FPGA-BASED HARD CO-SIMULATION OF TYPICAL INDUCTIVE POWER TRANSFER (IPT) SYSTEM

Sumer S. Harden[1] and [2]Haroutuon A. Hairik
[1]Electrical Engineering Depart. Basrah University Basrah Iraq
[2]Computer Engineering Depart. Basrah University Basrah, Iraq.

ABSTRACT

This paper presents a novel approach for the field programmable gate array (FPGA)-based hard co-simulation of typical inductive power transfer (IPT) system. The implemented control algorithm is in an environment of the Spartan-3A/3AN (FPGA) kit board, while the power section and the load are simulated in Matlab/Simulink environment. An applicable example of a direct AC to AC converter, in the power stage, was used to generate a resonance current with high frequency, for inductive power-transfer (IPT) system and discussed in short notes. Such a system is constructed by different natural components such as power converter, different elements and a well-designed control system that requires special and suitable software like Matlab/Simulink software package, which develops the direct AC-AC converter model for the input power side. The proposed control algorithm was implemented based on Spartan-3A / 3AN (FPGA) with an automatically generated VHDL code that was used for the implementation. The software used is the Xilinx System Generator (SysGen) which is a very beneficial toolbox that works in the MATLAB/Simulink environment with a library of several important blocks serving defined functions implemented in the FPGA. It is also possible to convert the implemented model into VHDL code. It is also possible to convert the implemented model into VHDL code. The use of the (SysGen)with its two main advantages over traditional methods, possibility of implementing algorithm matches the function exactly as in the simulation and it is not required to create two different models (one for the simulation and the other for the implementation). The simulation results confirm the accuracy of the proposed control system as well as the feasibility of the overall Spartan-3A/3AN (FPGA) based control circuit.

KEYWORDS: Inductive Power Transfer, AC-AC Direct Converter, Spartan-3A/3AN (FPGA), Xilinx System Generator, Matlab/Simulink.

1. INTRODUCTION

An uncompensated circuit model of IPT system is shown in Fig. 1, which can be considered the most fundamental figure [1].
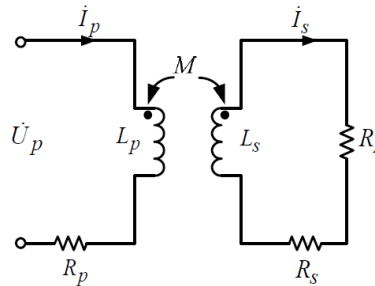
Fig. 1. Equivalent circuit of the IPT system.

Assuming that voltage and current are sinusoidal, the induced voltage in secondary winding due to the primary current I_p is given as $j\omega M I_p$, and the reflected voltage in the primary winding due to the secondary current I_s, is given as $-j\omega M I_s$

where
"M" is used for the mutual inductance and ω is the angular frequency [2].
For the case of IPT system, unlike the transformers in which the primary and secondary windings are wound on the same magnetic core, to avoid the leakage of inductance, and to establish a good coupling [3]. However, the large air-gap between the primary and secondary windings causes the contactless transformer has poor coupling performance so as not to transfer power at high efficiency and applied for large-scale implementation [4].The power transmission of the IPT system from the sending (primary) static coil to the receiving (secondary) movable one been based on the first principles of electromagnetic induction [5].

II. modeling of AC-AC Direct,type converter
Figure 2. Shows the power stage of the converter circuit. It has four MOSFET switches
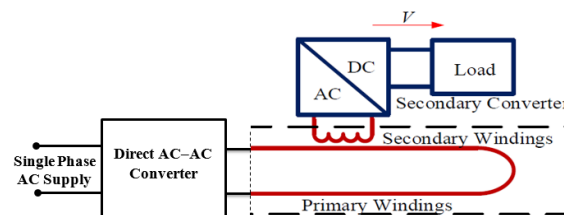

