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SIMPLIFYING SWITCHED BOND GRAPHS USING RESIDUAL SINKS TO ENFORCE CAUSALITY: APPLICATION TO MODELING THE Z-SOURCE INVERTER

Matías A. Nacusse[a,b], **Sergio J. Junco**[b]

[a]*CONICET – Consejo Nacional de Investigaciones Científicas y Técnicas.*

[b]*LAC, Laboratorio de Automatización y Control, Departamento de Control, Facultad de Ciencias Exactas, Ingeniería y Agrimensura, Universidad Nacional de Rosario, Ríobamba 245 Bis – S2000EKE Rosario – Argentina.*
nacusse@fceia.unr.edu.ar, sjunco@fceia.unr.edu.ar

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Abstract. This paper addresses the problem of modeling the monophasic Z-source inverter in the bond graph (BG) domain. The Z-source inverter is a standard voltage source inverter (VSI) fed through a diode and an LC network. The dynamics introduced to the circuit by the LC network, added to the nonlinear behavior of the VSI and the diode, which results in several switched dynamic modes, makes this configuration very difficult to study and simulate. The main advantage of the Z-source inverter over the standard VSI is that the former can rise or drop the output voltage of the VSI at the same stage and, also, that it avoids the need of using dead time delays between commutations. This latter improvement is enabled by the possibility of shooting-through two power elements in the same leg of the VSI, as the DC-link source is protected by the LC network.

This work revisits the results in (Vázquez Sieber et al. 2008) with the aim of presenting a fully object oriented bond graph model of the Z-source inverter where each BG component represents one and only one physical phenomenon, with a minimum numbers of switched elements, and whit integral-only causality assigned to the energy storage elements. To handle the switching in the BG domain the switched power junction (SPJ) formalism is selected and the residual sink concept is used to avoid the derivative causality. Some simulation results are shown to prove the correct performance of the model.

1 INTRODUCTION

Frequently in engineering problems abrupt changes in physical systems are considered to occur instantly. This is mainly due to the fact that the behavior the engineer is interested in has a time scale much bigger than that of the abrupt change, and that the details inside the time window of this change are not relevant to the behavior under study. Thus, ignoring them results in saving time and effort. As this practice departs from the assumptions of continuity and smoothness underlying classical physics, it requires special modeling, simulation and analysis tools to handle the systems it yields, see (Mosterman and Biswas, 1998) for a detailed discussion of modeling and simulation issues related to this problem.

The classical bond graph representation of continuous physical systems can be extended to switched physical systems by introducing a few extra BG components. Many formalisms for ideal switching modeling have been proposed in the BG domain: MTFs modulated with gain taking only the discrete values 0 and 1 (Karnopp and Rosenberg 1992), (Asher 1993), (Dauphin-Tanguy and Rombaut 1997); an ideal switch as a new bond graph element (Strömberg, Top, and Söderman 1993); a switch as an ideal current source and a voltage source (Demir and Poyraz 1997); switching bonds (Broenink and Wijbrans 1993); controlled junctions (Mosterman and Biswas 1995, 1998); Petri nets to represent discrete modes and transition between modes (Allard, Helali, Lin, and Morel 1995); and the SPJ or Switched Power Junction formalism. See (Umarikar and Umanand 2005) for an introduction to the latter modeling technique and a brief description and discussion of the pros and cons of all the others. Out of these formalisms, this paper chooses the SPJ concept to model mode switching, i.e., the switching among the different BGs, each of them corresponding to a continuous mode or dynamical subsystem of the switched system. This concept is based on the introduction of two new junction elements, the 0_s or switched-zero junction, and the 1_s or switched-one junction. Using them it is possible to represent all of the switched system operation modes in a unique (switched) BG. In (Junco et al. 2007) the SPJs have been interpreted in terms of the classical 0- and 1-junctions and MTFs modulated by a gain taking the values 0 or 1. In (Nacusse et al. 2008) the implementation of the 0_s and 1_s as new standard elements of the 20sim (Controllab Products B.V) basic library has been presented and used in a case study to automatically manage all the mode changes of the switched system.

The switching between modes can cause the physical system to win or loose degrees of freedom, which, in the BG domain, implies the connection or disconnection of storage elements in integral or derivative causality. Depending on the different mode constraints the connection (or disconnection) of storage elements can produce discontinuities in the state. This is associated with an instantaneous lost of a finite amount of energy in the system (violation of the energy conservation principle), to which a power impulse is associated. This latter fact implies that an eventual re-initialization of the states after the commutation should be computed invoking the principles of conservation of generalized momentum or generalized charge, depending upon the kind of energy storages being involved in the state jumps (Borutzky 2004).

