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Modelling and simulation of power electronic systems using a bond graph formalism

Rui Esteves Araújo*, Américo Vicente Leite[†], Diamantino Silva Freitas*

* Faculty of Engineering, University of Porto, R. Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal
fax: +351 22 5081443
e-mail: raraujo@fe.up.pt, dfreitas@fe.up.pt
[†] Polytechnic Institute of Bragança, Quinta de Sta. Apolónia, Apartado 134, 5300 Bragança, Portugal
e-mail: avtl@ipb.pt

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Abstract

This paper deals with the modelling of power electronic systems using the bond graph formalism. The switching components are modelled using an ideal representation so that a constant topology system is obtained. The purpose of the present contribution is to discuss a technique that combines bond graph energy-flow modelling and signal-flow modelling schemes for simulation and prototyping of signal processing algorithms in power electronics systems. In this paper, we will discuss models of the use of fully-controlled, semi-controlled and non-controlled switches in the field of power static converters. By concept, a simulation environment can be examined at different abstraction or hierarchy levels. The approach in this paper is, accordingly, the formulation of a simulation task at different levels: component level, topology level, functional description and implementation description. The paper concludes with two practical examples of simulation of power electronics systems.

1 Introduction

The analysis, design and practical implementation of power electronics systems without computer simulation is extremely laborious, time-consuming and therefore expensive. Thus modelling and computer simulation plays an important role in design and analysis of such systems.

1.1 Motivation

Power electronic systems are systems that involve phenomena with very different values of time constants. In consequence, the establishment of a single model that enfolds in full form all the phenomena, would have as advantage the universality, and as probable inconvenient the impossibility to evidence, in efficient mode, the dominant behavior of the system in question. It still can be added that, due the high complexity of the model we would have an excessively long time of simulation.

There are essentially two different approaches to the modelling and simulation of a switched power converter. One is to approximate the abrupt changes by instantaneous transitions and use equation solvers capable of handling discrete events. The resulting model is then referred to as a hybrid system in that it combines discrete transition conditions with continuous differential equations. Another approach is to employ purely continuous models and conventional solvers. The design of such solvers is constantly improved and hence the approach may become more and more powerful with time. The latter approach is adopted and evaluated below.

The purpose of this paper is to present a unified method for modelling and simulation of power electronics systems using a bond–graph formalism with constant topology and the Simulink[®] program.

Modelling in the bond graph formalism for various mechanical systems is well documented [1]. On the contrary, very few references are available in the electrotechnical area. Today, this situation is

changing as shown in some recent publications [2,3]. The present work is another example.

1.2 *Literature Review and Paper Contribution*

A brief review of the literature follows. Various software packages for simulation have been proposed in the recent years, for electronic circuits, like SPICE® [4] and SABER® [5], power networks, like EMTP [6] and EUROSTAG [7], or specialised simulation of power electronic systems, see among many references, for example, SIMPLORER® [8], POSTMAC [9], SIMSEN [10], ANSIM [11], and PSCAD [12]. More recently, a lot of attention has been given to libraries of models for the various components of a power electronic system, developed in the Matlab/Simulink environment, in order to explore the computational power and flexibility and integrate the visual design facilities. In [13], an interactive power electronic system simulation package, SIMUSEC is presented ("Simulation des Systèmes Electrotechniques en Commutation"). In synthesis, it is a basic library of 1-level functional blocks with somewhat restricted capabilities. Paper [14] gives an overview on the subject of modelling and simulation of power electronic converters and makes only reference to a library of models for a Simulink environment called SIMUPELS, also directed to the power electronics converter and electrical machines, without more details. Another reference is the MatEMTP [15], a transient analysis program based on Matlab M-files, that can perform EMTP type simulations entirely in Matlab. In [16], the package Power System Blockset is presented. This tool uses the Simulink environment to represent common electric components and electric machines found in power electronic systems.

The Vector Control Signal Processing (VCSP) presented in previous work [17,18], besides the mathematical processing, also allows a quite flexible and open simulation activity space, by use of its own, independently developed and mostly innovative, library of block functions. However, bearing in mind that simulation activities sooner or later require code production for real-time control applications, in particular for rapid prototyping of the target systems, VCSP was designed also to bridge this gap. Therefore, in VCSP a graphical environment of Simulink is used to build a true development system for power electronics system algorithms and their higher level blocks, supported by a comprehensive set of simulation and estimation tools. The results are prepared for immediate code generation using the Real-Time Workshop™ of Simulink®.

