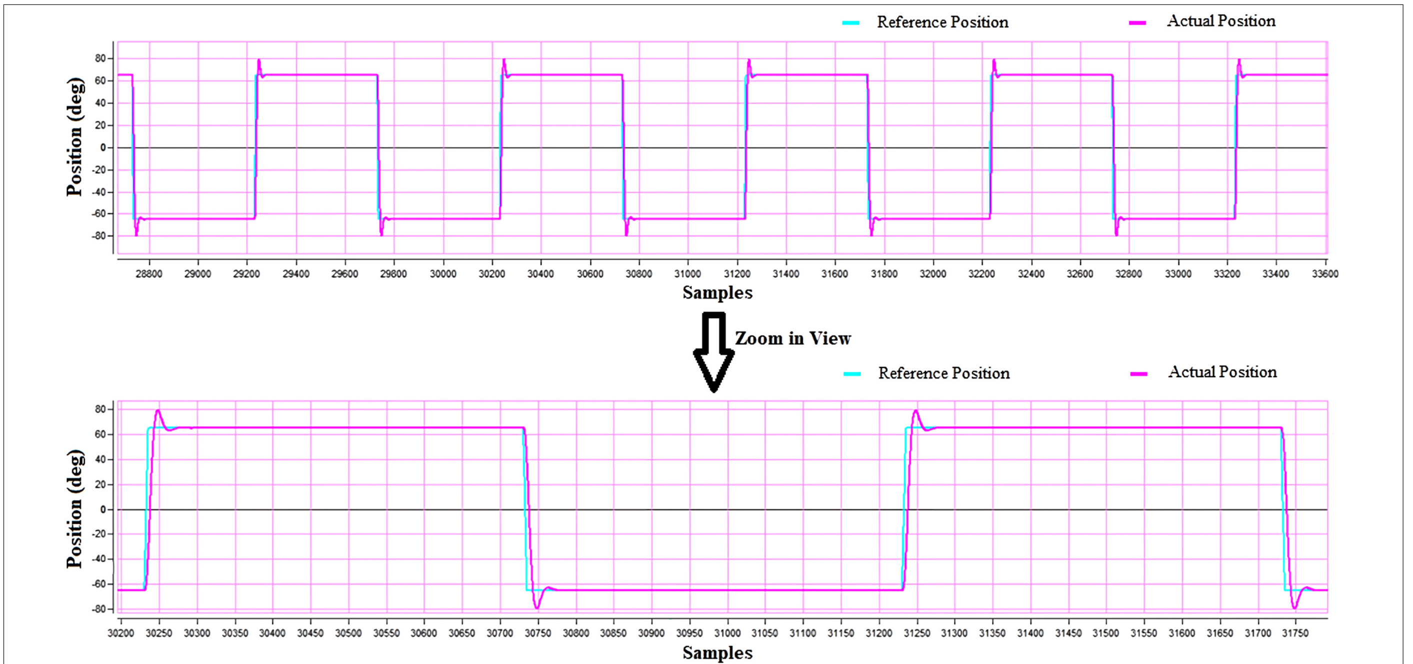

Fig. 13. Experimental test results for proposed IFC method on position control for 1 Hz.