Fig.2. Schematic of the IPT system

with LC resonance circuit. The supply frequency of AC voltage Up is 50Hz, while the frequency of output current I_s is30 kHz. The operation of this model according to the switching sequence, shown in Table 1, can be subdivided in to four modes of operation (Shown in Figs.4-7) [6]. Two of them operating in the positive half-cycle of input supply and the other two in the negative half-cycle. Each half period have two states: energy injection and free-oscillation state.
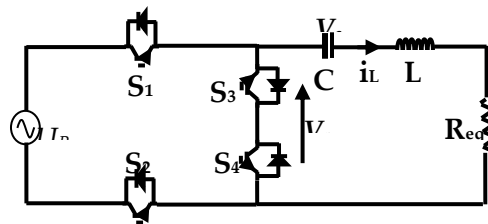

Fig.3. AC-AC Direct converter

Table1. The four mode operation conditions

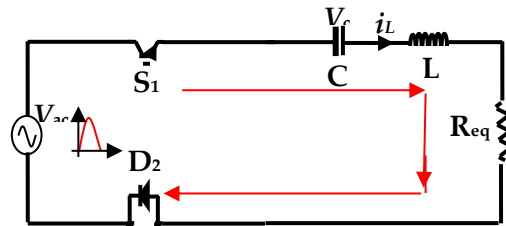| Mode	Input Voltage	Resonant Current	Switches/Diodes status
Mode I	$V_{ac} > 0$	$i_L > 0$, and previous $i_L < -I_{ref}$	S1/D2 on S2/S3/S4/D1/D3/D4 off
Mode II	$V_{ac} < 0$	$i_L < 0$, and previous $i_L < +I_{ref}$	S2/D1 on S1/S3/S4/D1/D3/D4 off
Mode III	$V_{ac} > 0$	$i_L < 0$	S4/D3 on
	$V_{ac} < 0$	previous $i_L > +I_{ref}$	S1/S2/S3/D1/D2/D4 off
Mode IV	$V_{ac} < 0$	$i_L < 0$	S3/D4 on
	$V_{ac} > 0$	previous $i_L > -I_{ref}$	S1/S2/S3/D1/D2/D3 off

Mode I:

Energy injection state [$i_L > 0$ & $V_{ac} > 0$

Fig.4. First mode of operation.

Mode II:

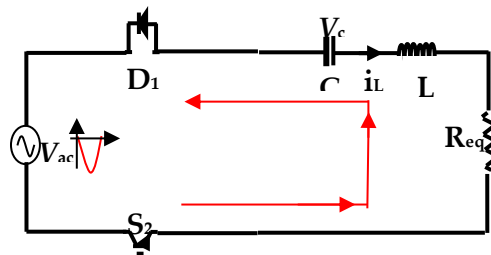Energy injection state [$i_L < 0$ & $V_{ac} < 0$]

Fig.5.Second mode of operation

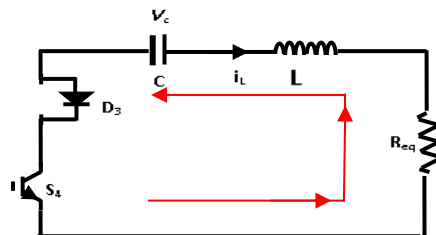Mode III: - Free oscillation state.

Fig.6. Third mode of operation
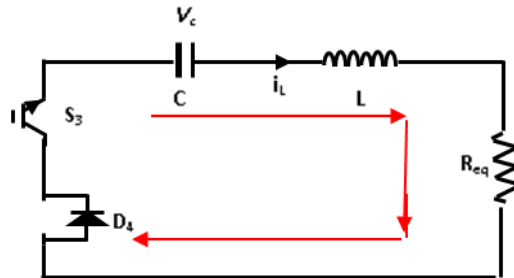
Mode IV: -

Free oscillation state

Fig.7 Fourth mode of operation.