This paper addresses the problem of modeling the monophasic Z-source inverter in the bond graph domain. The Z-source inverter first presented in (Peng 2003) is a standard voltage source inverter (VSI) fed through a diode and a LC network. The LC network introduces a non-minimum phase dynamics to the circuit (Gajanayake et al. 2005) which added to the nonlinear behavior of the VSI and the diode makes this configuration very difficult to study and simulate. For these reasons it is important to have a reliable model of the Z-source inverter that makes its analysis and study feasible.

The main advantage of the Z-source inverter over the standard VSI is that the Z-source inverter can rise or drop the output voltage of the VSI at the same stage and avoids the need of using dead time delays between commutations. This improvement is due to the shoot-through voltage vectors generated by closing two power elements in the same leg.

In (Vázquez Sieber et al. 2008) a bond graph model of the Z-source inverter was presented. In that model, all the individual modes were first separately modeled and then joined together through SPJs to build the overall switched BG. Due to the voltage and current constraints of each mode, some BG components of the LC network present alternating causality assignment (integral and differential, depending on the switching mode), which calls for a duplication of these BG components to handle the switching. As each of these causality-alternating, duplicated elements represents in fact a unique physical phenomenon, this modeling approach is not Object Oriented Modeling (OOM) compliant. On the other hand, derivative causality unavoidably appears if an I or C component changes its causality, which is an undesirable feature regarding simulation. By adding some parasitic BG components the causality constraint, which forces derivative causality, can be broken and models can be obtained with integral-only causality. However these parasitic components increase the model order and make it stiff for simulation purposes, entering in conflict with the ideal switch approach chosen to model the commutations. Besides this, the parasitic components are usually not related to the physical system from a macroscopic point of view, which complicates the task of parameterizing them.

Employing an OOM approach in which each BG component represents a single physical phenomenon, this work revisits the modeling task carried out in (Vázquez Sieber et al. 2008). To avoid the need of using twin elements to perform the change of causality at the mode switching, a residual sink (Borutzky 2004) element is added to maintain the preferred integral causality in the circuit. The residual sink component injects the necessary effort or flow in order to make vanish the power conjugated variable into the sink. This bond graph component adds an algebraic constraint to the system equations which is solved off line for this model.
Another problem associated to the change of causality between modes is the possible appearance of discontinuities in the states which is solved with the re-initialization of the storage elements after a switching occurrence (Nacusse and Junco 2010).

Summarizing, this work present a fully object oriented bond graph model of the Z-source inverter, which reduces the number of SPJ employed and presents integral-only causality assignment in the energy storage elements, making this model easily understandable and more efficient for simulation purposes.

The paper is organized as follows: Section 2 addresses some background results; Section 3 presents the BG model of the Z-source inverter; finally, in Section 4, some simulation results are shown to prove the correct performance of the model.

2 BACKGROUND

This section introduces the SPJ formalism to handle commutations in switched systems and the residual sinks components to enforce integral-only causality assignment in the storage elements.

2.1 Switched Power Junctions

Switched power junctions (SPJ) 0_S and 1_S (Umarikar and Umanand 2005) are a generalization of the standard 0- and 1-junctions in which more than one bond can graphically impose effort (0_S) or flow (1_S) to the junction. In the classical BG formalism this produces a causality conflict and is not allowed. To prevent from causality conflicts in the new elements, control signals are added to the junctions. Only one of these control signals is allowed to have the value 1 at a given time instant, the remaining signals are zero. In this way, only one of the bonds imposing effort (0_S) or flow (1_S) is selected (i.e., becomes operative) and the value zero is imposed to the power co-variables of the remaining bonds, which results in their disconnection.

Figure 1 shows the SPJ with causality assignment and Equations 1 and 2 express the mathematical relationships, for the 0_s and the 1_s respectively, among the power variables and the control signals injected to select the appropriate bond. The control signals are denoted with U_i, they take values over the set {1, 0}.

