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Hardware in the Loop Co-Simulation of an FPGA Based Sine Pulse Width Modulator for Variable Speed AC Drives

***Abstract**. This paper presents a Hardware-In-the-Loop (HIL) co-simulation of SPWM generator for variable speed AC motor drive. This approach allows us to connect the physical FPGA development board that implements the Sine Pulse Width Modulation (SPWM) generator to the Matlab/Simulink environment software in which the power part composed of an inverter and an AC motor is modeled. The HIL co-simulation benefits from the powerful features of the FPGA board in generating PWM pulses at high switching frequencies, and on other side, it gains from the Simulink tools in giving more flexibility and freedom in order to perform different functional tests without any risk that can be happen in case of experimental tests. Detailed co-simulation and experimental results of the AC motor variable speed drive are successfully achieved, showing that the user can run the AC motor at any desired speed.*

***Streszczenie**. W artykule przedstawiono symulację sprzętową w pętli (HIL) generatora SPWM do napędu AC o zmiennej prędkości. Takie podejście pozwala nam podłączyć fizyczną płytkę rozwojową FPGA, która implementuje generator modulacji szerokości impulsu sinusoidalnego (SPWM) z oprogramowaniem środowiska Matlab / Simulink, w którym modeluje się część mocy złożoną z falownika i silnika prądu przemiennego. Kosymulacja HIL korzysta z funkcji płyty FPGA w generowaniu impulsów PWM przy wysokich częstotliwościach przełączania, a z drugiej strony zyskuje dzięki narzędziom Simulink, zapewniając większą elastyczność i swobodę w celu wykonywania różnych testów funkcjonalnych bez żadnego ryzyka może się to zdarzyć w przypadku testów eksperymentalnych. Z powodzeniem uzyskano szczegółową współsymulację i wyniki eksperymentalne przemiennika częstotliwości z silnikiem prądu przemiennego, pokazując, że użytkownik może uruchomić silnik prądu przemiennego z dowolną pożądaną prędkością. (**Analiza układu modulacji PWM stosowanego w napędzie AC z wykorzystaniem układu FPGA**)*

Keywords: FPGA; Hardware In the Loop (HIL), co-simulation; SPWM; modulation index; carrier frequency; logic elements; AC motor drive.
Słowa kluczowe: FPGA; Sprzęt w pętli (HIL), współsymulacja ; SPWM; indeks modulacji; częstotliwość nośna; elementy logiczne; Napęd AC.

Introduction

To prepare This generally, an induction Motor (IM) runs at its rated speed when is directly connected to the main supply. However, many applications need variable-speed operations, for example, in the IM-based centrifugal pump, a speed reduction of 20% leads to an energy saving of approximately 50% [1]. In such applications, both the magnitude and the frequency of the AC power supply must be controlled to adjust the rotor speed. This can usually be achieved by using the PWM-based voltage inverter in which the input DC voltage remains constant, and the AC output voltage is adjustable in magnitude and frequency [2]. Since it has a large range of output voltage and frequency, the PWM strategy has been proven to be one of the most adapted techniques for the control of voltage inverters [3]. Most analogue circuits implementing PWM control schemes are based on "natural" sampled switching strategies. Recently, a switching strategy referred to as "regular sampling" PWM is considered to have a number of advantages when implemented digitally. They are immune to noise and are less susceptible to voltage and temperature changes; hence, the digital implementation is advantageous over analogue implementation [4,5].

Field programmable Gate Array (FPGA) devices are widely used for the implementation of high performance and large-size circuits thanks to the speed advantage of instruction-level parallelism available through direct hardware execution on the FPGA. Even more, another important issue in using FPGAs is their reconfiguration and reusable hardware architectures for rapid prototyping of the digital systems [6,7]. Recently, some work has been conducted in generating Sine PWM (SPWM) using FPGA. For the SPWM technique that was introduced in [8], 841 logic elements are used; the carrier frequency is fixed, and the modulating frequency is adjusted by one Hz step. In references [1,8-10] the modulating frequency is fixed at 50Hz and the modulation index is limited only to two levels 50 % and 75%. An SPWM scheme has been implemented using a microcontroller in [9,11]. Two algorithms to generate SPWM are introduced in [12], without any hardware implementation.