III. CONTROL Circuit Operation

The feedback inputs to control circuit are output (load) current i_L and input supply voltage V_{ac} as shown in Fig.8 and through Table1, value I_{ref} are required also to implement the required control signals. The converter typical current waveform and its associated switching signals for both positive polarity input voltage and its negative polarity shown in [6] are constructed to fulfill the required four operation modes. It is clear from this table that parameters like $\hat{i}_L$ which represents the peak of load current i_L
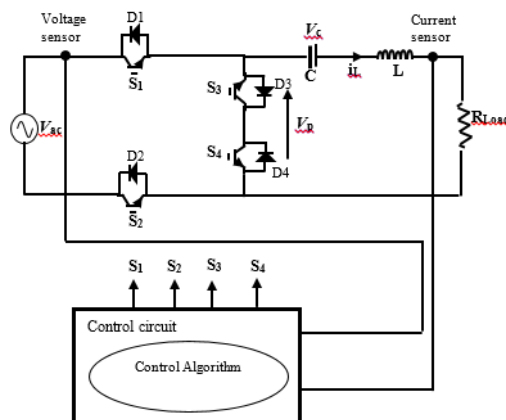

Fig.8. Complete circuit of the used AC-AC converter with its controller and feedback signals

VI. HARDWARE CO-SIMULATION (HWCOSIM)

System Generator (SysGen)is a digital signal processing (DSP) design tool from Xilinx which is one of the American famous technological company that is a main supplier of the programmable devices.

Designer in (SysGen) is thinking in the same manner as Matlab Simulink environment and can be integrated with Simulink block set to test or help in the design in a friendly way. This system is a well-organized modeling tool that facilitates the FPGA prototype hardware [7]. It extends Matlab/Simulink software package to provide a new developed modeling space that is well suited to future required hardware design. The tool provides a suitable high-level and friendly abstraction that is easy and self-compiled into the FPGA simply by a push of button [8].

Hardware co-simulation (HWCOSIM) was carried-out by selecting Xilinx Spartan-3A FPGAStarter Kit Board. Hardware Co-Simulation (HWCOSIM) is a feature in System Generator (SysGen) that allows Matlab/Simulink users to run the full or part of a SysGen design on the FPGA and dramatically increase the simulation time speed [9].

The proposed work was carried as shown in the following blocks. Figure9 shows HWCOSIM implementation of the direct type converter with the IPT system.

The complete implemented FPGA environment Simulink model of the power stage for the direct type converter model is presented in Fig.9. The power stage consists of four MOSFET switches and resonance circuit tank with L= 2.8µH, C=0.1µF to achieve the 30kHz resonance frequency and a load resistance of R_L=1Ω. Figure.10 represents the control stage in which hardware co-simulation (HWCOSIM) was carried-out by selecting the (SysGen) of the Xilinx Spartan-3A FPGA Starter Kit Board. The control circuit shown its blocks in Fig.10 consists of three main subsystems:

Peak current detector.
Comparator circuit.
Gate Drive Circuit
Each block is built using Xilinx (SysGen) tools with master clock period 10 ns.

The advantage of using System Generator can be summarized as: reducing the time spent by the designer for simulation of the system, flexibility due to update the design parameters in quickly and test the effect on the system, The HDL files of the system can be generated using compilation for ISE and Xilinx FPGAs, (SysGen) blackest can be integrated with Matlab/Simulink blocks for helping and co-simulating the system designing. The design can be implemented in optimal way with minimum cost [10]

VII. RESULTS AND DISCUSIONS
The simulation results of AC-AC Direct converter are shown in Figs.11-14. These figures show the input and output currents, with frequency 30 kHz also the envelope of the output current (represents the peak

value) which tracks the variation of input reference current. The results taken for different reference values (3,5,7, and 10) Amps.

