# Performance analysis of Direct Torque Control of Induction Motor using Snetly real-time Controller

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***Abstract*—In the last decade, researchers and scientists have been attracted to the innovations and progress in the field of power electronics and drives. The demand for real-time prototype controllers is rapidly increasing in field-oriented control (FOC) methods. Among those, field-programmable gate array (FPGA) digital controllers are widely used in the speed estimation of Sensorless AC drives. Due to non-linearity, complex calculations involved in the rotating AC machines cause hardware issues related to the implementation and monitoring of control systems in real-time industrial applications. In this work, a novel Xilinx ARTIX-7 FPGA-based Snetly real-time controller is designed and proposed for Direct Torque Control (DTC) of induction motor drive. The performance analysis of the drive is validated and verified using MATLAB/Simulink Software and the results are compared with the proposed Snetly controller. The proposed prototype controller shows robust performance and the results are presented in this paper using numerical simulations. In the future, the proposed controller can compete with other controllers in the extended areas of modern AC drives.**

***Keywords—induction motor, field programmable gate array, direct torque control, Snetly real-time controller***

## I. INTRODUCTION

In recent times, induction motors have attracted the research community in the field of high-performance AC drives with parallel progress in power electronics[1]. Induction motors are employed in variable-speed applications, due to their advantages of rugged construction, free maintenance, low cost, robustness, and can operate in hostile environments[2].

In AC drives, Induction motors are used in the commercial applications of vector control and scalar control applications. Among them, vector control of field-oriented control methods is used for advanced applications in power and industrial drives including machine tools, steel, and paper machines[3]. Further, induction motors have found themselves in the areas of Sensorless speed estimation in Electric Vehicles and their allied areas. However, cost and reliability are the key parameters for the selection of a motor that is used for various applications[4].

In the last decade, there are several methods have been developed to control the induction motor to address precise and quick control of the motor flux and torque and to reduce the control algorithm complexity involved in the advanced vector control methods[5]. However, the real-time computation is higher and demands high switching power devices for the induction motor drive due to their time-varying nature and higher nonlinearity. To deal with this, advanced FPGA real-time prototype controllers are preferred in the field of AC drives[6],[7],[8]. Among the various topologies, the DTC technique is simpler than the other FOC methods. In DTC, there is no position or speed sensor required to measure the speed which reduces the cost and improves reliability. Moreover, the processing time is very low, due to this a better torque response is achievable since there is no usage of the PWM modulator in the technique[9].

From the literature, DTC can be implemented in different ways such as the lookup-table method, Space vector modulation (SVM) based DTC, and other modified DTC techniques[10],[11],[12]. The methods are much popular and successful in achieving constant switching frequency, torque ripple reduction, the selection of voltage vectors, and artificial intelligence-based speed controllers employed for DTC algorithms[13]. In conventional practices, microcontrollers or Digital Signal Processors (DSP) are used to realize the vector control algorithms. The complex calculations and the nonlinearity nature of rotating AC machines require higher sampling rates and higher computation times to execute each instruction of the controller. In such cases, the hardware implementation is to be difficult and requires skilled engineers to solve the complex models[14],[6],[15].

In this work, a novel Xilinx ARTIX-7 FPGA Snetly real-time controller is designed and proposed to study the performance analysis of a DTC-fed induction motor drive. Using the real modular system, the prototype controller provides good accuracy and lower computation time. Unlike traditional practices, the hardware design is easy and also development and deployment are done on the same platform. The DTC model is designed in MATLAB/Simulink and then the same model is designed in the Snetly platform. The results are validated and verified by using both MATLAB/Simulink and the Snetly prototype controller environment.

This article is organized as follows: Section II covers a detailed discussion of the DTC scheme. The proposed controller design is introduced with the MATLAB/Simulink model in Section III. The comparative results are validated

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to verify the effectiveness and robustness of the proposed controller and Simulink software of the DTC scheme presented in Section IV. Finally, the conclusion points depict the overall summary of the article covers in Section V.

## II. Direct Torque Control

### A. The Principle of DTC

In variable frequency drives, DTC is used to control the torque and then finally speed of the three-phase AC electric motors. In this technique, motor magnetic flux, and torque is estimated by using the voltage and current measurement. The DTC technique is an accurate method to get better and fast torque dynamics in high-efficiency applications[9].

