

FPGA Based High Performance Torque and Flux Estimator

Tole Sutikno¹, Aiman Zakwan Jidin², Auzani Jidin³, Nik Rumzi Nik Idris⁴

Abstract – This paper presents a new design of the torque and stator flux estimators for Direct Torque control (DTC) for Field Programmable Gate Array (FPGA) implementation, which permit very fast calculations. An alternative variable word-size approach in two's complement fixed-point format is used for the implementation, in order to minimize calculation errors and the hardware resource usage. The simulation results of DTC model in Matlab, which performed double-precision calculations, are used as references to digital computations executed in FPGA implementation. The Hardware-in-the-loop (HIL) method is used to verify the minimal error between Matlab simulation and the experimental results, and thus the well-functionality of the implemented estimators. Copyright © 2011 Praise Worthy Prize S.r.l. - All rights reserved.

Keywords: Direct Torque Control, FPGA, HIL, MATLAB/Simulink, Torque and Flux Estimator

Nomenclature

ADC	Analog to digital converter
DSP	Digital signal processing
DTC	Direct torque control
FOC	Field oriented control
FPGA	Field programmable gate array
HIL	Hardware-in-the-loop
I_a, I_b	a and b components of the stator current in abc reference frame
I_D, I_Q	D and Q components of the stator current in stationary reference frame
P	Number of pole pairs
φ_s	Stator flux
φ_D, φ_Q	D and Q components of the stator flux in stationary reference frame
R_s	Stator resistance
S_a, S_b, S_c	Switching states of phase a, b, c
T_e	electromagnetic torque
T_s	Sampling time
V_D, V_Q	D and Q components of the stator voltage in stationary reference frame
V_{DC}	DC link voltage
VHDL	VHSIC hardware description language
VHSIC	Very-high-speed integrated circuits

I. Introduction

DTC scheme has gain popularity to be implemented for motor drives. The main reason for its popularity is due to its simple structure, especially when compared with FOC scheme, which was introduced a decade earlier. This scheme is well known as robust control as it is less dependency on machine parameters, without the complex field orientation block, speed encoder and the inner regulation loop [1]-[13].

Since DTC was first introduced by Takahashi (1986) [14] and Depenbrock (1988) [15], several variations to its original structure were proposed to overcome the inherent drawbacks of DTC such as, inconstant switching frequency, torque ripple, and high sampling requirement for digital implementation [2]-[8], [16]-[18].

For digital implementation, the DTC algorithm is frequently implemented in a Microcontroller or DSP [2], [4], [12], [17], [19]-[23]. However, serial calculations are performed and therefore, they cannot execute fast computation without any losses. As an adequate solution, fast calculations are performed by using FPGA [24]-[29]. Moreover, the high sampling time is the crucial part which allows the minimization of torque ripple [17], [24]-[29].

However, it is not easy to implement DTC in FPGA hardware. The hardest part in the DTC implementation is the torque and flux estimations [24]-[25], [27]-[30]. Toh [17] has implemented all parts of the DTC in FPGA hardware, unless torque and flux estimator part. As a result, she only succeeds to make the sampling time limited to 55 μ s. Actually, Monmasson [24] has developed the implementation of DTC in FPGA hardware, but because it using third party (MATLAB/Simulink with the Xilinx System Generator fixed-point toolbox), so the sampling time limited to 50 μ s. Ferreira [31] also has difficulty to increase the sampling frequency, and he only succeeds to improve till 25 μ s. In the other research, despite an increasing of processing time till 20.34 μ s has been achieved by Utsumi [32], but the sampling time of the DTC still 25 μ s. References [20]-[22] were worse; they use the sampling frequency 150, 100 and 100 μ s respectively.

This main contribution of the research presents a new design of the torque and flux estimator of DTC for FPGA implementation, using two's complement fixed-point representation with variable word sizes through the

estimation process, and to improve the sampling time till 5µs. The validation of the implementation is done by verifying the experimental results during the motor's steady state.

II. Direct Torque Control

Figure 1 represents the topology of a DTC drive. The estimated flux magnitude and torque are compared with their references values. Torque and flux comparators are consisted of three and two-level hysteresis respectively. Besides, the sector judgment evaluates the position of the stator flux vector in DQ coordinates.