Furthermore, Fig.14 describes the firing pulses for the proposed circuit under input reference Iref=5 amp. Throughout the work, it is found that Matlab Simulink and Xilinx System Generator to be an effective development tool. The graphical nature of modeling made it easy to design efficiently and analyze the results quickly, which greatly reduced the development time. In this method, programming errors are eliminated during thep developing phase comparing with the hand written VHDL. In this paper, the detailed theoretical analytical study on converter used in IPT and its digital implementation practices are explained, and a hard co-simulation facilitating the development and implementation process of FPGA-based digital controller was described. The method seems to be faster and provides a greater degree of confidence than traditional hand written VHDL coding. The algorithm was automatically generated from Simulink models using the Xilinx Spartan-3A FPGA board. The hard co-simulation shows the importance of the method. This method is expected to be useful for prototype development of other power electronic converters and electric drives with more complicated interfacing and control algorithms. The presented results are confirming the performance of the converter for any current set value.

REFERENCES

[1] Javier Vázquez, Pedro Roncero-Sánchez and Alfonso Parreño Torres,*Simulation Model of a 2-kW IPT Charger with Phase-Shift Control: Validation through the Tuning of the Coupling Factor:* Electronics 2018, 7, 255; doi:10.3390/electronics7100255.

[2] Hong Zhou, Bin Zhu, Wenshan Hu, Zhiwei Liu, and Xingran Gao, *Modelling and Practical Implementation of 2-Coil Wireless Power Transfer Systems:*Hindawi Publishing Corporation Journal of Electrical and Computer Engineering Volume 2014, Article ID 906537, 8 pages http://dx.doi.org/10.1155/2014/906537.

[3] Saeed Hasanzadeh, SadeghVaez-Zadeh, *Efficiency analysis of contactless electrical power transmission systems:* Energy Conversion and Management, Volume 65, January 2013, P. 487-496.

[4] Myunghyo Ryu, Honnyong Cha, Yonghwan Park, and JuwonBaek, *Analysis of the Contactless Power Transfer System using Modelling and Analysis of the Contactless Transformer:* 31st Annual Conference of IEEE Industrial Electronics Society, 2005. IECON 2005, p. 1036-1042.

[5] Muhammad Asri Zainal Abidin, Wan Ismail Ibrahim and MohdShawalJadin, *Design of Inductive Power Transfer (IPT) for Low-Power Application:* ARPN Journal of Engineering and Applied Sciences, VOL. 10, NO. 21, NOVEMBER 2015, p. 9807-9812.

[6] Hao Leo Li, Aiguo Patrick Hu, , and Grant Anthony Covic, *A Direct AC–AC Converter for Inductive Power-Transfer Systems:* IEEE Transactions on Power Electronics, Vol. 27, No. 2, February 2012, p, 661-668.

[7] Jiuchao Li, Yao Zhao, and Jiuchao Li, *Co-simulation Research Based on Electromagnetic Induction of Wireless Power Transfer:*2017 7th International Conference on Mechatronics, Computer and Education Informationization (MCEI 2017),Part of series Advances in Computer Science Research, 2017,p. 577-580.

[8] WentaoWang, Wenying Yang, and Venkata Dinavahi, *Co-Simulation Interfacing Capabilities in Device-Level Power Electronic Circuit Simulation Tools: An Overview:* International Journal of Power Electronics and Drive Systems (IJPEDS) Vol. 6, No. 4, December 2015, pp. 665 – 682.

[9] Xilinx, System Generator for DSP User Guide UG640 (v 14.3) October 16, 2012.This document applies to the following software versions: ISE Design Suite 14.3 through 14.7.