### B. The Control algorithm of DTC

The following steps need to be considered in the DTC implementation [9].

STEP-1: Measure the three-phase current $\left(i_{abc}\right)$ and voltage $\left(V_{abc}\right)$. Using Clark Transformation, measured three-phase current and voltage converted into two-phase current $(i_{s\alpha}, i_{s\beta})$ and two-phase voltage $(V_{s\alpha}, V_{s\beta})$ respectively.

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{1}$$

Where $X$ represents voltage or current or flux

STEP-2: In the stationary reference frame, calculate the vector flux $(\hat{\Psi}_{s\alpha}, \hat{\Psi}_{s\beta})$, total stator flux $(\hat{\Psi}_s)$, and the position of the flux given by

$$\hat{\Psi}_{s\alpha} = \int (V_{s\alpha} - i_{s\alpha} R_s)\, dt \tag{2}$$

$$\hat{\Psi}_{s\beta} = \int (V_{s\beta} - i_{s\beta} R_s)\, dt \tag{3}$$

$$\hat{\Psi}_s = \sqrt{(\hat{\Psi}_{s\alpha})^2 + (\hat{\Psi}_{s\beta})^2} \tag{4}$$

The angle between the estimated stator flux components $(\hat{\Psi}_{s\alpha}, \hat{\Psi}_{s\beta})$ is given by the following sectors;

Sector-1: $-\frac{\pi}{6} : \frac{\pi}{6}$ Sector-2: $\frac{\pi}{6} : \frac{\pi}{2}$

Sector-3: $\frac{\pi}{2} : \frac{5\pi}{6}$ Sector-4: $\frac{5\pi}{6} : -\frac{5\pi}{6}$

Sector-5: $-\frac{5\pi}{2} : -\frac{\pi}{2}$ Sector-6: $-\frac{\pi}{2} : -\frac{\pi}{6}$

STEP-3: The value of torque can be estimated by using the following equation,

$$\hat{T}_{em} = \frac{3}{2}\frac{P}{2}\left(\hat{\Psi}_{s\alpha} i_{s\beta} - \hat{\Psi}_{s\beta} i_{s\alpha}\right) \tag{5}$$

Where $P$ = Number of Poles, $T_{em}$ = Electromagnetic Torque

STEP-4: Calculate the next switching using the switching table concerning the change in torque $(d_T)$, flux $(d_\psi)$, and position of the flux. The switching table can be constructed as shown in TABLE I.

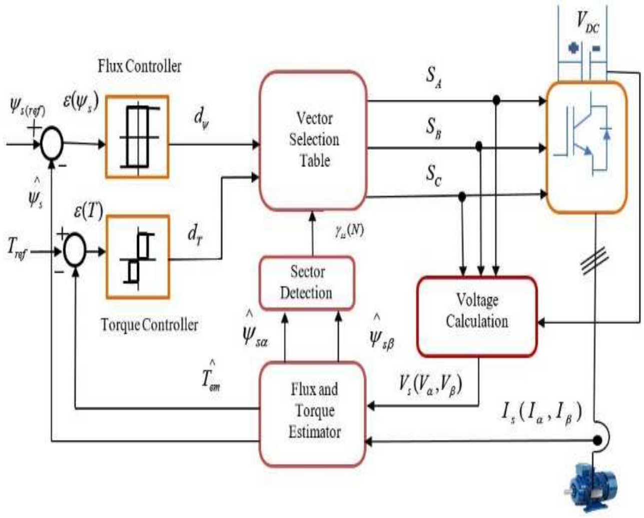


Fig. 1. Block diagram of DTC fed Induction motor drive system

TABLE I. Switching Table of Inverter Voltage Vectors

| $d_\psi$ | $d_T$ | Voltage Vector and Sector Number (S-1 to S-6) | | | | | |
|---|---|---|---|---|---|---|---|
| | | ***S-1*** | ***S-2*** | ***S-3*** | ***S-4*** | ***S-5*** | ***S-6*** |
| 1 | 1 | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_1$ |
| | 0 | $X_7$ | $X_0$ | $X_7$ | $X_0$ | $X_7$ | $X_0$ |
| | -1 | $X_6$ | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ |
| 0 | 1 | $X_3$ | $X_4$ | $X_5$ | $X_6$ | $X_1$ | $X_2$ |
| | 0 | $X_0$ | $X_7$ | $X_0$ | $X_7$ | $X_0$ | $X_7$ |
| | -1 | $X_5$ | $X_6$ | $X_1$ | $X_2$ | $X_3$ | $X_4$ |