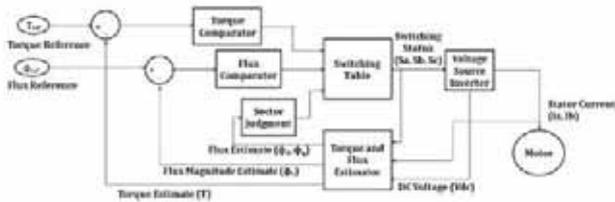


Fig. 1. DTC topology

The switching table produces the switching statuses according to the output of torque and flux comparators and the sector judgment. Those switching statuses are connected to the inverter, which is connected to the motor. They are also used as the input for torque and flux estimation.

To estimate the stator flux and the electromagnetic torque, several parameters need to be determined. Firstly, the stator currents from the motor I_a and I_b , are transformed into DQ coordinates, which are adequate to DTC algorithm, as follows:

$$I_D = I_a \tag{1}$$

$$I_Q = \frac{\sqrt{3}}{3} (I_a + 2I_b) \tag{2}$$

At the same time, by using the switching status (S_a , S_b and S_c) produced by the switching table, the stator voltages in DQ components are determined:

$$V_D = \frac{V_{dc}}{3} (2S_a - S_b - S_c) \tag{3}$$

$$V_Q = \frac{\sqrt{3}}{3} V_{dc} (S_b - S_c) \tag{4}$$

Then, using the calculated I_b , I_q , V_d and V_q , the estimation of the stator flux in DQ coordinates are performed as follows:

$$\varphi_D = \varphi_{D_{old}} + (V_D - R_S I_D) T_s \tag{5}$$

$$\varphi_Q = \varphi_{Q_{old}} + (V_Q - R_S I_Q) T_s \tag{6}$$

Notice that R_s is the estimated stator resistance, while T_s is the implementation sampling time. In addition, equations (5) and (6) correspond to the integration using Back Euler Method. As a matter of fact, [21]-[22] suggested that a filter should be added to the integrator in the practical implementation. Thus, equation (5) and (6) become:

$$\varphi_D = (\varphi_{D_{old}} + (V_D - R_S I_D) T_s) \cdot (1 - \omega_c T_s) \tag{7}$$

$$\varphi_Q = (\varphi_{Q_{old}} + (V_Q - R_S I_Q) T_s) \cdot (1 - \omega_c T_s) \tag{8}$$

Finally, equation (9) calculates flux magnitude by using a square root calculation, whereas the electromagnetic torque is estimated in equation (10):

$$\varphi_s = \sqrt{\varphi_D^2 + \varphi_Q^2} \tag{9}$$

$$T_e = \frac{3}{4} P (I_Q \varphi_D - I_D \varphi_Q) \tag{10}$$

III. FPGA Based Proposed Torque and Flux Estimator Architecture

The algorithm of torque and flux estimation is implemented in an architecture consisted of five main blocks, as shown in Figure 2. This architecture has six inputs: two 21-bit currents I_a and I_b and three switching status S_a , S_b and S_c . At the end, it produces four outputs: the estimation values of torque (T_e), flux (φ_s) and sector. The sampling time chose is 5 µs, which is limited by the ADC used.

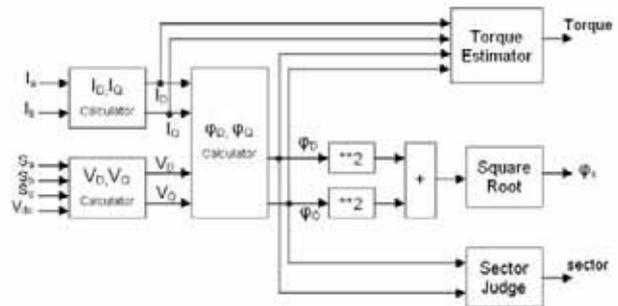


Fig. 2. Block Diagram of torque and flux estimators

All the equations which are modeling the motor behavior is implemented in a two-stage-pipelined architecture, as presented in Figure 3. Several mathematical operations are performed in parallel. At the first stage, stator currents and voltages in DQ-coordinates are calculated in parallel so that those results can be used to estimate the stator flux in the same stage.