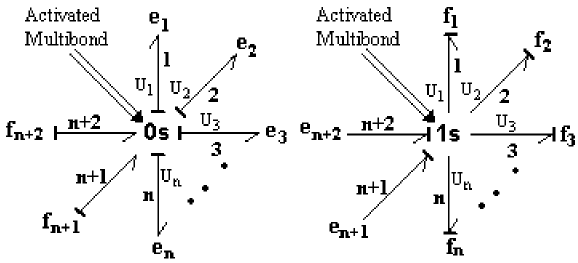

Figure 1: Switch Power Junctions with causality assignment.

$$\begin{aligned} \mathrm{Effort} &= \mathrm{U_1 e_1 + U_2 e_2 + \cdots + U_n e_n} \\ \mathrm{f_i} &= \mathrm{U_i(f_{n+1} + f_{n+2})} \quad ; \quad \mathrm{i = 1, \ldots, n} \end{aligned} \tag{1}$$

$$\begin{aligned} \mathrm{Flow} &= \mathrm{U_1 f_1 + U_2 f_2 + \cdots + U_n f_n} \\ \mathrm{e_i} &= \mathrm{U_i(e_{n+1} + e_{n+2})} \quad ; \quad \mathrm{i = 1, \ldots, n} \end{aligned} \tag{2}$$

In (Junco et al. 2007) the SPJs have been interpreted in terms of the classical 0- and 1-junctions and MTFs modulated by a gain taking the values 0 or 1. In (Nacusse et al. 2008) the implementation of the 0_S and the 1_S as new standard elements of the 20sim basic library has been presented, available for download at http://www.fceia.unr.edu.ar/dsf/I&D/BG.html.

2.2 Residual sinks

There are two kinds of residual sinks, effort residual sinks (rSe) and flow residual sinks (rSf). A residual sink outputs the necessary effort or flow in order to make vanish the power conjugated variable entering into the sink.

A residual sink element can be interpreted as an energy store where it parameter tends to zero. For example, an effort residual sink can be interpreted as a C element in integral causality:

$$\mathrm{C\dot{e} = \Delta f}$$

If the parameter C tends to zero, then $\dot{e}$ is determined by the algebraic equation $\Delta f = 0$.

Figure 2 shows the graphical representation of the effort and flow residual sink used in (Borutzky 2009).

Figure 2: Effort and flow residual sink

The residual sink introduces an algebraic constraint to the system equations which in some cases can be solved analytically and programmed in the simulation software.

3 MODELING THE Z-SOURCE INVERTER

This section presents a full OOM approach to modeling the monophase Z-source inverter sketched in Figure 3. First, the transistor bridge is modeled with fixed causality using SPJs and a flow residual sink. Later on, the LC network is added and the diode is modeled using a 0_S and an effort residual sink.

The Z-source inverter can work in six different operation modes which are carefully analyzed to obtain the different constraints of each mode. At last, the control laws for the residual sinks are obtained.

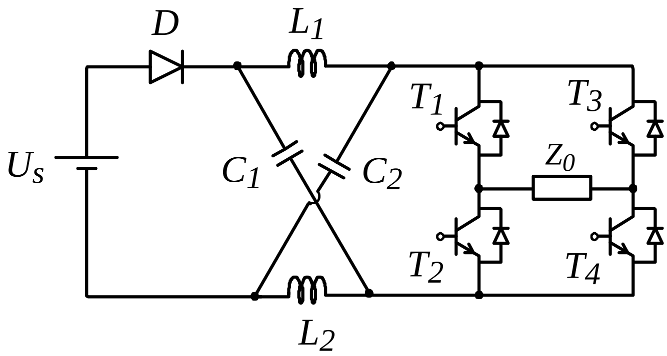

Figure 3: Schematic Circuit of the Z-source inverter

3.1 Transistor bridge model

Figure 4 shows the schematic circuit of a Transistor Bridge where the power transistors are considered as ideal switches. This transistor bridge is controlled by four input signals that correspond to the bases of the power transistors. With four switches, up to 2^4 circuit configurations can be constructed. However, not all of these configurations are allowed in some cases. For instance, if considering the standard monophasic voltage source inverter, only four modes are allowed, because only one power element on one leg is allowed to be switched on at any given time instant. So, to make a functional model of the standard monophasic voltage source inverter only two control inputs are needed. Figure 5 shows the switched BG (SwBG) model of the transistor bridge that allows these four standard circuit configurations.