In our earlier work we dealt with a functional description for modelling a static converter. In this paper we go one step further and model the static converter with bond graph formulation. The originality of this blockset consists of extending Simulink for use in the design, simulation, and rapid prototyping of complex digital signal processing algorithms in power electronic systems, such as some vector control methods. Together with Real-Time Workshop it can also be used as a tool for teaching and demonstration. In fact, signal processing for vector control systems theory is typically taught using a block diagram approach because it conveys the information efficiently and allows students to learn quickly.

In section 2 we give a brief description of preliminary aspects. Next, we present several models to switching components. In section 4 the previous models are used for modelling of the static converters. We present several examples of the application of the proposed method in section 5 and give the corresponding results using the VCSP blockset. Finally, in section 6 conclusions are given.

2 Preliminaries

This section introduces some basic concepts to understand the main ideas presented in paper. In first place, we will describe how to use decomposition into subsystems and modelling levels, next an introduction to integration in Simulink is presented. A brief introduction on to the bond graph modelling technique is finally introduced.

2.1 Decomposition in subsystems and modelling levels

A typical power conversion system is constituted by five subsystems: the power supply, the static power converter, the electric filters, the electrical and mechanical load and the control system (command and regulation) as described in figure 1. As each subsystem has specific characteristics, it results in a wide range of time constants and hence systems of differential equations with a large dynamic range of variables to solve using a simulator. A practical approach requires models with very different levels of detail. The models which describe the elements of the power conversion system need to have different levels for each element, that is to say a multilevel model. The design of the decomposition into different levels is a non-trivial aspect. Conceptually, we can so view a simulation environment at different abstraction levels with formulation of a simulation task at correspondingly different modelling levels:

- Component level: blocks of this type provide a small number of basic passive and active elements like : resistances, capacitors, diodes, thyristors and transistors;

- Electric circuit level: blocks of this type describe the circuit topology: in other words, the interconnections between the component level nodes.

- Functional description: the block is modeled by a "black box" with functionality to explain logical and mathematical relations among the signals but says nothing about its implementation, for example, inverters, rectifiers, DC-DC converters.

- Description for implementation: blocks of this type are characterised by a high degree of transparency for the code generator that produces C code directly from the block diagram. Typically this is useful for the control level.

This model building methodology satisfies the following properties: - compositionality in terms of elementary models; - graceful extendibility from simple models to detailed models. As the above description levels correspond to different types of blocks, when modelling, it is important to decide
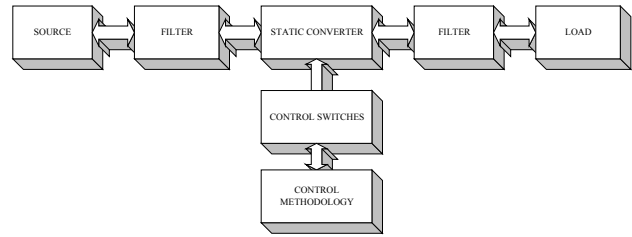

Fig. 1. A reference decomposition of a power conversion system into subsystems.

the level of accuracy needed, before starting constructing the models. The price to pay for a very accurate model is very often a lower simulation speed. In another perspective, to obtain efficient code generation it is very important to use the discrete blocks. Any modelling effort should be driven by the goals. The user should clearly understand the utility of each model, and should formulate and configure it so that it serves the intended goals. The most accurate model is frequently not the best model.

2.2 Integration in Simulink®

Simulink is a program for simulating dynamic systems and Matlab provides powerful evaluation of the simulation results. It follows the principles of modular design, object-oriented design, reusable blocks, support for project hierarchy and self-documentation, because it inherently illustrates the algorithm being performed. This simulation environment provides interactive control and observability of the design at execution time. It is possible to change parameters and immediately observe the results with waveform displays. Unfortunately, it is quite difficult to model electrical circuits directly in Simulink, because it does not accept schematics or netlists. If you want to do it you have to represents the circuits by mathematical formulae which must be set up a new for each and every change in the circuit. In our approach this step is implemented by the graphical user interface of the Simulink that allows users to select the necessary blocks and do their interconnection. The bond graphs formalism is used as a modelling language that provides rules for verification of the causality. Simple examples of application were given in previous work [17, 18]. The proposed method has been implemented in

Simulink environment under the form of a blockset.