The resulted currents and flux are used to determine the flux magnitude and the torque estimation in the second stage. A 62-bit non-restoring square root is implemented in order to compute the flux magnitude.

bits (6 integer bits plus 16 fractional bits). Nevertheless, it is stored in 7.16 bits to avoid overflow, which may happen during the addition operation. Next, when the addition result is multiplied by $\frac{1}{3}\sqrt{3}$, which coded in 1.18 bits, I_q should be represented in 8.34 bits. But, it is truncated to 6.16 bits.

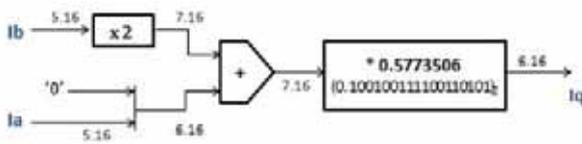
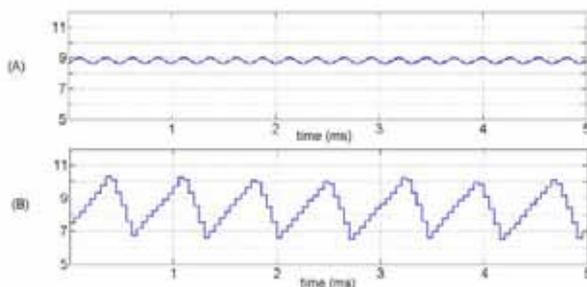


Fig. 5. The example of I_q calculation

III.3. Sampling Time

The sampling time T_s is $5\mu s$. Therefore, all the operations involved in this model were performed within this period.

Notice that the use of high sampling frequency is important in DTC implementation, for the purpose to minimize the torque ripple. The sampling time used for DSP implementation is normally much bigger than T_s , which is not less than $50\mu s$. Therefore, it is reduced by a factor of 10 for this FPGA implementation and thus, lower torque ripple is produced, as shown in Figures 6.



Figs. 6. The effect of sampling time to torque ripple; (a) Estimated torque for $T_s=5\mu s$; (b) Estimated torque for $T_s=50\mu s$

IV. Experimental Results

The validation of designed torque and flux comparators was performed based on Hardware-in-the-Loop (HIL) method. The DTC model in Matlab Simulink was simulated and then, the same data I_a , I_b , S_a , S_b , and S_c used for the simulation were copied from Matlab workspace to VHDL codes, as the inputs for the targeted FPGA. The VHDL codes were simulated in Modelsim before being synthesized and implemented in Altera DE2 EP2C35F672C6. The test design flow is presented in Figure 7, and the photograph of the hardware experimental setup is shown on Figure 8.

The experiments were executed for three different motor's speeds: low speed, middle speed and high speed. All the experimental results were compared to the validated Matlab simulation results.