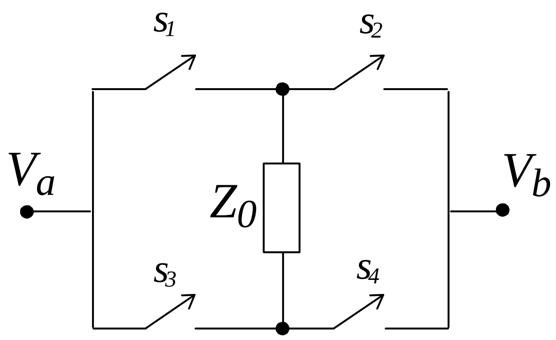

Figure 4: Switch scheme of the transistor bridge

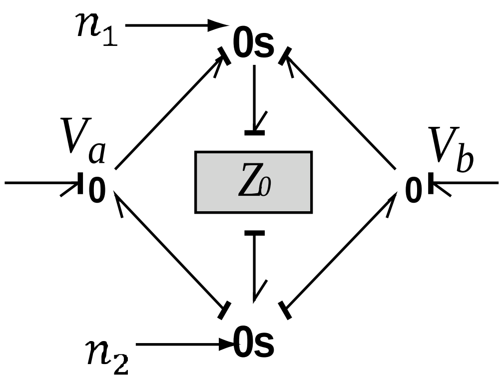

Figure 5: SwBG model of the standard transistor bridge

However, for the transistor bridge depicted in Figure 4, there are in fact nine different switch combinations that impose a voltage to the load. These voltages can be represented as vectors in a reference plane. There are two active and two null vectors, which are the four voltage vectors produced by the standard monophasic voltage source inverter as modeled above, and five shoot-through null voltage vectors. These latter five vectors can be generated by closing simultaneously two transistors on the same leg.

To obtain the fully functional SwBG model of the transistor bridge, that contains the shoot-through null voltage vectors and maintain the effort-in fixed causality into the load, an extra SPJ and a flow residual source are added.

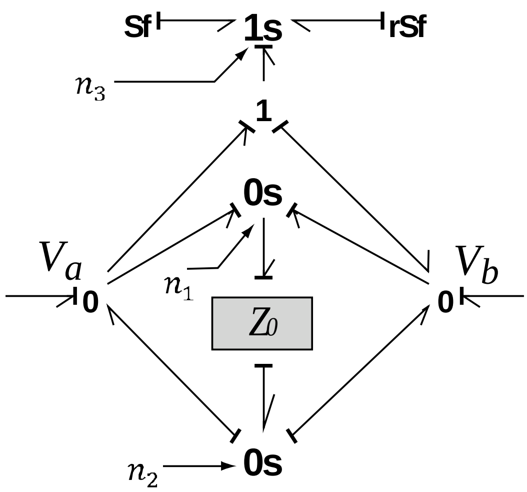

Figure 6: Fully functional SwBG model of the transistor bridge

The flow source imposes zero flow when the standard null/active voltage vectors are applied. When a shoot-through null vector is applied, then the 1_S selects the residual sink bond, which imposes the necessary flow to make the effort difference zero, $V_a - V_b = 0$.

Figure 7 shows the eight different circuit configurations for the BG transistor bridge model of Figure 6. Note that the ninth voltage vector, produced when the four transistors are closed, is equivalent to any other shoot-through null vector.

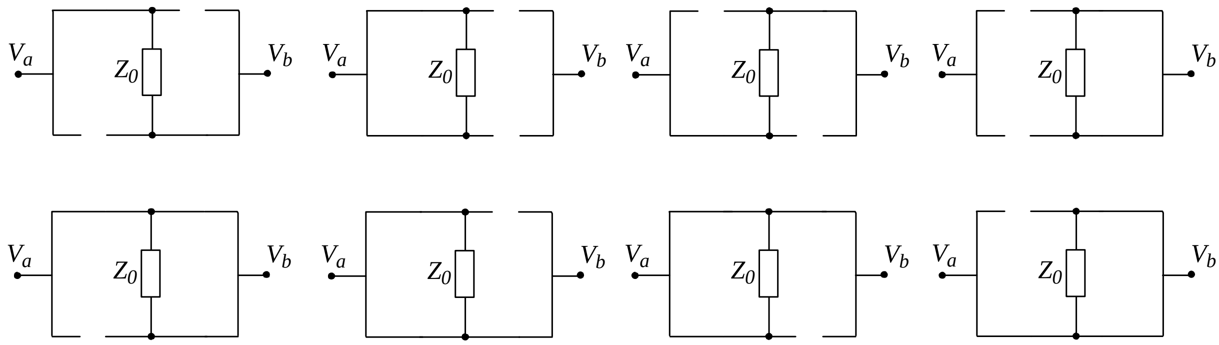

Figure 7: Switch combinations of the transistor bridge of Figure 6

3.2 Z-source model

Figure 8 depicts the redrawn Z-source schematic circuit of Figure 3 to better show the different modes of the switched system. From the point of view of the LC network the transistor bridge can connect the load (active voltage vector), disconnect it (standard null vectors) or create a short-cut (shoot-through null voltage vectors). For all these cases the diode can be in conduction/on-state or not. Figure 9 depicts the six different modes of the Z-source inverter.