The overall block diagram of the DTC technique is presented as shown in Fig. 1. The desired stator flux and electromagnetic torque are compared with the corresponding estimated values. The comparative results are analyzed through a hysteresis band controller. Three-level hysteresis comparator and the two-level hysteresis comparator are used to control the electromagnetic torque and the stator flux respectively.

The switching table can be determined using the information of comparators and the flux vector. The inverter Voltage switching vector or voltage reference vector is determined by the increment and decrement of flux and torque commands. These can be determined by comparing the estimated values of flux and torque [16].

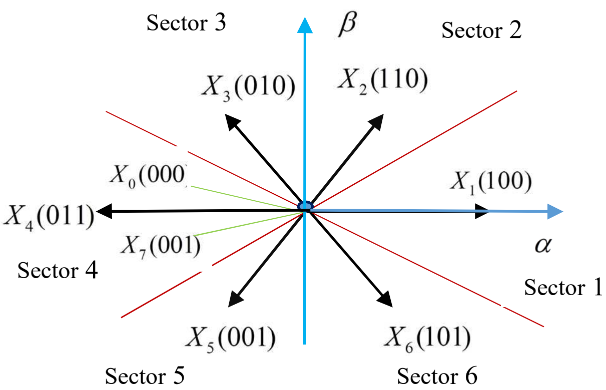


Fig. 2. Schematic of Stator flux and Inverter voltage vectors

## III. SYSTEM DESIGN

In this section, DTC can be implemented step by step in MATLAB/Simulink and the Snetly platform in the following subsections.

### A. *DTC design using MATLAB/Simulink*

The DTC method is implemented in MATLA/Simulink software as shown in Fig. 3.

*a) Flux and Torque Estimator*

The flux and torque estimation is the critical part of the DTC design. In this block, the transformation blocks, and low pass filters are used to estimate torque and flux. The flux and torque estimator block is implemented and shown in Fig. 4.

*b) Direct Torque Control Block in Simulink*

The two hysteresis controllers are used for flux and torque. The overall DTC block is implemented in Simulink as shown in Fig. 5.