2.3 The bond graph formalism

Created by Paynter [1], the bond graph formalism allows to model continuous systems and by extension, the continuous part of hybrid dynamical systems. The bond graph is a combination of bonds. A bond is a path through which power is flowing from one point to another. Therefore, a bond graph shows the flow of power that occurs in a system. Based on the analogies between the various fields of physics, this formalism can model with a unified approach the several engineering components of mechanics, electricity, hydraulics, thermodynamics, etc..[1,2,3]

In the graphical formalism, based on power transfer by bonds that represent the transfer of energy (see figure 2), power is the product of two generic variables: the effort e and the flow f. In the electrical case, the effort can be the voltage and the flow the current. Using the terminology of the electrical field, the ideal switch is represented by non linear IC elements. In other words, a switching device is represented in simulation by a binary valued impedance with a very high value when in blocked sate and with a very small impedance while it is conducting. The binary impedance is controlled by a logic based on the current through the device and the voltage across it and the state of the device. In order to avoid an algebraic loop, the switching inductance cannot be set to zero. Each switching device adds an extra state to the electrical circuit model.

The general structure of an non-causal bond graph in the case of hybrid systems using an ideal model for the switches is represented on the figure 3. The power sources block represents the effort sources (Se) or flux sources (Sf) in the system. The IC bloc represents the storage elements : inertial elements, capacitive elements and switching components.
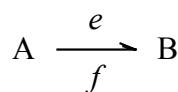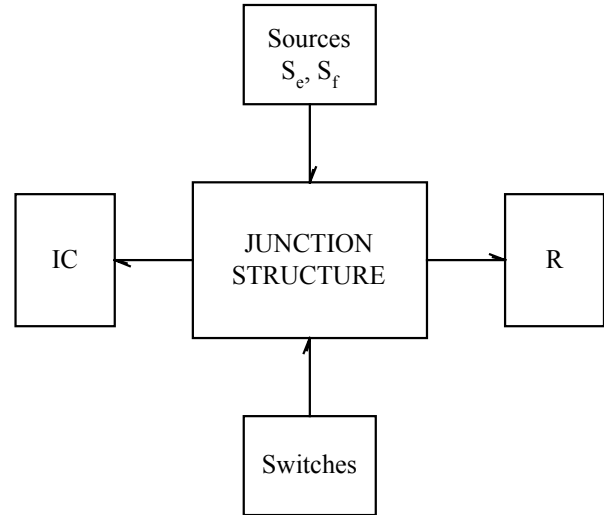

Fig. 3. The general structure of an acausal bond graph.

The R bloc contains the dissipative elements. Finally, the junction structure bloc, constituted of bonds and nodes, allows to represent the topology of the circuit. Form the bond graph of figure 3 called a non-causal bond graph, the assignement of a procedure called causality allows to organize the effort/flow variables of the external bonds in terms of inputs/outputs of the junction structure. Graphically, the causality is represented by a stroke that indicates, by convention, in which way the effort is applied, the flow being applied in the other way. In the case of figure 4, A imposes the effort to B and B the flow to A. For storage elements, according to the position of the causality stroke, we define the notion of integral and derivative causality. In integral causality the constitutive relation between the effort and the flow is under an integral form, and in derivative causality under a derivative form [2]. A procedure called Sequential Causal Assignment Procedure allows to assign the causality to the whole bond graph that then becomes a causal bond graph.
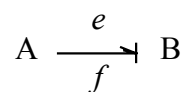

Fig. 2. The graphical representation of the power transfer.

Fig. 4. An example of the application of the causality.

3 Modelling of power semiconductor devices

Various models describing semiconductor components exist. The complexity of the model is selected depending on the purpose of the simulation. In power conversion systems it is not advantageous to employ complex models of switching devices for the global operation of the static converter. The power semiconductor model implements a macro-model of the semiconductor. It does not take into account either the geometry of the device or the complex physical processes underlying the state change. Power switches can be modelled as functional blocks composed by two models: a switches model associated with R and L elements and a logical model that controls the switching characteristics of the device [19].

In a static converter the types of elements to consider are:

- the non-controlled switches (diodes);

- the semi-controlled switches (thyristors);

- the fully-controlled switches (transistors).

This set of power switching devices allows to construct the different types of power switches necessary to the implementation of the some types of static converters.