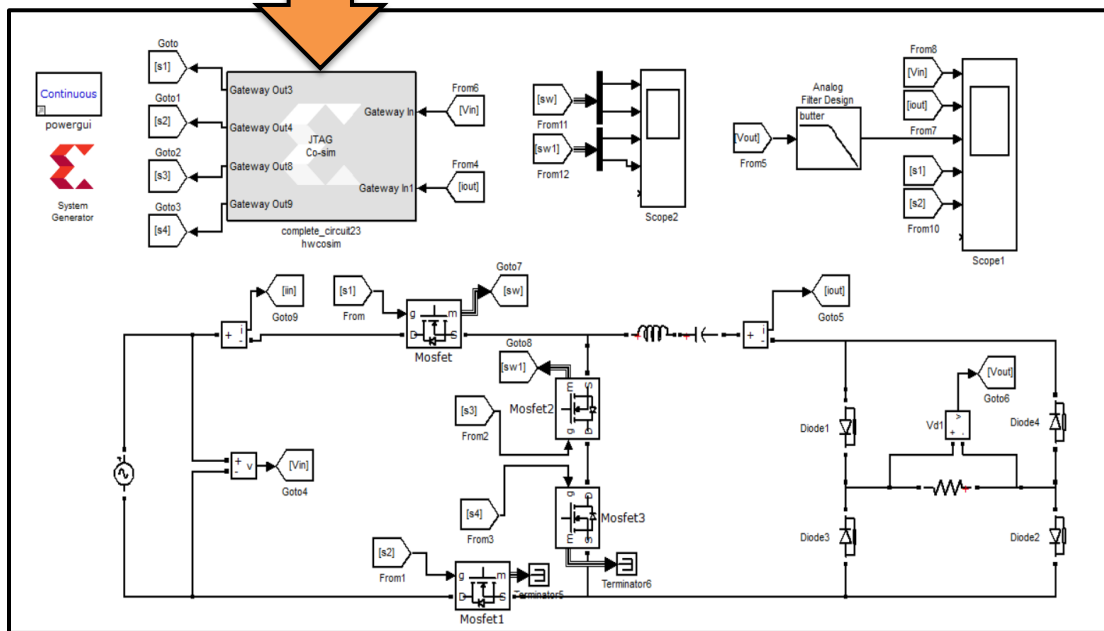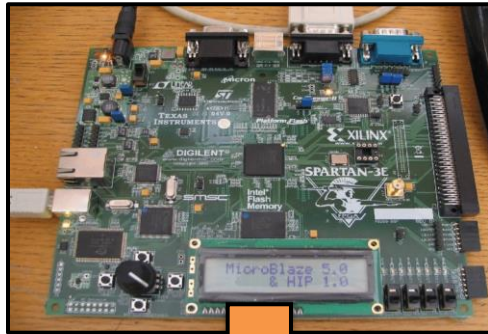[10] Xilinx Release 10.1 (2008). "System Generator for DSP: Getting Started Guide".

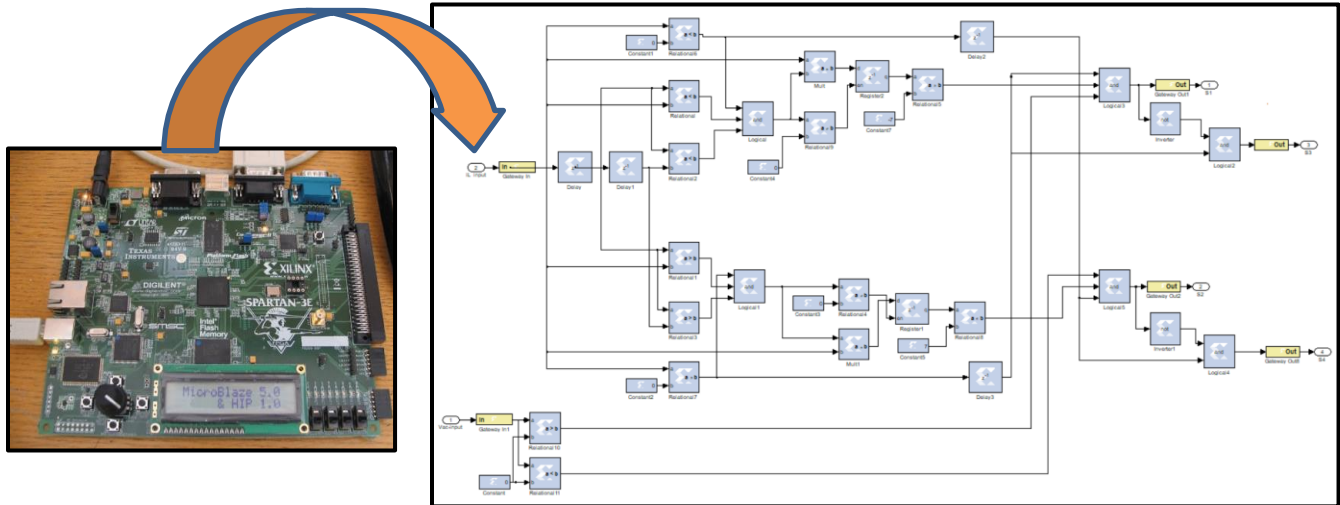**Fig. 9 Shows HWCOSIM implementation of the direct AC-AC converter with the IPT system**