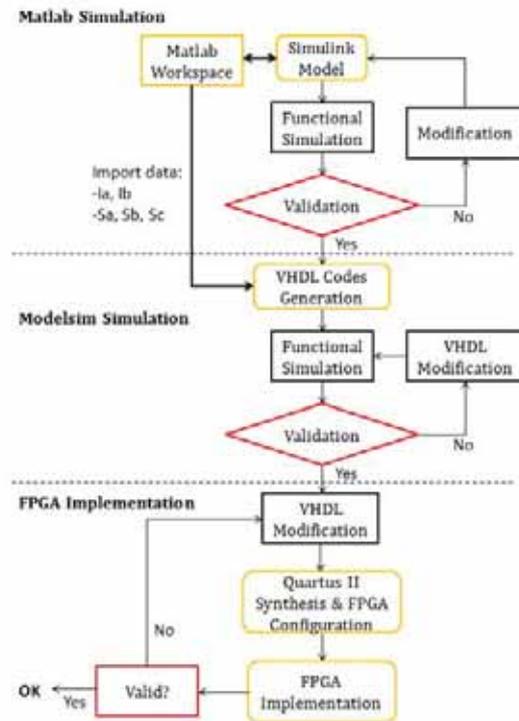


Fig. 7. Top-down test design flow

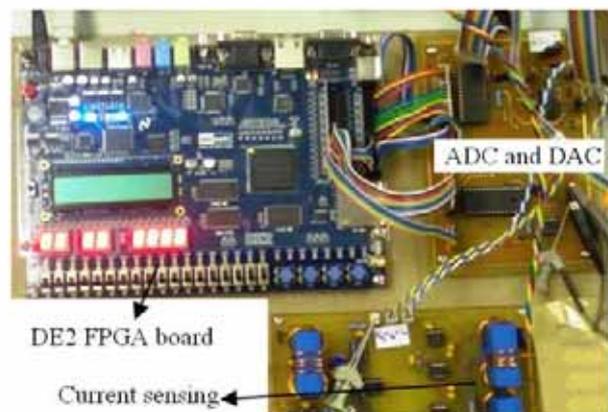


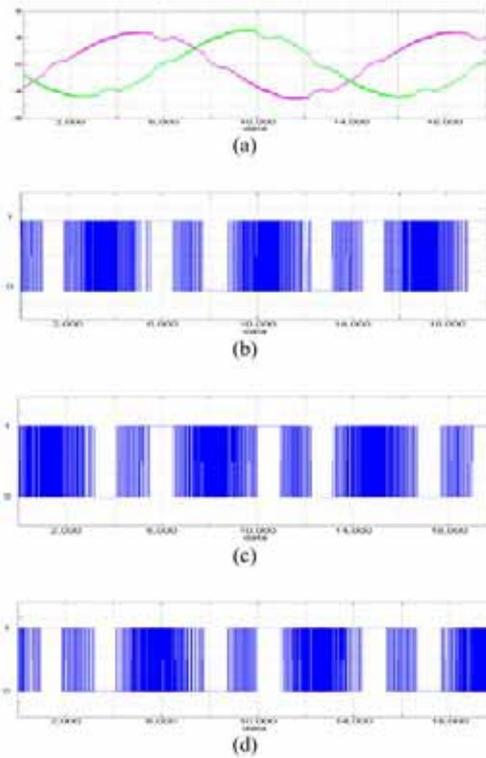
Fig. 8. The hardware experimental setup

Since the hardware resources in FPGA are limited to store all the inputs and the outputs, the tests were taking place only during certain periods of motor's steady state. The implementation results were observed on the oscilloscope.

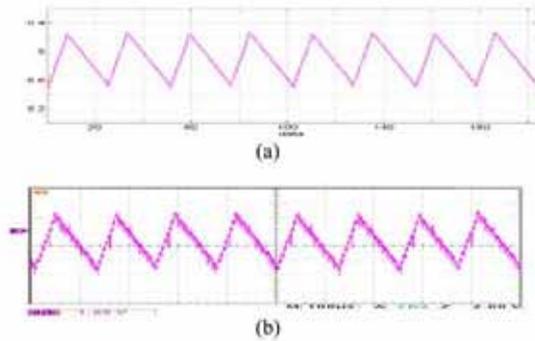
Figure 9 presents the input of the low-speed test while Figures 10 to 12 shows the comparisons between Matlab simulations and the experimental results.

For the middle-speed test, the inputs were set as presented in Figure 13, whereas the comparison between the experimental results and Matlab simulations are shown in Figures 14 to 16.

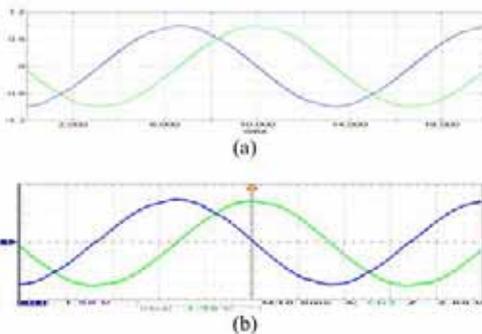
Finally, in the high-speed test, the inputs were set as presented in Figure 17 and the comparison between the experimental results and Matlab simulations are shown in Figures 18 to 20.