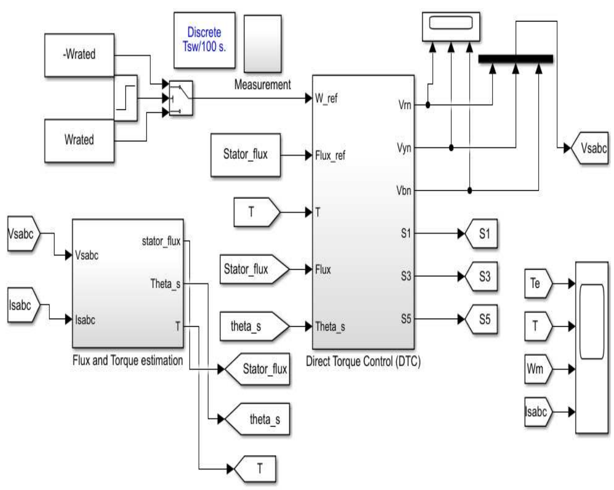


Fig. 3. Block diagram of overall DTC design in MATLAB/Simulink

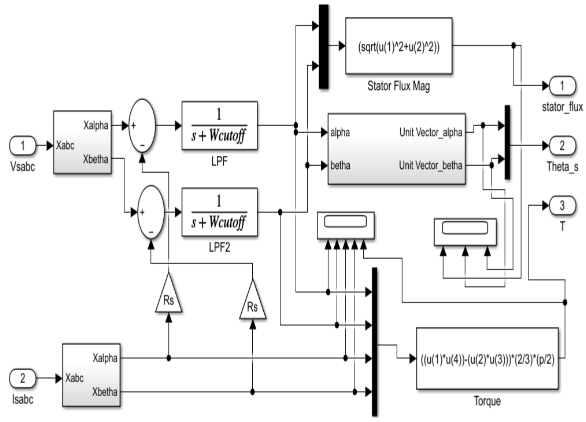


Fig. 4. Flux and Direct torque control block in MATLAB/Simulink

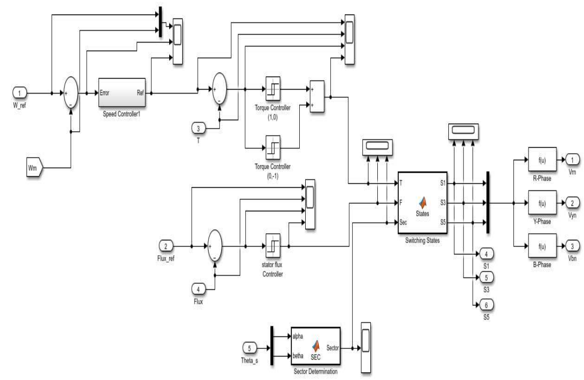

Fig. 5. Schematic of DTC block in MATLAB/Simulink

### B. *DTC design in the Snetly platform*

The DTC is implemented in the Snetly platform as shown in Fig. 6. The detailed individual blocks of the proposed controller are shown in Fig. 7 and Fig. 8. The detailed description of each block of the Snetly controller is described in TABLE II.

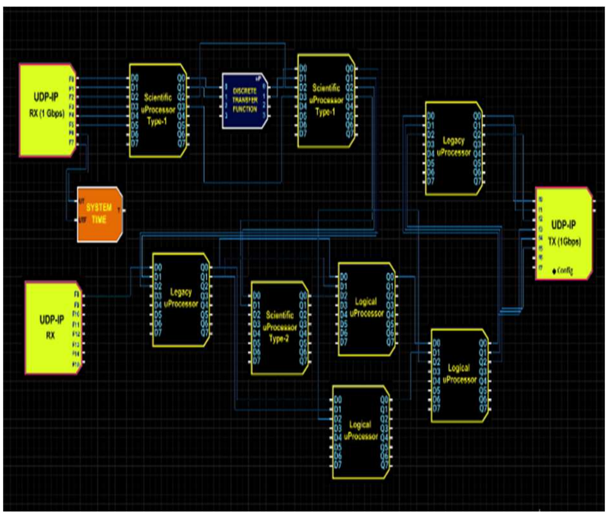

Fig. 6. Block diagram of overall DTC design in the Snetly platform

The prototype controller consists of inbuilt 15 independent processors: six scientific, six legacy processors, and three logical processors. Also, the built-in compiler and assembler help to convert the custom script to assembly code and assembly to binary code respectively. The availability of 32-bit registers, four-channel DSO, seven-channel logic analyzer, and four-channel plotter are helpful to design the custom design and verification.

TABLE II. SNETLY CONTROLLER

| Name of the Block | Description |
|---|---|
| UDP_IP RX | Block communicate with MATLAB interface to Receive data via Gigabit ethernet (speed 1GBPS) and the data format is IEEE754 32-bit floating point. Receive 8-channel input data from MATLAB. |
| UDP_IP TX | Block interacts with MATLAB interface to Transmit data via Gigabit ethernet(speed 1GBPS). The data format is IEEE754 32-bit floating point. Transmit 8-channel input data to MATLAB. |
| SCIENTIFIC TYPE1 PROCESSOR | The 32-bit processor is used to develop the model-based design with a maximum sample time of 10 uS.<br>Each processor has 255 Register with IEEE754 floating point data format |
| SCIENTIFIC TYPE2 PROCESSOR | The 32-bit processor is used to develop a model-based design with a maximum sample time of 10 uS.<br>Each processor has 255 Registers with IEEE754 floating point data format. |
| LEGACY PROCESSOR | The 32-bit processor is used to develop a model-based design with a maximum sample time of 10uS.<br>Each processor has 255 Registers with IEEE754 floating point data format. |
| LOGICAL PROCESSOR | The 32-bit processor is used to develop a model-based design with a maximum sample time of 10uS.<br>Each processor has 255 Registers with IEEE754 floating point data format. |
| SYSTEM TIME | Maximum sample time 10uS |