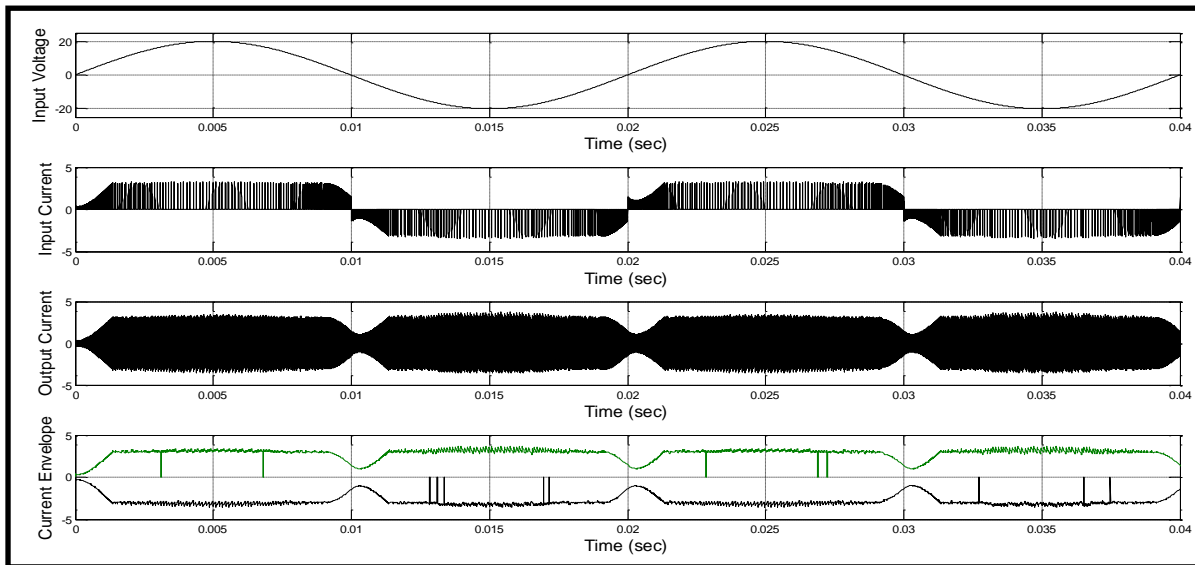**Fig. 10 -Xilinx (SysGen) block diagram of the control stahe**