Within HIL environment, a real hardware to be tested interacts with a virtual system (i.e., a simulation based on mathematical model) that replaces a part of the real system or component to be tested. Comparing with conventional ways for testing equipment, HIL techniques can provide a low cost and a fast implementation process [13]. HIL co-simulation is addressed in the literature into two main categories. The first approach is based on hardware extension with PC [14]. For example, a Matlab/Simulink based real-time platform running on a PC was used as real-time simulator for boost power amplifier in [15]. A signal hardware-in-the-loop model of electric vehicle that combines driving system and vehicle model running in real time is implemented in dSPACE ds1103 control card, and co-simulated with Matlab environment [16]. Panayiotis et al proposed an interactive real-time digital control system with a Hardware-in-the-Loop magnetic levitation system. The host-target real-time environment is implemented using Mathworks tools, a data-acquisition board, and C++ compiler, for educational purposes in modeling and controls courses [17]. HIL simulation of voltage source converters based on time average method is proposed in [18], the simulated power plant is operated together with a real-time controller implemented on two separate digital platforms, a fast real-time simulation based on a scalable technique, which uses arrays of digital signal processors on commercially available boards plugged into a conventional PC, is proposed. HIL co-simulation has been also used in [19] to implement real-time power system RTPS models with frame times of 10ms. All the above-mentioned works have disadvantages in terms of computing power since the execution is performed sequentially.

As a second approach, another type of HIL is introduced in [20], [21] and [22] to bring more accuracy to the simulation results, the real parts of the controlled plant were actually simulated using a specific purpose simulator, and the designed controller is implemented in a real-time environment. This makes the design process restricted to that specific application. However, since the HIL setup is application specific, it is not possible to be generalized for other designs, and the real-time simulators used for this purpose are very expensive [20].

Parallel processing in FPGAs enables the implementation of the specific methodologies that dramatically reduce the sequencing of the operations in the CPUs. Moreover, the use of the FPGA development board as a simulator is a cheaper solution for HIL co-simulation. In electronic power converters, we distinguish two levels of system real-time control; the first is the fastest level where the PWM pulses that drive the power switches are generated at high frequency, at this level the configurable rapid hardware like FPGA is generally preferred. The second control level related to calculated reference voltages and currents, which is slower than the first level (some milliseconds of sampling time), is achieved by using only a simple processor or DSP.

The main contribution of this paper is the Hardware-in-the-loop (HIL) co-simulation of the SPWM, associated with an inverter and an AC motor. Altera FPGA DE2 board is used to implement an optimized SPWM generator as a first control level, and the power part is modeled in MATLAB/Simulink environment as a second level. This can be considered as a low-cost effective tool for rapid prototyping and testing new hardware digital systems and can be further extended to closed-loop control.

A fully customized SPWM IC will be designed with a reduced number of logic elements (LEs). The reference inputs related to the required modulating and carrier frequencies are defined by the user with high resolution. Thanks to the use of 8-bit data signed format, the modulating signal frequency can be adjusted by a 0.5 Hz step, and the amplitude level by exactly 0.78 % step. In addition, both carrier frequency and dead time can be chosen by the user according to the characteristics of the selected power switches. The designed SPWM generator will be tested based on hardware in the loop (HIL) co-simulation technique.

The paper is organized as follows: In Section 2, a variable-speed AC drives principle, including SPWM generator design, is presented. General description of the co-simulation environment for the whole speed drive is illustrated in Section 3 with simulation and experimental results.

System Overview

The system overview of the variable-speed drive for an AC induction motor is shown in figure 1.