The diode is a semiconductor device that is controlled only by the voltage across it. The ideal diode presented here does not model forward voltage, since this is usually of little interest in system simulation. Therefore, the diode is simply an ideal switch that turns on when the voltage between anode and cathode becomes positive and turns off again when the current through the component tries to become negative. The thyristor can conduct current only in one direction, like the diode. In addition to the diode it can be controlled by an external gate signal. The semi-controlled switch is modelled by an ideal switch that closes if the voltage between anode and cathode is positive and a trigger signal is applied at gate. The switch remains closed until the current tries to reverse. This device cannot be switched off independently of the current value.
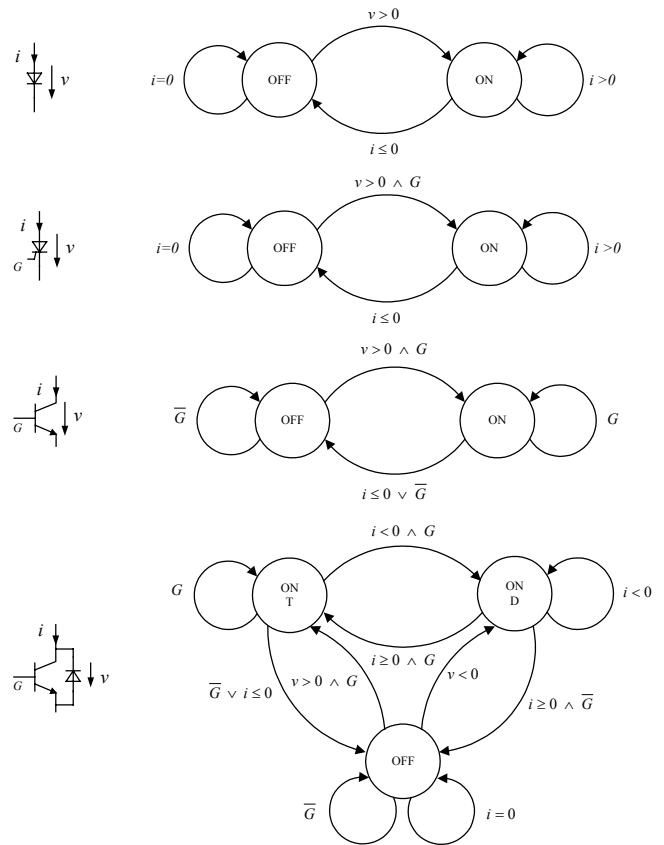

Fig. 5. The state graphs of the electronics switches.

The transistor it is fully-controlled by the external signal (gate). The thyristor switches on if the voltage between anode and cathode is positive and an external signal at gate is applied. It switches off either if the current tries to reverse or if the external signal becomes negative.

Finally, we make reference to the association of a transistor with a diode in anti-parallel. Figure 5 outlines the states graphs for all 4 types of switches. For more details about models see [19].

4 Modelling of power electronics systems

In this section the topic of the modelling of static converters is presented. Obviously, the construction of these models finds its foundations in the models of the power switches already presented in the previous section.

Numerical simulation methods for power electronics systems are currently classified in two classes: the methods of fixed topology and the methods of variable topology. In the first, the

switches are considered as non ideal components so that a constant circuit topology is obtained with a unique state equation and variable parameters. In this approach these are represented with non linear elements.

The second method is based on ideal switches. Since the switches modify the topology of the circuit the state equation changes when some power switches commutate. After that, two aspects relative to the morphology of the static converters are established:

- the first one, is that the generality of the converters industrially is presented with a topology in bridge.

- the second, it is that the type of conversion is intimately related to the type of power electronic switches that are used.

Having in account that the method presented here is of fixed topology and considering these two aspects, the principle of the topological modelling of the static converters can be enunciated as followed:

For a static conversion given with a bridge topology, the equations that describe the topology are independent of the type of conversion. In terms of bond graph, for a given topology in bridge the junction structure is the same and is independent of the type of components.