Fig.11. Result for I_{ref} = 3A(a) Input Voltage 20 Volt (b) Input Current (c) Output Current (d) Current Envelope.
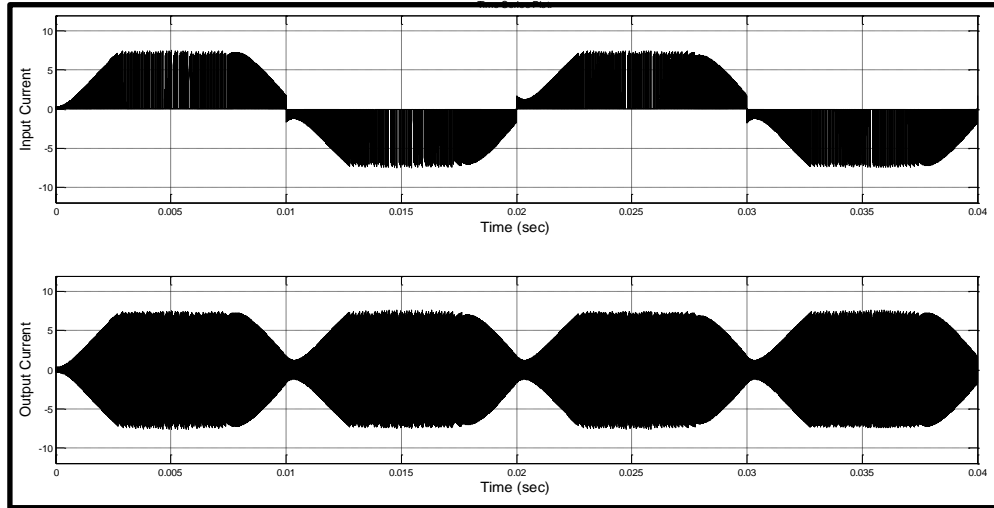
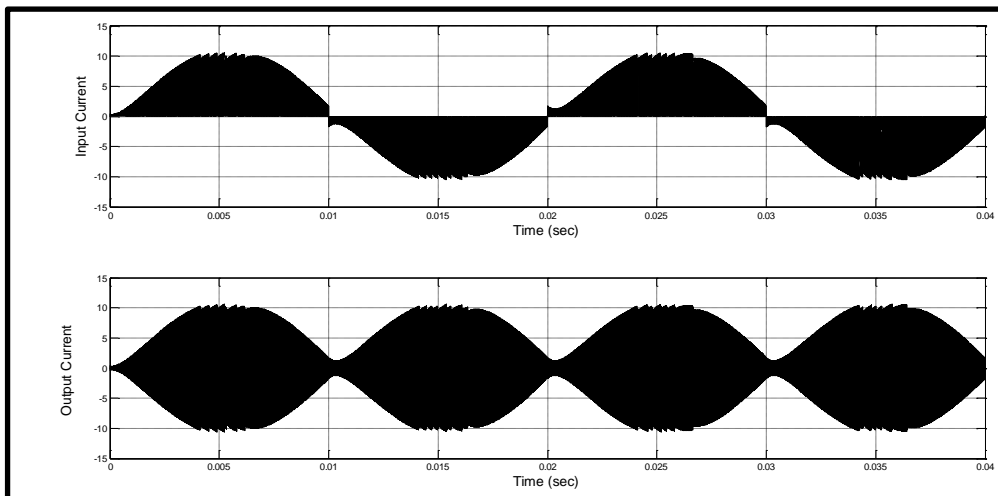**Fig.12. Result for I_{ref} = 7A (a) Input Current (b) Output Current**