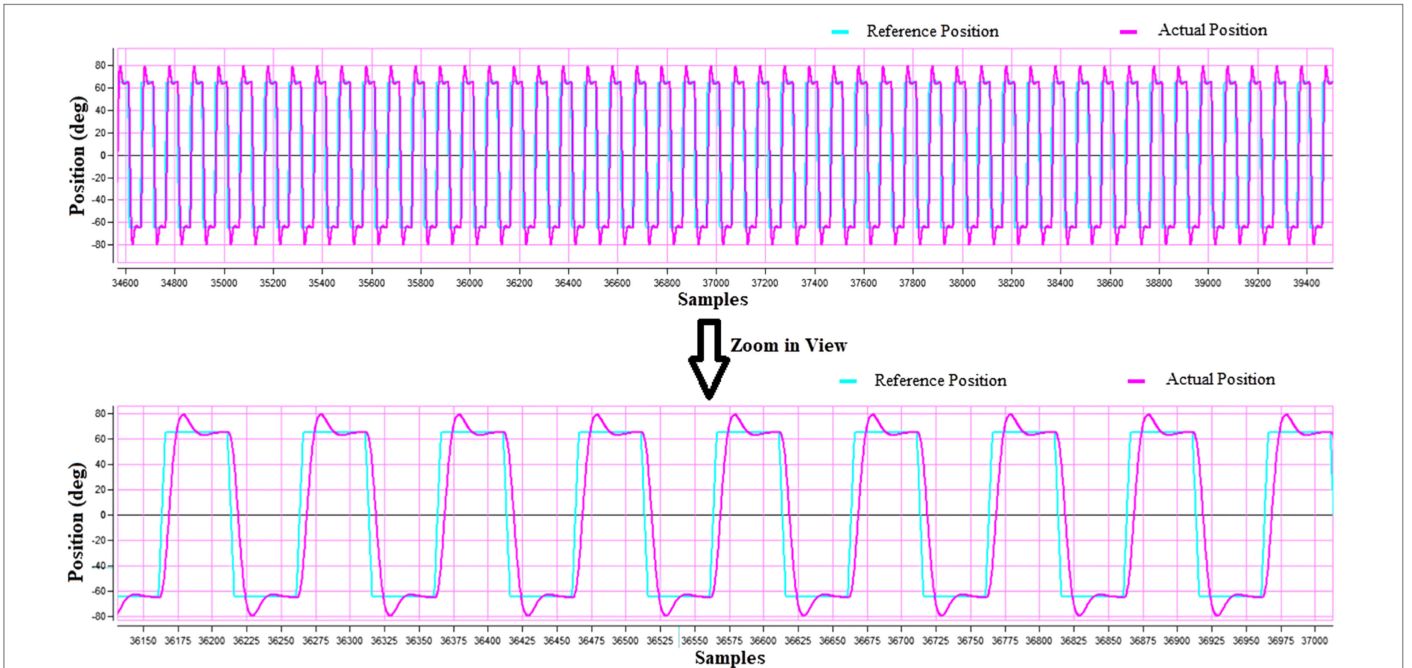

Fig. 14. Experimental test results for proposed IFC method on position control test for 10 Hz.

According to the position feedback data, BLDC motor can trace the commands that are 65° to −65°. The comparisons of experimental position control results for conventional PI control and IFC method are given in Table VII.

VI. CONCLUSION

In this paper, implementation and comparison of the BLDC motor used in different parts of the missiles with different control methods are discussed. Conventional PI and proposed IFC method are compared for BLDC motor controlling by means of simulation and experimental results.

Simulation studies were performed on MATLAB/ Simulink program. The conventional PI and proposed IFC method were analyzed by giving same current, speed, and position command on simulation. It is observed that although there are undesired oscillations in current, velocity, and position waveforms of the conventional PI controller, these oscillations are eliminated in proposed IFC method. According