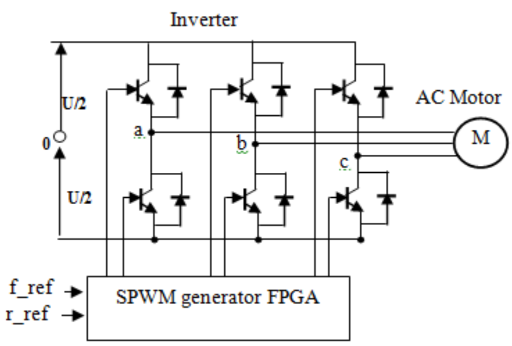

Fig.1 Three-phase inverter using controlled switches

The voltage inverter is controlled by the PWM pulses generated by the FPGA. The inverter output voltages are then used to feed an AC motor. The stator windings current generates a rotating magnetic field. This rotating field induces an electromotive force in the rotor, which in turn, produces a magnetic field in the rotor that attempts to align with the rotating magnetic field in the stator. This causes the rotor to rotate at a specific speed. We can adjust the motor speed by selecting the frequency reference (f_ref).

Sine Pulse Width Modulator SPWM

The basic idea to generate SPWM switching signals is to compare the sine signal Vr, (as reference), with a triangular carrier signal Vc. This is clearly illustrated in figure 2.

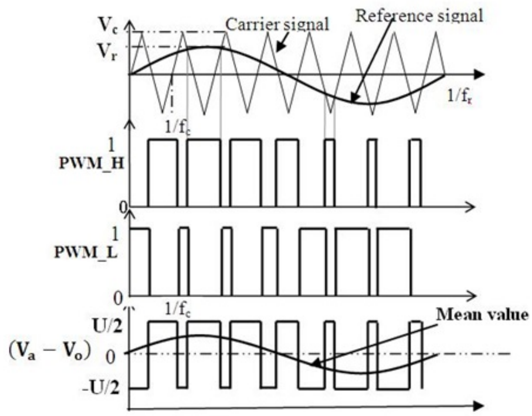

Fig 2. SPWM technique, PWM high pulses and low pulses, output

Two parameters characterize the modulation for a sinusoidal reference signal as follows:

The modulation index ma; this is the ratio of the amplitude of the reference to the peak value of the carrier:

(1) $$m_a = \frac{V_r}{V_c}$$

The frequency modulation index mf; this is the ratio between the carrier and reference frequencies:

(2) $$m_f = \frac{f_c}{f_r}$$

when m_f is sufficiently (greater than or equal to 6) the fundamental of output voltage (Va-Vb) has an RMS value [23]:

(3) $$V' = \frac{\sqrt{3}}{\sqrt{2}} m_a \frac{U}{2}$$

For a given input voltage U, the PWM enables the value of the output voltages to be controlled. The series expansion of the voltage (Va-V0), at fr frequency includes higher order harmonics with frequencies fr, 3fr, 5fr, 7fr,.., of higher orders. The PWM strategy does not reduce harmonic distortionm, it pushes the harmonics to higher frequencies which can facilitate the output current filtering [23].

HIL co-simulation of the speed variable drives

The proposed HIL co-simulation environment and the design flow are highlighted by figure 3. It relies mainly on DSP Builder as an efficient co-simulation tool between the real time HDL algorithm development based on Altera Quartus II software and the Matlab/Simulink environment.

The HIL block in AltLab library of the Altera DSP Builder Block-set enables the Hardware in the Loop functionality of the SPWM generator implemented on FPGA co-simulated with the Simulink model of the inverter and the AC-machine. The HIL block offers frame and burst modes of data transfer that are significantly faster than single-step mode when used with suitable designs, which increases significantly the simulation speed. The HIL block also makes available to the hardware a large Simulink library of sinks and sources, such as channel models and spectrum analyzers, which can give greater control and observability.

Construction of proposed system model

To confirm the effectiveness of the proposed architecture of SPWM generator , and test the functionality of the speed variable drives of figure 1, firstly, the three-phase SPWM generator is designed using fixed-point Altera DSP Builder library blocks in the Simulink environment and the power part (three-phase PWM inverter, AC machine) is built using Matlab/SimPower toolbox in discrete-time mode. The constructed model which consists of a squirrel cage motor in an open-loop speed control system. The stator is fed by a PWM inverter.