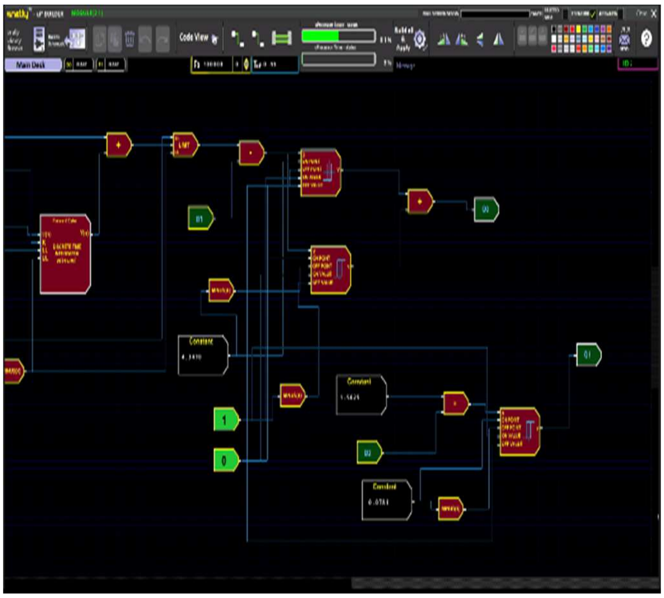

Fig. 7. DTC design in the Snetly platform

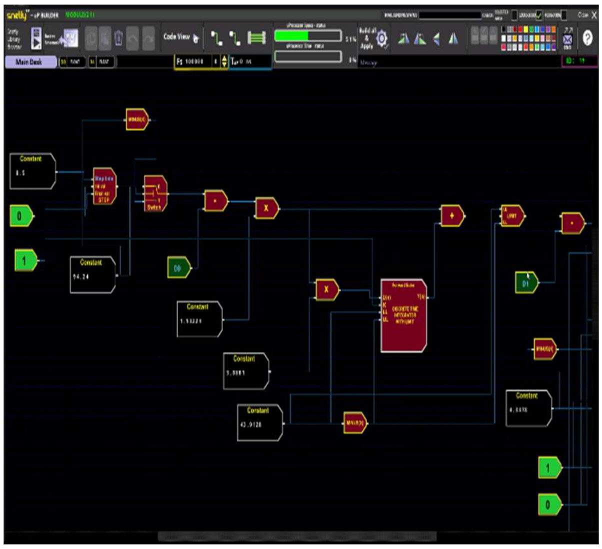

Fig. 8. DTC design in the Snetly platform

## IV. RESULTS AND DISCUSSION

### *A. MATLAB/Simulink Results*

The performance analysis of the DTC-based induction motor drive is developed and analyzed using MATLAB/Simulink software. The induction motor parameters are shown in Table III.

The rated load torque (Electromagnetic) of 42.44 N-m is shown in Fig. 9. The rated speed of 1000 rpm or 104.71 rad/sec and 900 rpm or 94.24 rad/sec is applied to the motor as shown in Fig. 10. The rated load torque is applied at 2 sec as shown in Fig. 9.

Due to the fast dynamic of DTC, the motor is reached its rated speed quickly, and then speed reversal is applied at 2 sec. The corresponding change in the motor speed is obtained rapidly as shown in Fig. 10. Also, the rated three-phase stator current is observed in Fig. 11.

The torque response is quite faster in comparison to the other FOC methods. The DTC method is highly useful in fast torque response applications.