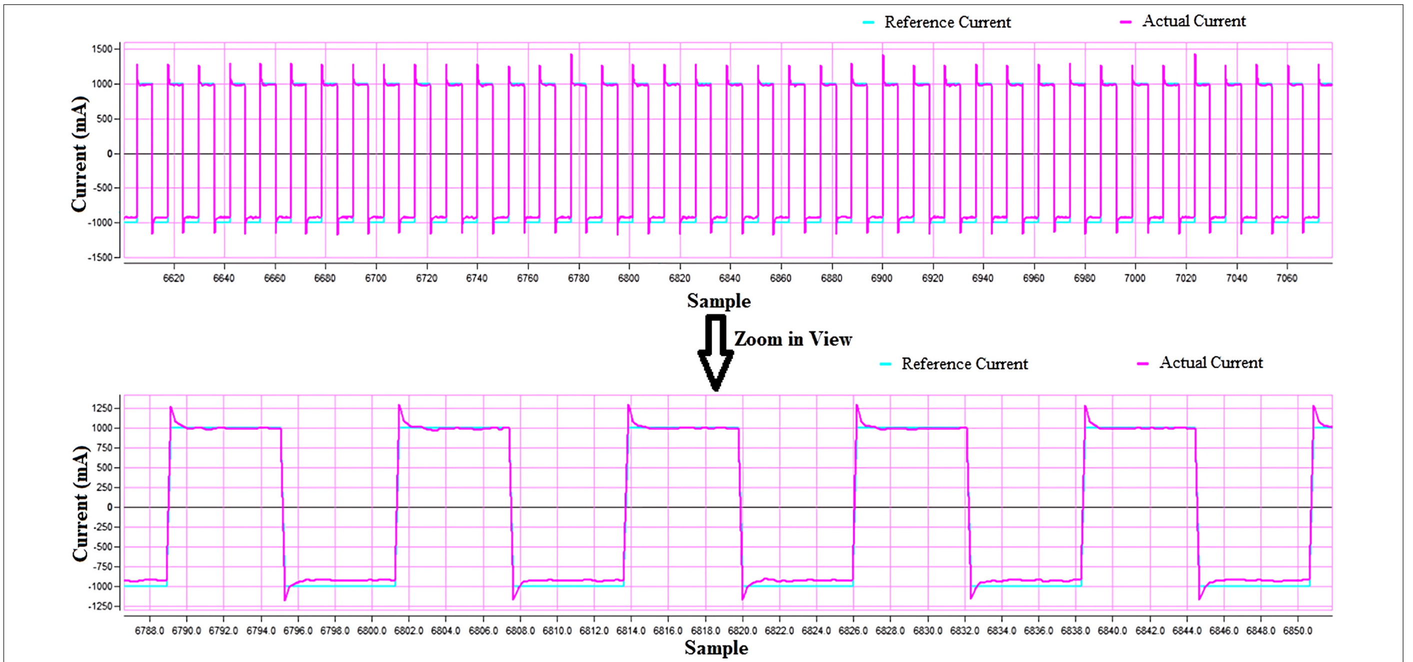

Fig. 15. Experimental test results for proposed IFC method on current control for 100 Hz.

TABLE V. MEASUREMENTS OF CURRENT CONTROL TEST FOR IFC METHOD

Measurements (IFC Method)	Value
Rise time	~0.16 ms
Settling time	~1.8 ms
Overshoot	20%
Steady-state error (positive command)	−3%
Steady-state error (negative command)	−3%

IFC, incremental fuzzy control;

TABLE VI. DATA TABLE OF IFC METHOD FOR CURRENT CONTROL TEST

Time (ms)	Current Command (mA)	Current Feedback (mA)
6815.4580	997.3839	997.3839
6815.7060	997.3839	997.3839
6818.1750	997.3839	997.3800
6823.8540	−997.3839	−926.5316
6825.0880	−997.3839	−961.9817

to the simulation results, the proposed IFC is more stable and robust than the conventional PI control method.

Experimental studies were performed by FPGA-based electronic board. In conventional PI control method, there are many unwanted current feedbacks between 0 and 1600 mA for 1000 mA reference input current. These feedbacks are unwanted for both controllers. Proposed IFC method has no unexpected current feedback as in conventional PI control method. Also rise time, settling time, overshoot, and steady-state error are tested for both control methods. The results of IFC method are slightly better than conventional PI control methods. These experimental studies prove once again that the proposed IFC method is better than the conventional PI control method. Therefore, implementation of proposed IFC method instead of conventional PI control method will improve the performance of missiles and extensions.

TABLE VII. DATA TABLE OF POSITION CONTROL TESTS FOR PI AND IFC METHODS

	Time (ms)	Position Command (Angle)	Position Feedback (Angle)
IFC method	30 231.2600	−65.0000	−65.0390
	30 265.5800	65.0000	64.5970
	30 274.4700	65.0000	64.9480
	30 731.5100	65.0000	65.0390
	30 759.6600	−65.0000	−65.0390
	30 775.9500	−65.0000	−65.0390
Conventional PI control method	30 058.5200	−65.0000	−64.9480
	30 070.3700	65.0000	64.6650
	30 082.2200	65.0000	65.9280
	30 094.3200	65.0000	64.4595
	30 571.8500	−65.0000	−65.6185
	30 595.3100	−65.0000	−64.5440

IFC, incremental fuzzy control; PI, proportional-integral control.

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