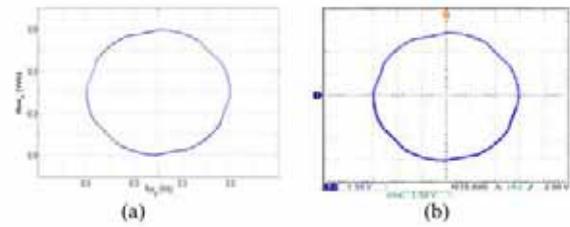
Figs. 9. The inputs for low-speed test
(a) Stator Currents Ia and Ib; (b) Sa; (c) Sb; (d) Sc



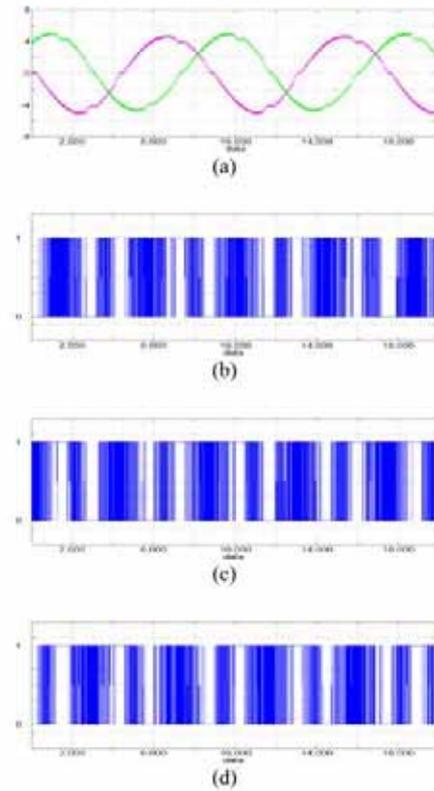
Figs. 10. Comparison of the torque estimation in low-speed test;
(a) Matlab simulation, (b) the experimental result



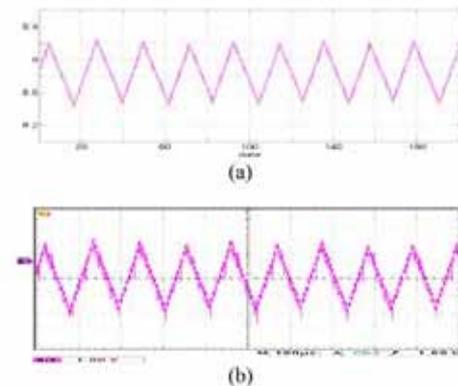
Figs. 11. Comparison of the flux estimation (φ_D , φ_Q) in low-speed test; (a) Matlab simulation, (b) the experimental result



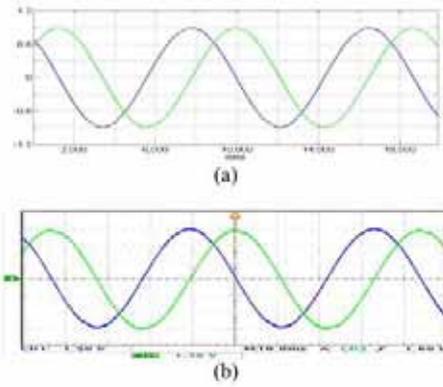
Figs. 12. Comparison of the flux locus in low-speed test;
(a) Matlab simulation, (b) the experimental result



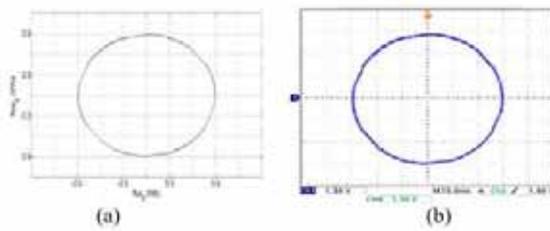
Figs. 13. The inputs for middle-speed test
(a) the stator currents Ia and Ib; (b) Sa; (c) Sb; (d) Sc