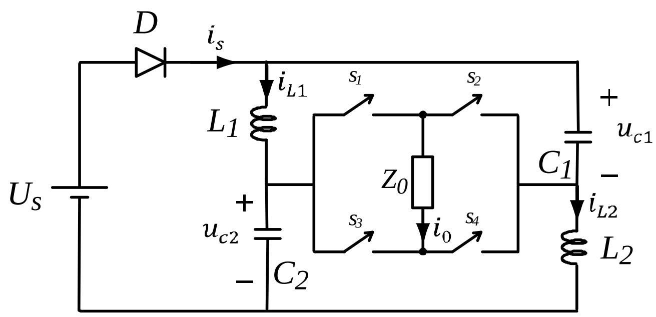

Figure 8: Schematic circuit of the Z-source inverter

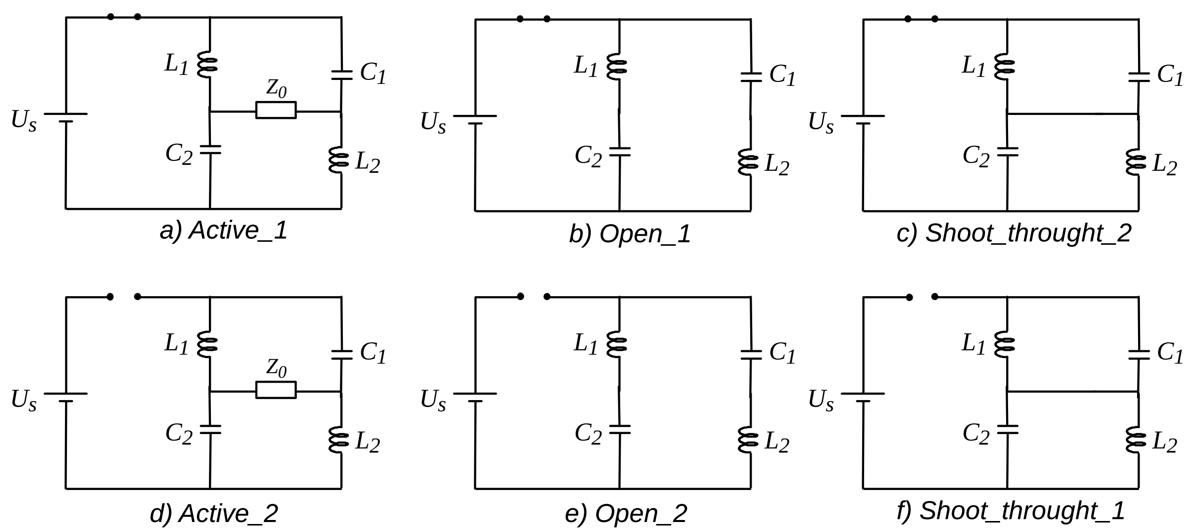

Figure 9: operation modes of the Z-source inverter.

3.2.1 Z-source modes

The Z-source inverter can switch between modes by two different ways. One is forced by external events generated by the PWM signal, which excites the transistor bases, and the other, by internal state events forcing the diode to switch between the off- and the on-states.

When a null vector is applied, the dynamics of the load current (i_0) evolves without restraint to the dynamics of the inductors currents (i_L). Depending on the values of these currents after the switching, the system can enter in different modes in a not controlled way. For all modes, the diode passes to the off-state when its current tends to be less than zero, and passes to the on-state when its voltage tends to be greater than zero.

Active modes:

When the Z-source is in *Active_1* mode and in absence of external events the switched system remains in this mode until the supplied current by the voltage source $i_s = 2i_L - i_0 < 0$ (see Figure 8). After this internal event occurs, the diode passes from on- to off-state entering in *Active_2* mode. In this mode, the switched system has the current constraint $2i_L = i_0$, and, in absence of an external event, the switched system will remain in this mode.

When an external event occurs, this means a null vector demands to be applied, the constraint between i_0 and $i_L$is relaxed and the voltage source will supply the necessary current to fulfill $i_s = 2i_L$. Note that if the switched system is in mode *Active_2* with $i_L > 0$ and a null vector is applied, then a voltage impulse limited by the diode D occurs to balance the fluxes at the inductors making the switched system to pass to *Open_1* mode instantaneously.