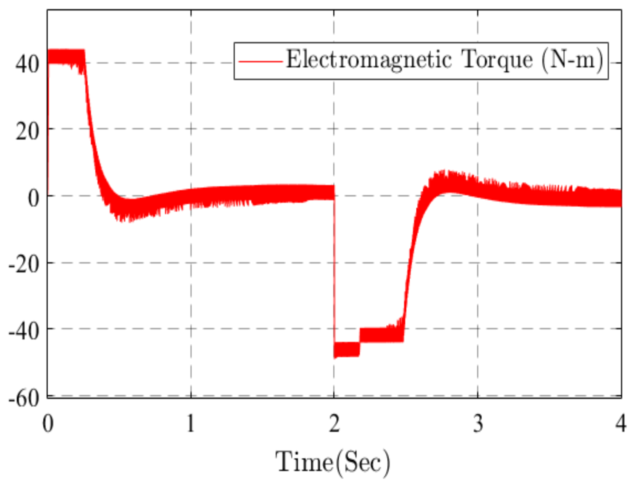


Fig. 9. Electromagnetic Torque response

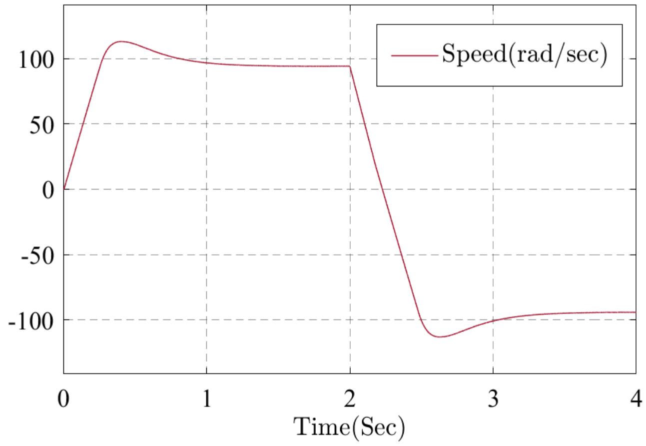


Fig. 10. Speed response

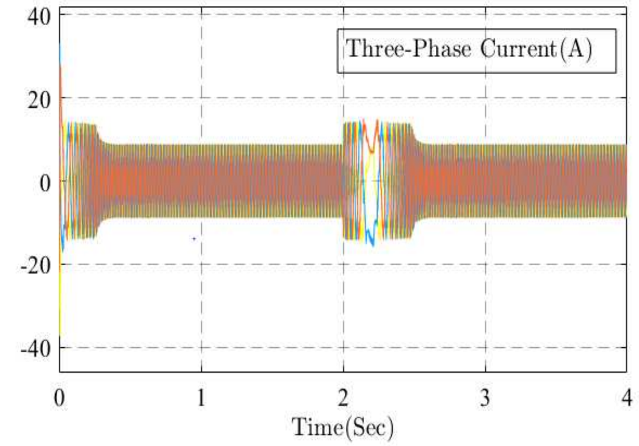


Fig. 11. Stator current response

TABLE III. THREE-PHASE INDUCTION MOTOR

| Name Plate Details | Squirrel Cage Type | |
|---|---|---|
| | ***Parameter*** | ***Value*** |
| 4 kW,<br>Three-phase,<br>415 V,<br>11 A,<br>6 Pole,<br>50 Hz,<br>1000 rpm | Stator Resistance | $R_s = 2.86\ \Omega$ |
| | Rotor Resistance | $R_r = 2.86\ \Omega$ |
| | Stator Inductance | $L_s = 0.1639$ H |
| | Rotor Inductance | $L_r = 0.1639$ H |
| | Mutual Inductance | $L_m = 0.1521$ H |
| | Moment of Inertia | $J = 0.11$ kg-m$^2$ |
| | Coefficient of friction | $B = 0.011$ |

## *B. Result analysis using the Snetly platform*

To verify and validate the Simulink results, the DTC design is implemented in the Snetly design platform. The proposed controller is observed under 10 sec time intervals. The various factors such as Electromagnetic torque, Speed, and Three-phase stator current are shown in the following Figures. At 4 sec, the rated load torque is applied and the motor speed response is shown in Fig. 12 and Fig. 14. The speed and torque response is obtained similarly to simulation results.

The reference flux and the estimated flux in the overall drive system are presented in Fig. 13. The change in reference speed causes an abrupt change in stator current. The high inrush current affects the stator winding and mitigates the service life of an engine. The stator current response of the DTC-fed induction motor is shown in Fig. 15.