The Clock block is configured to generate 13.5 MHz as a main clock for the designed system; the discrete time for Simulink model is chosen 74 ns in order to realize a real time co-simulation. At this stage, this model is compiled, and it can be simulated, but only in Simulink environment DSP builder software without FPGA board. In order to perform Hardware in the loop co-simulation a HIL block is used, which contain the SPWM generator design for FPGA implementation as shown in figure 4. The five inputs of three-phase SPWM block.

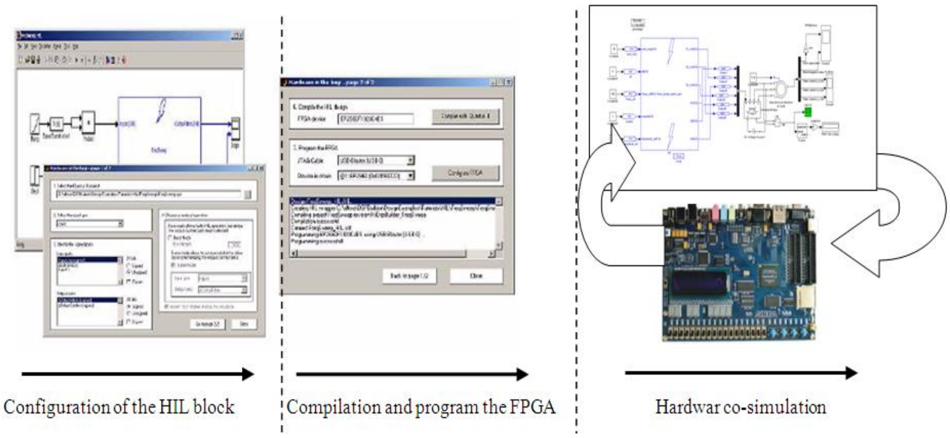

Fig 3. HIL Design Flow

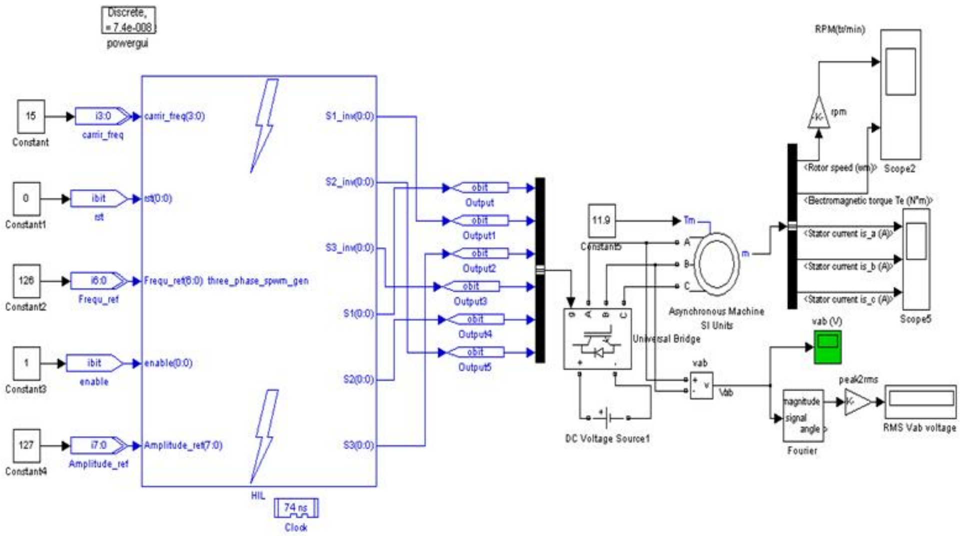

Fig.4. HIL. Simulink Model of variable speed drives for HIL co-simulation Design Flow

HIL co-simulation results

The HIL co-simulation is realized using the Altera DE2 development and education board, which include Cyclone II 2C35 family EP2C35F672C6 FPGA device in a 672-pin package, and EPCS16 serial configuration device. The used Simulink model of the Asynchronous Machine block with the following parameters is chosen as a load: 3HP - 220 V- 60 Hz – 1725 rpm. The Dc bus voltage is set at 350 Volt, a Joint Test Action Group (JTAG) interface links the Simulink model and the FPGA board. The Simulink environment provides all references for three-phase SPWM generator implemented in FPGA such as the carrier frequency, the fundamental frequency and the modulation index. PWM pulses are then generated to control the IGBT gates of Simulink model of the inverter in Matlab/Simulink environment, subsequently monitoring electrical and mechanical quantities and analysis can be easily performed.