Null modes:

When the system is in *Open_1* mode then the supplied current is $i_s = 2i_L$ and it will remain in this mode until $i_s < 0$ and the diode passes from on- to off-state making $i_L = 0$ and entering in *Open_2* mode.

In *Shoot-through_1* mode $i_s = 0$ and i_L will evolve freely. In *Shoot-through_2* mode $U_s = 2u_C$ and $i_s = 2i_L$. If the switched system enters in this mode when $U_s > 2u_C$, then a positive current impulse is produced to balance the capacitors charges. This impulse is not limited and may damage the circuit, so to enter to this mode the voltage constraint $U_s = 2u_C$ must be accomplished.

When any null vector is applied to the load and an external event tries to change to an active voltage vector, depending on the relation between i_0 and i_L e.g. $2i_L - i_0 < 0$, then, to satisfy the constraint $2i_L = i_0$, a voltage impulse limited by the free-wheels diodes of the transistor bridge is produced making the switched system enter in the not controlled *Shoot-throug_1* mode. The system remains in this mode until $2i_L = i_0$. On the contrary, if $2i_L - i_0 > 0$, the voltage impulse is limited by the diode D, making the system to switch to *Active_1* mode and i_L must be initialized in $\frac{i_0}{2}$.

3.2.2 Z-source BG model

In this subsection the SwBG model of the Z-source inverter is presented. First, the different states of the diode are separately modeled, then, they are joined through 0-SPJ. Figure 10 shows the BG model of the Z-source inverter when the diode is in on-state. Note that this model can represent the *Active_1*, *Open_1* and *Shoot-through_2* modes.

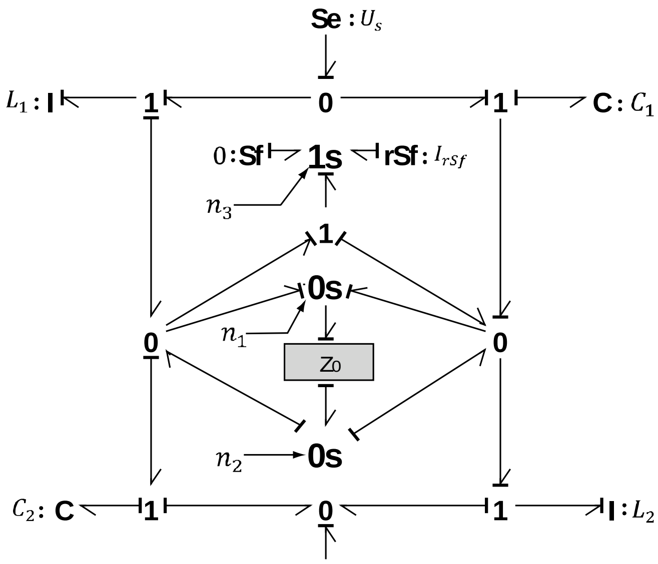

Figure 10: SwBG model of the Z-source inverter when the diode is in on-state.

Figure 11a shows the BG model of the Z-source inverter when the diode is in off-state. Note that the inertia I corresponding to the inductance L_1 is in derivative causality. To avoid this derivative causality an effort residual sink is added as depicted in Figure 11b.