Based on this principle we can state that the graph that represents a converter is always the same and, what distinguishes the models are the power switches used. In other words, the concept of model of the *universal converter* can be introduced that is organized by the number of arms and the type of power switching devices in each arm. With the
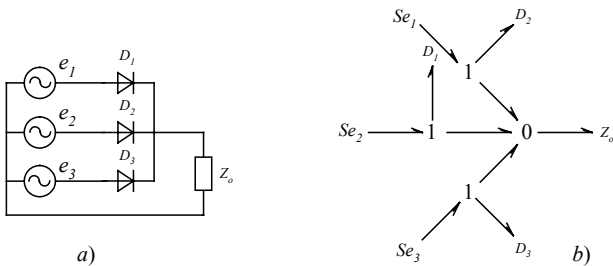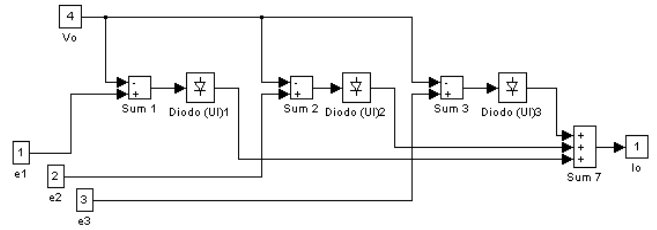

Fig. 7. Block diagram of simulation of the rectifier.

objective of exemplification of the construction of the topological models for the static converters a simple assembly is considered that allows to facilitate the explanation of the concepts that are in the base of the now presented modelling. This is a three-phase rectifier, illustrated in figure 6 (a). The bond graph of the rectifier is shown in figure 6 (b). The block diagram of the Simulink model of the static converter is shown in figure 7.

5 Application examples

The purpose of this section is to describe two application examples that are used in this paper to illustrate the techniques implemented in Simulink environment. The two examples show the ease of use and generality of the method. In the first example a three-phase controlled rectifier is simulated (see figure 8), controlled with a Proportional Integral (PI) controller. The theoretical foundation of the use of linear controllers in this type of rectifiers can be found with great detail [20].
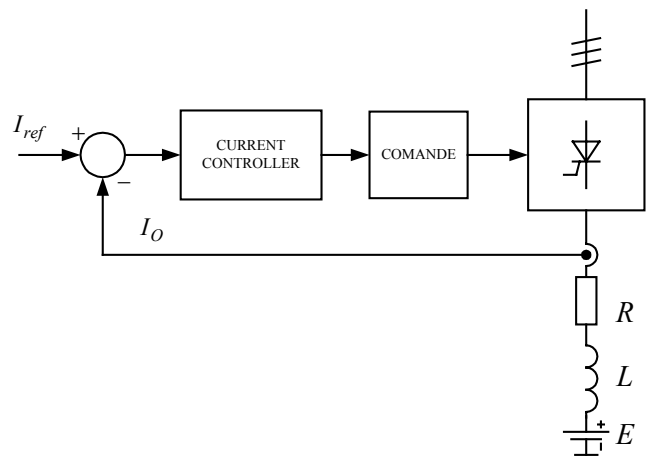
The second example is a complete closed-loop

Fig. 6. The electrical circuit (a) and bond graph of the rectifier (b).

Fig. 8. Three phase full wave rectifier with *RLE* load and line inductance.
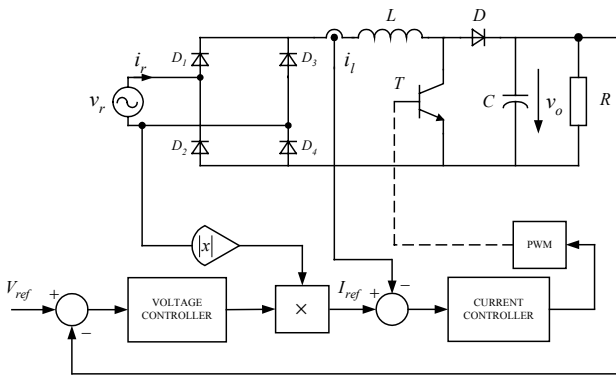
Fig. 9. Schematic diagram of closed loop power factor corrector (PFC).

Fig. 10. Block diagram for a three phase full wave rectifier with *RLE* load.

power-factor corrector (PFC) using a current mode controller [21]. The circuit is show in figure 9. It consist of the boost power stage, bridge rectifier and the controllers blocks. The output voltage is sensed and compared to a voltage reference. A voltage controller is built with a PI controller. The output of the voltage controller is the input of a multiplier. The other input of the multiplier is the rectified line voltage. The multiplier output sets the reference for current controller built with other PI controller. The output of the current loop controller is the input to the pulse-with modulator. The comparator output controls the power switch. This example is used to illustrated how VCSP handles a relatively complex, highly non-linear circuit with a reasonable number of switch elements.