The carrier frequency is set at 1.98 KHz, this corresponds to an m equal of 33 (60 Hz x 33 =1980). It is recommended in [24,25] that the frequency modulation factor mf to be an odd multiple of three and that the value be as high as possible. The modulation index is set at 0.97, and the fundamental frequency is set at 60 Hz. The 3 HP machine is connected to a constant load of its nominal value (11.9 N.m).

Figure 5 shows waveforms of the first complementary pair of generated SPWM pulses, which control the first inverter arm IGBTs, and the inverter output line to line voltages, which fed the AC machine, here the reference frequency is set to 60 Hz.

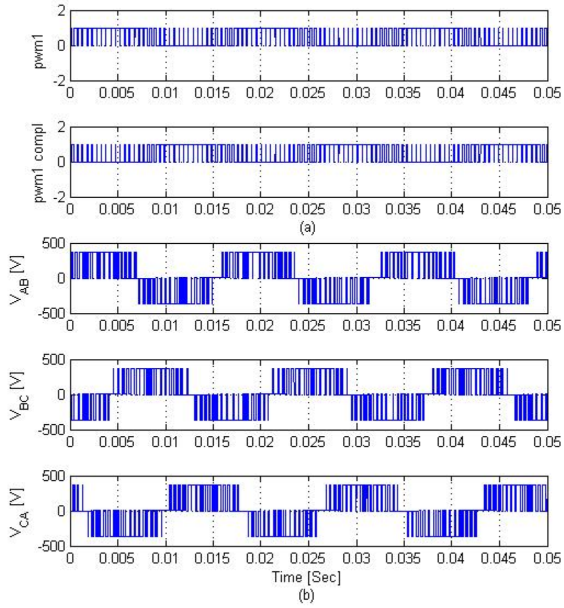

Fig .5. Waveforms of SPWM signal, and inverter output line to line voltages for 60Hz
(a) Waveforms of generated spwm 1 pulse and it’s complementary.
(b) Inverter output line to line voltage VAB, VBC , VCA

Fig 6 (a) and (b) shows the waveforms of stator currents, and their zoom area at steady-state, which are approximately sinusoidal and are 120° shifted.

At starting, the magnitude of the 60 Hz current reaches 90 A peak (64 A RMS) whereas its steady-state value is 10.5 A (7.4 A RMS). We can see that all the harmonics (multiples of the 1980 Hz switching frequency) are filtered by the stator inductance, so that the 60 Hz component is dominant. The stator current unbalancing is mainly due to the absence of the neutral point of the power part (DC bus, inverter). Furthermore, to reach a nominal rotor speed the modulation index is chosen higher enough. The current stator is little noisy, which means that we are very close to the over-modulation region, and it may be also due to the delay between the Simulink software that implements the inverter and the Induction machine model, and the real time generated Sine PWM pulses.

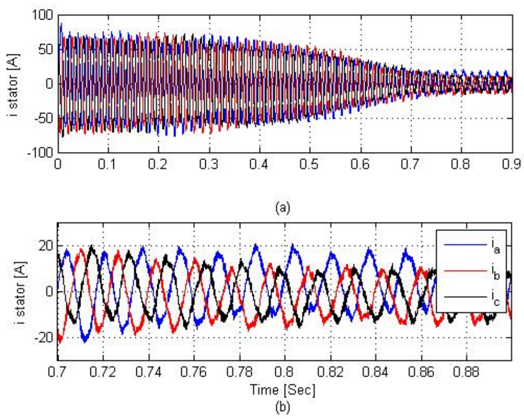

Fig .6. Co-Simulation results
(a) Waveforms of stator currents ia, ib, ic for 60Hz frequency reference, (b) The zoom area for 0.7 sec to 0.9 sec.
(b)

The first graph of figure 7 (a) shows the machine's speed going from 0 to steady-state speed of 1720 rpm, after 0.8 s. The second graph (b) shows the electromagnetic torque developed by the machine. Because the stator is fed by a PWM inverter, a noisy torque is observed. However, this noise is not visible in the speed because it is filtered out by the machine's inertia.