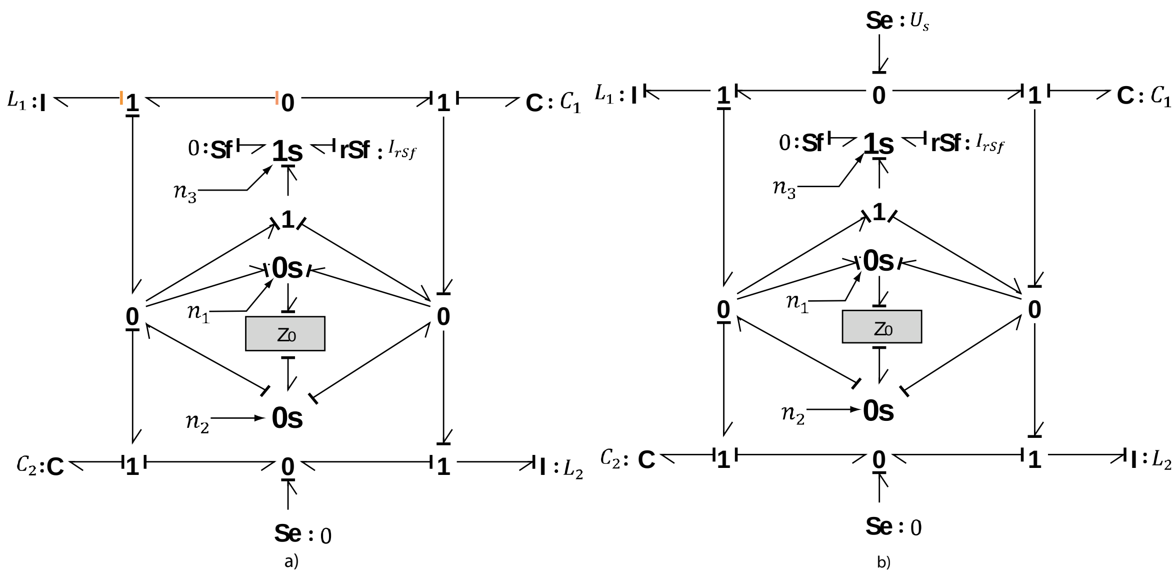

Figure 11: Z-source model when the diode is in off-state. a) with L1 in derivative causality, b) with effort residual sink.

Finally, to handle the commutations between the states of the diode, a 0-SPJ is added to switch between the effort source element and the effort residual sink, combining the models of Figure 11b and Figure 10. Figure 12 represent the complete SwBG model of the Z-source inverter with all the storage elements in integral causality.

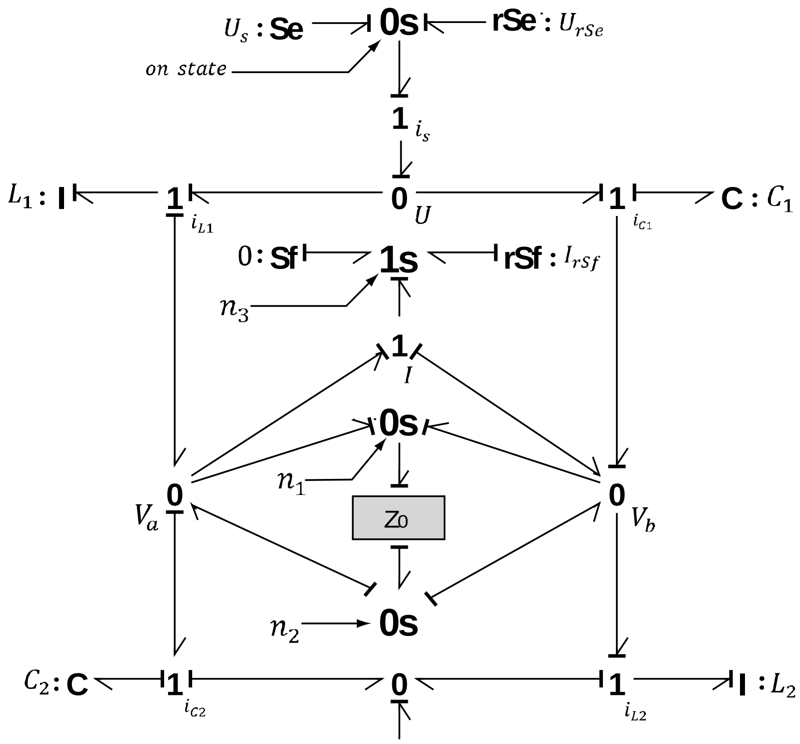

Figure 12: SwBG model of the Z- source inverter.

As explained in Section 2.2, the residual sinks component add and algebraic constraint to the system equations which can be solved on-line in most of the BG simulation software as 20sim with the *constraint* sentence (Help 20sim 4.1). However this sentence does not work well in switched systems. For this reason, it is necessary to solve these algebraic constraints off-line. The next subsection explains the off-line solution to this problem.