5.1 Closed loop thyristor rectifier simulation

The circuit shown in figure 8 is used to show the operation in closed loop of the three phase thyristor which feeds an *RLE* load. The three phase bridge is fed by a three phase source with internal leakage inductance and resistance. The numerical illustration consists of analyzing the performance of the controller in tracking of the trajectory of the current intensity. Thus, the initial value of the reference current is 25A and for a time equal to 0.04 s the reference is to subject to a variation in step for the value of 50A.
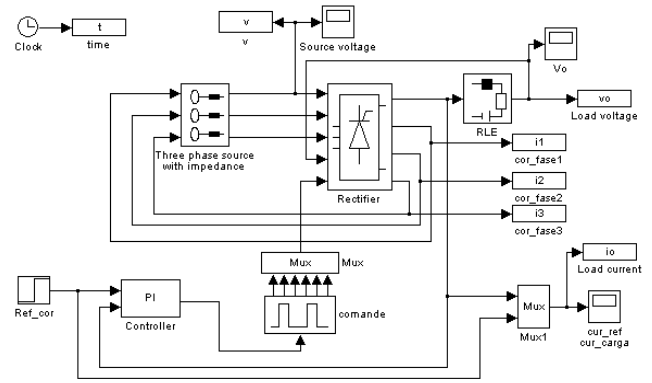
The block diagram of simulation in closed loop is shown in figure 10. To obtain the presented results the following parameters of the source and the load were considered:

$$V_m = 220\sqrt{2}\ \text{V}, \omega = 314\ \text{rad/s}, R_s = 0.01\ \Omega,$$
$$L_s = 1\ \text{mH}; R = 5\ \Omega, L = 20\ \text{mH}, E = -120\ \text{V};$$

Simulation of the circuit with these parameters produced the waveforms of figure 11. The output current follows the reference input and it can be observed that the system has a good dynamic response good. It is also possible to observe the conduction overlap of the thyristor due to the source inductance. The typical line current waveforms are shown in figure 12. These curves show that the simulation is working correctly in the Simulink environment for such a kind of situation.
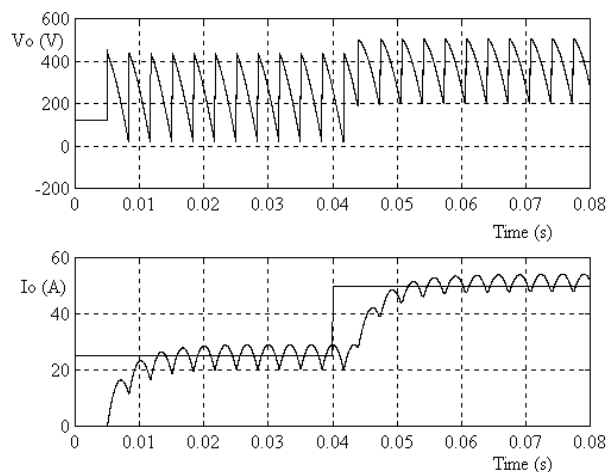
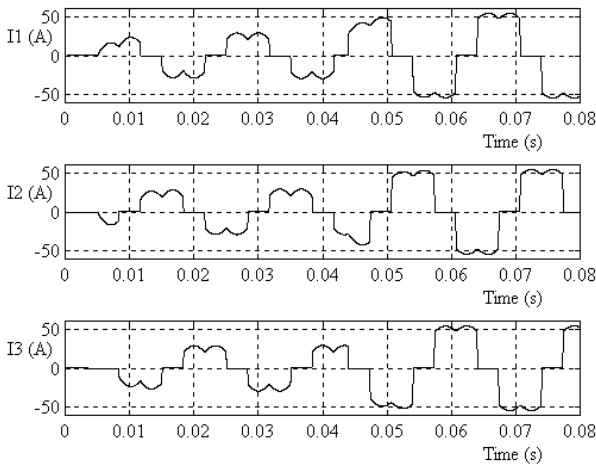

Fig. 11. Output voltage and load current.

Fig. 12. Line current waveforms.