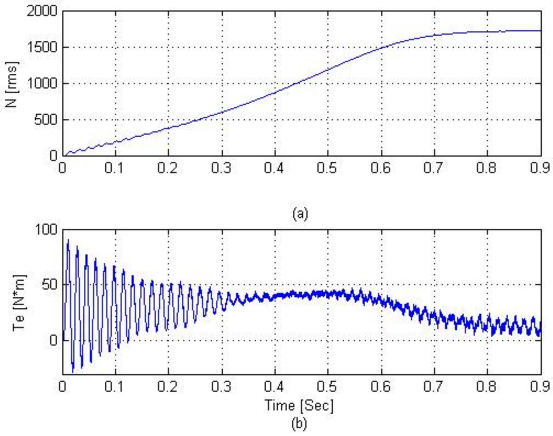

Fig .7. (a) Machine speed (b)Electromagnetic torque

As shown in fig 8, the implemented variable AC drive that allows changing the rotor speed corresponding to the desired frequency reference by 0.5 Hz step, which corresponds to 10 rpm for the actual rotor speed.

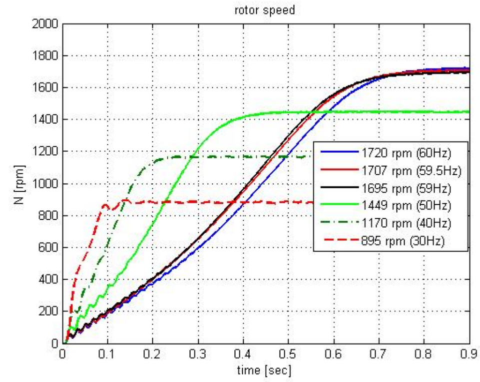

Fig.8. Machine’s rotor speed at some different frequencies values

Finally, fig 9 shows the rotor speed and developed electromagnetic torque, in both, simulation by SIMULINK software only and by HIL co-simulation in order to verify system functionality.

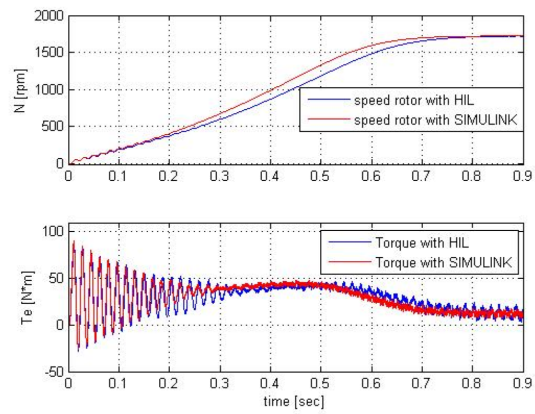

Fig .9. simulation results of machine’s speed and developed electromagnetic torque in SIMULINK and HIL.

Experimental results

Fig 10 illustrates the hardware setup used for experimental validation of proposed SPWM which is implemented on the FPGA. To test the functionality of the design an inverter based on MOSFETS is constructed to be used in feeding a squirrel cage AC machine. It is connected in a triangle configuration. The DC bus voltage is set to 314 V. The AC motor characteristics are summarized as follows:

$$U(Y/\Delta) = 380/220\ \text{V}, \quad 0.78/1.32\ \text{A}$$
$$P = 0.25\ \text{Kw}, \cos\varphi = 0.78, \Omega_n = 1350\ \text{rpm}, f = 60\text{Hz}$$