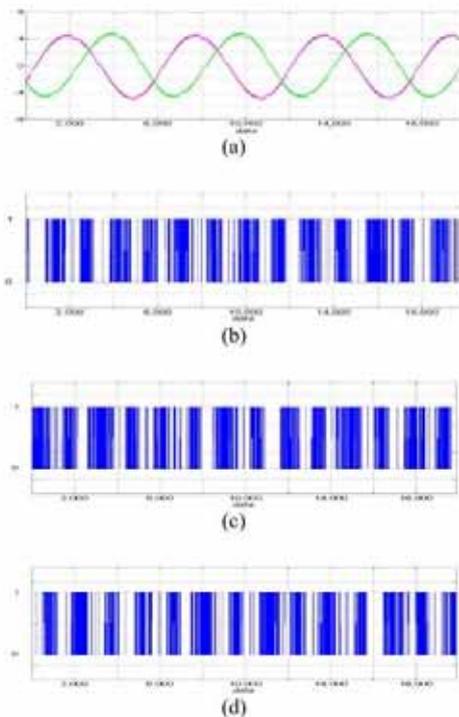
Figs. 14. Comparison of the torque estimation in middle-speed test;
(a) Matlab simulation, (b) the experimental result



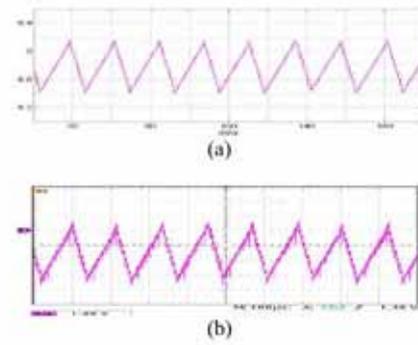
Figs. 15. Comparison of the flux estimation (φ_D, φ_Q) in middle-speed test; (a) Matlab simulation, (b) the experimental result



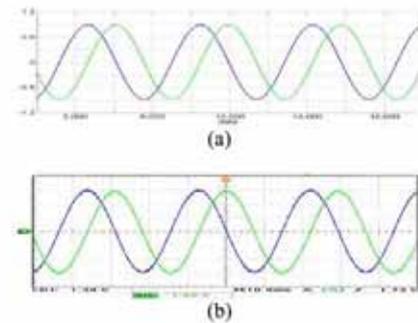
Figs. 16. Comparison of the flux locus in middle-speed test; (a) Matlab simulation, (b) the experimental result



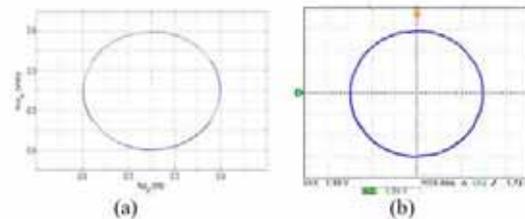
Figs. 17. The inputs for high-speed test (a) the stator currents I_a and I_b ; (b) S_u ; (c) S_b ; (d) S_c



Figs. 18. Comparison of the torque estimation in high-speed test; (a) Matlab simulation, (b) the experimental result



Figs. 19. Comparison of the flux estimation (φ_D, φ_Q) in high-speed test; (a) Matlab simulation, (b) the experimental result



Figs. 20. Comparison of the flux locus in high-speed test; (a) Matlab simulation, (b) the experimental result

The experimental results shown were corresponded well with the simulation in Matlab, which was done in double-precision computation. Besides, the implementation of the algorithm was also validated for different motor's speed. It can be observed by comparing the form of the estimated torque triangles or the number of flux waveform complete cycle visualized within the same period, for example.

V. Conclusion

FPGA is an alternative for the realization of a high-performance DTC implementation owing to its high processing frequency, which is a reliable device to be utilized for any high-speed execution digital signal processing algorithm which cannot be obtained by any DSP application. The choice of word sizes, the binary format and the sampling time used are very important in order to achieve a good implementation of the estimators. This paper has presented high performance torque and

flux estimator of DTC based on FPGA using two's complement fixed-point representation through the estimation process. The implementation has successfully improved the sampling time till 5 μ s to reduce the torque and flux ripple for the DTC drives. The experimental results have verified during the motor's steady state. The design, which coded in synthesizable VHDL, utilized 2093 logic elements for the implementation on Altera EP2C35F672C6 device, producing very precise estimations with minimal quantization and calculation errors.

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