5.2 Closed loop power factor corrector

Figure 13 shows the Simulink model of a complete closed loop power factor correction (PFC). The dynamic performance of the circuit was obtained by applying two changing operating conditions: the initial value of V_o is different from zero and a step change is applied in the output voltage reference. The simulation results are shown in figures 14 and 15. In this test, for $t = 0$ s the initial value of V_o is 350 V and the output voltage reference is 400V and steps from 400V to 450 V at $t = 0.4$ s. The waveforms in figure 14 illustrate the PFC dynamic performance. In figure 15, we observe the the phase voltage and the line current are in phase. These results have been obtained with the following parameters:

$V_m = 220\sqrt{2}$ V, $\omega = 314\,\text{rad}/\text{s}$, $R = 0.25\,\Omega$,

$L = 3\,\text{mH}$, $F_c = 10\,\text{kHz}$;

$R = 70\,\Omega$, $C = 2200\,\mu\text{F}$, $V_0(0) = 350$ V;

In conclusion, these plots show that the converter system functions very well and validates the Simulink models to power switches used in the simulation.

6 Conclusions

A unified method for modelling of power electronic systems using bond graph energy-flow modelling and signal-flow modelling schemes has been presented. This modelling technique has been
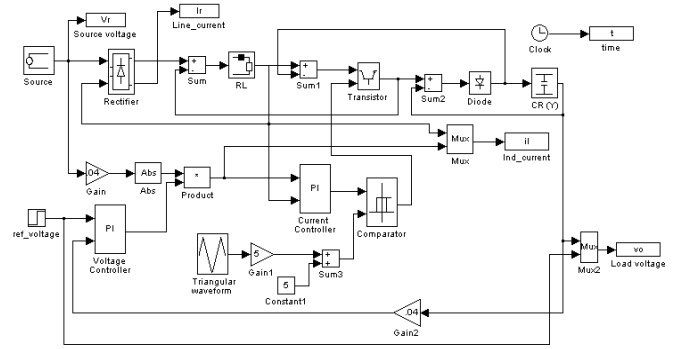

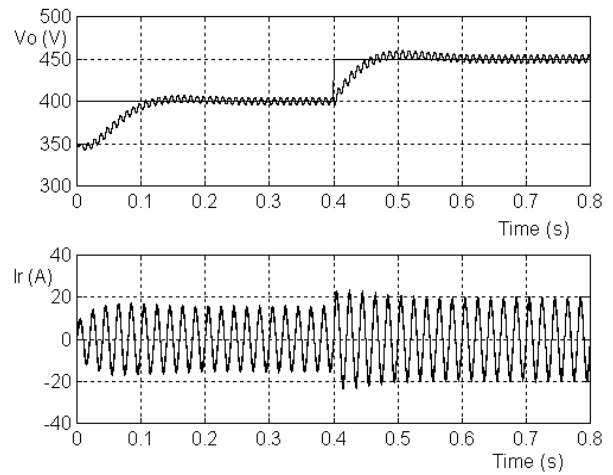Fig. 13. Simulink model of closed loop power factor correction.

Fig. 14. Response to the step of the input reference of the voltage controller.
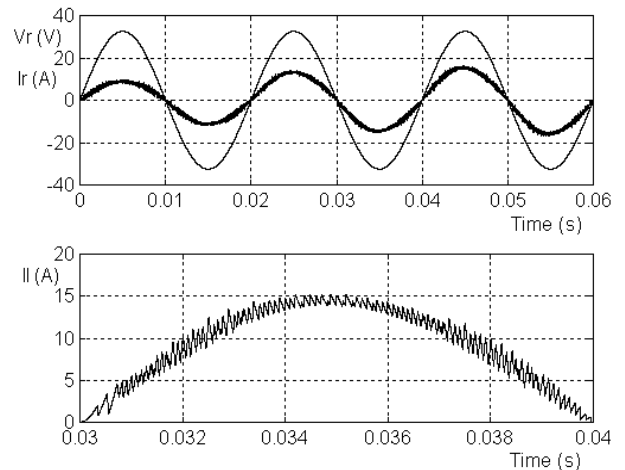

Fig. 15. Source voltage and current waveforms.

developed for simulation of power electronics using Simulink environment. By using the bond graph formalism it is possible to combine linear

and nonlinear circuits, static converters and control blocks in the same Simulink diagram. Since the models for the objects of a power conversion system are quite different, they must therefore be modelled in different levels. The application examples show that these ideas can be applied for modelling and simulation of large systems where the behaviour of a digital control is crucial for the operation of the power conversion system. An advantage of using Simulink environment is access to sophisticated scripts and functions embedded in various Matlab toolboxes. Two typical examples using the proposed methodology have been presented to illustrate the possibilities of VCPS in power electronics systems.

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