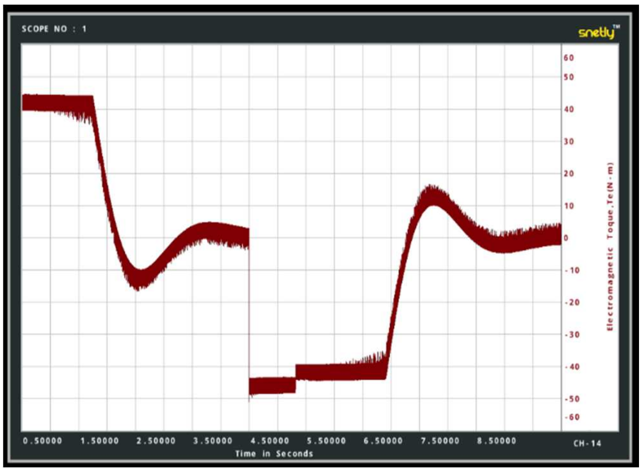


Fig. 12. Electromagnetic Torque response in the Snetly controller

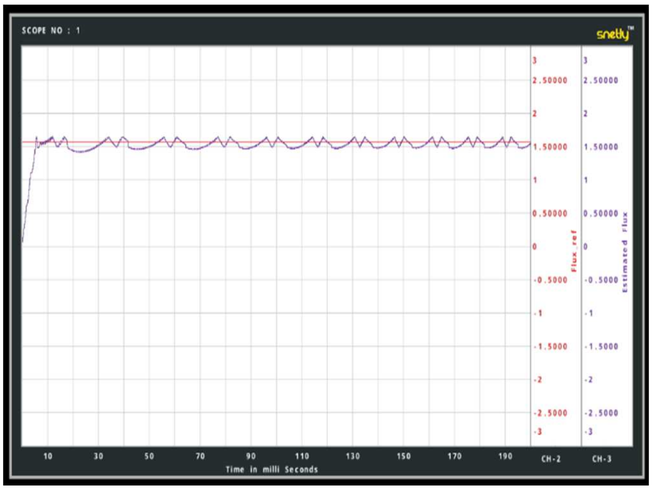


Fig. 13. Reference and estimated flux at reference Speed in the Snetly controller

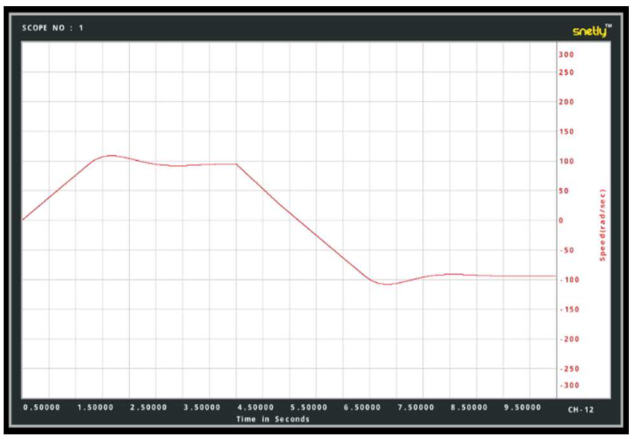


Fig. 14. Speed response in the Snetly controller

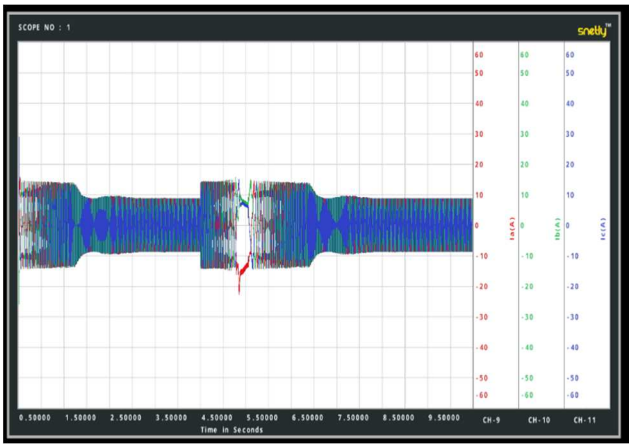


Fig. 15. Stator current response in the Snetly controller

## V. CONCLUSION

In this work, a novel FPGA-based Snetly real-time controller is designed to study the performance analysis of the DTC of an Induction motor drive. The proposed controller is having Xilinx ARTIX-7 FPGA Controller with a 150 MHZ Clock source. The real-time controller is highly useful in high-performance AC drives.

The following important conclusions can be drawn from this research work is as follows: The Change in Motor speed causes a change in torque response and the current deviation in the DTC-fed induction motor drive. To deal with this, fast FPGA controllers Xilinx ARTIX-7 FPGA are preferred in AC drives, Due to its simple structure, the hardware implementation cost and complexity are reduced with good reliability.

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