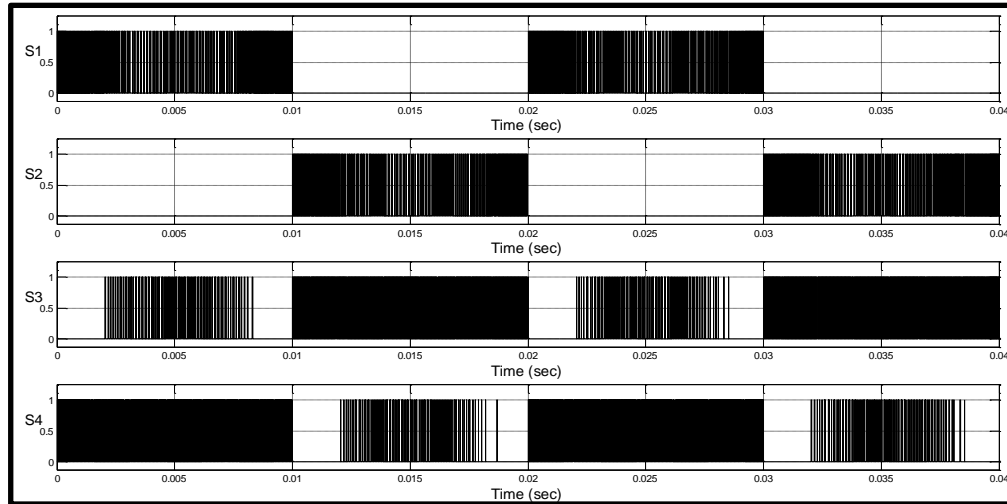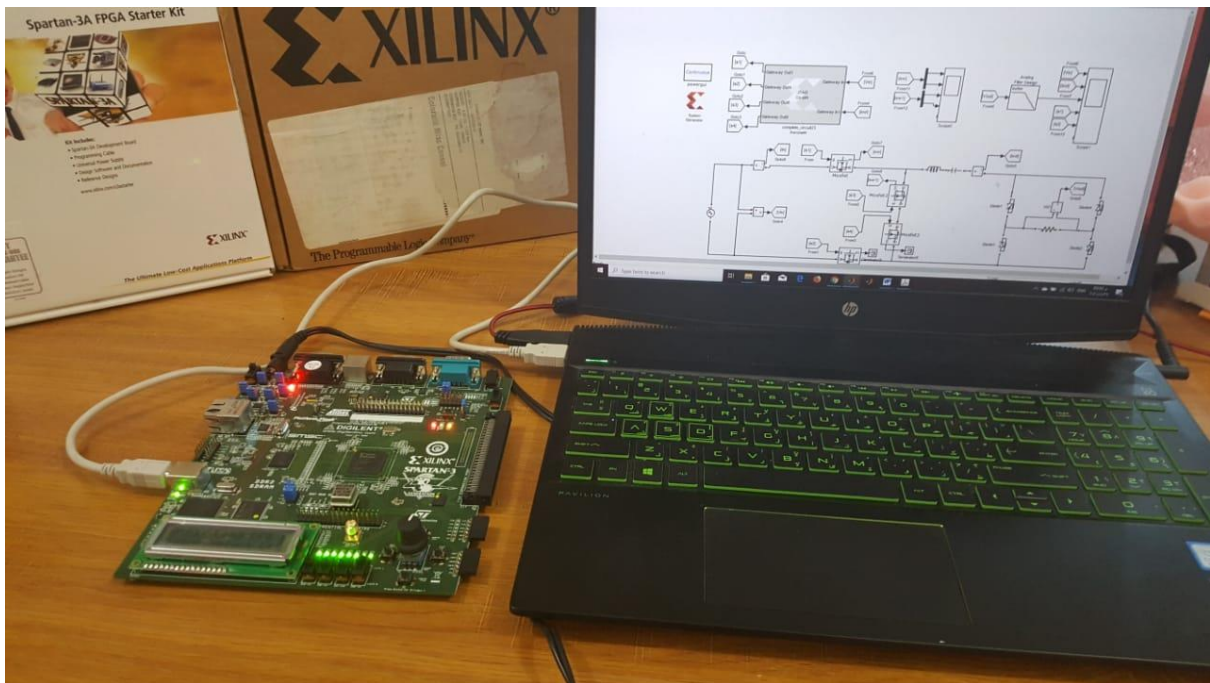**Fig.13. Result for I_{ref} = 10A(a) Input Current (b) Output Current**

Fig.14 Firing pulses for switches

Fig.15 Complete layout of the hard co-simulation