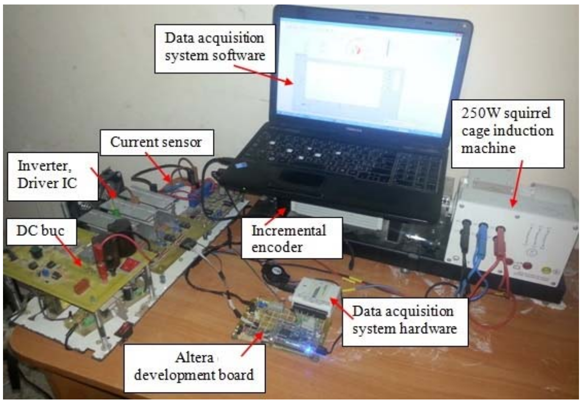

Fig .10. Hardware setup for experimental validation

The FPGA SPWM module is configured in real time to generate the PWM pulses corresponding to 60Hz frequency and ma=0.85, that related to the desired amplitude. Fig 11.a illustrates the three stators currents ia, ib, ic at steady-state when the AC motor reaches its nominal speed, The FFT analysis of a phase stator current as illustrated in fig 11.b shows that the THD is 1.273%, which it means that the current is purely sinusoidal and confirms the achieved performance of the designed SPWM modulator.

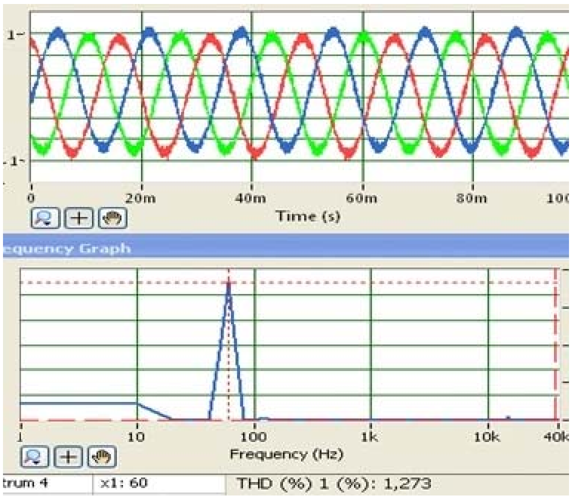

Fig .11. Experimental results . (a) Three phase stator currents ia, ib, ic for 60Hz frequency reference, (b) Harmonic spectrum of ia phase current

Conclusions

This paper presents a Real-time HIL co-simulation based on FPGA used for variable-speed AC motor drives. A complete System-Level design using several software tools from Quartus software and Matlab/SIMULINK environment has been described. The proposed architecture of SPWM generator is implemented in Altera DE2 development board, which includes Cyclone II 2C35 family EP2C35F672C6 FPGA device, and the power part, which is composed of the three-phase inverter and the AC motor, is built with Matlab/SimPower Systems. Then, experimental results were presented. The constructed system worked properly, and it can generate a wide range of frequencies with high resolution, which allows the variation of the machine rotor speed by about 15 rpm step. Through this HIL design methodology, control systems can be easily tested, and the risk in experimental manipulation can be greatly reduced. Hence, HIL techniques can provide lower cost and faster implementation than the conventional ways of equipment testing.

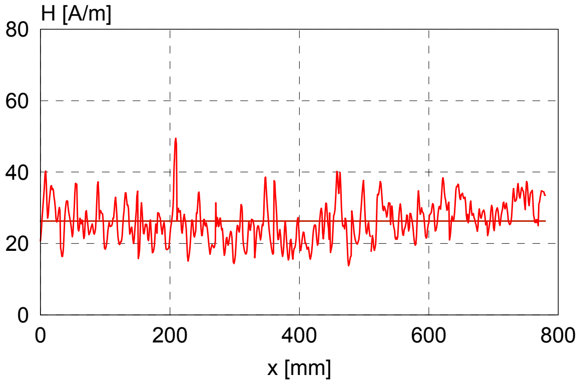

Fig.3. An example of a graph

Similarly as in the case of the figures the best width of the tables is the width of the column – 8cm. An example of a table is presented below.

Table 1. The parameters of the sensor

Sensor type	Dimensions [mm]	Sensitivity [mv/T]
B50/A	20×20×200	20.2
B80/C	50×20×200	30.5
C20/G	40×30×800	70.4

Acknowledgments to be inserted at the end of the article using type size 9 and Arial italic.

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