3.3 Solving the algebraic constraints

The state equations of the Z-source inverter are obtained reading directly from the SwBG model of Figure 12.

$$\dot{i_{L2}} = \frac{1}{L_2}(U - u_{c1}) \tag{3}$$

$$\dot{i_{L1}} = \frac{1}{L_1}(U - u_{c2}) \tag{4}$$

$$\dot{u_{c1}} = \frac{1}{C_1}[i_{L2} + i_0(n_1 - n_2) - I] \tag{5}$$

$$\dot{u_{c2}} = \frac{1}{C_2}[i_{L1} + i_0(n_1 - n_2) - I] \tag{6}$$

Where L_1 and L_2 are the respective inductances values of the inductors L_1 and L_2 and C_1 and C_2 are the capacitance values of the capacitors C_1 and C_2. Note that if $L_1 = L_2 = L$ and $C_1 = C_2 = C$ then $i_{L1} = i_{L2} = i_L$ and $u_{c1} = u_{c2} = u_c$.

$$U = \begin{cases} U_s & if\ diode\ is\ in\ on-state \\ U_{rSe} & if\ diode\ is\ in\ off-state \end{cases}$$

$$I = \begin{cases} 0 & Standard\ modes \\ I_{rSf} & Shoot - through\ modes \end{cases}$$

Where U_{rSe} and I_{rSf} are the effort and flow injected by the effort and the flow residual sink respectively. To obtain the mathematical law for U_{rSe}:

$$i_{L1} + i_{C1} = 0 \quad (7)$$

Where i_{C2} is the capacitor current (see Figure 12) equal to:

$$i_{C1} = i_{L2} + i_0(n_1 - n_2) - I \quad (8)$$

$$\dot{i_{L1}} + \dot{i_{C1}} = 0 \quad (9)$$

So, replacing (4) and (8) in (9) then:

$$\frac{1}{L}(U_{rSe} - u_c) + \dot{i_L} + \dot{i_0}(n_1 - n_2) - \dot{I} = 0 \quad (10)$$

If the Z-source is not in a shoot-through mode then $I = 0$ and U_{rSe} is

$$U_{rSe} = -\frac{L}{2}[\dot{i_0}(n_1 - n_2)] + u_c \quad (11)$$

Where $\dot{i}_0$ is replaced by the appropriate state equation of the load.
If the Z-source is in a shoot-through mode then $n_1 = n_2$ and

$$U_{rSe} = \frac{2}{L}\dot{I} + u_c \quad (12)$$

In a Shoot-through mode $I = I_{rSf}$ must be such that:

$$V_a - V_b = 0 \quad (13)$$

$$\dot{V_a} - \dot{V_b} = 0 \quad (14)$$

Reading from the BG of Figure 12 and replacing in (14) yields to:

$$\dot{u_{c2}} - \dot{U} + \dot{u_{c1}} = 0 \quad (15)$$

$$2\dot{u_c} - \dot{U} = 0 \quad (16)$$

If the diode D is in on-state then $U = U_s$ (*Shoot-through_2* mode) and:

$$2\dot{u_c} = 0 \quad (17)$$

Replacing (5) into (17) then

$$\frac{2}{C}\left[i_L - I_{rSf}\right] = 0$$

$$I_{rSf} = i_L \quad (18)$$

Equation (18) is valid only for *Shoot-through_2* mode. If the diode D is in off-state (*Shoot-through_1* mode) then:

$$\frac{2}{C_2}\left[i_{L1} - I_{rSf}\right] = \dot{U} \tag{19}$$

Using (12) and (19), with the appropriate selection of the initial conditions, the mathematical laws for the residual sinks when the system is in *Shoot-through_1* can be obtained in integral form.

In this work a series RL load is considered whose state equation is (20). Replacing this equation into (11) yields to the effort residual sink law for the *Open_2* mode.

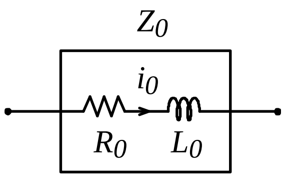

Figure 13: Load

$$\dot{i_0} = \frac{1}{L_0}\left[-R_0 i_0 - (V_a - V_b)(n_1 - n_2)\right] \tag{20}$$

4 SIMULATION RESULTS

The model obtained in Section 3 was implemented in the simulation software 20sim (Controllab Products B.V) with the following simulation parameters; $U_s = 240V$, $C_1 = C_2 = 1\mu F$, $L_1 = L_2 = 35mH$, $R_0 = 200\Omega$ and $L_0 = 100mH$. The external events are generated through a unipolar PWM signal, with a fixed Shoot-through time period, triangle carrier of frequency $10KHz$ and a sine reference of frequency $50Hz$.

Figure 14 shows from top to bottom the signals which identify the applied voltage vector (n_1, n_2, and n_3), the signal that indicates when the system enter in a not controlled shoot-through mode (ST), the diode state, the output current i_0, the source current i_s and the error effort $(V_a - V_b)$ which is equal to zero when the system is in a shoot-through mode.

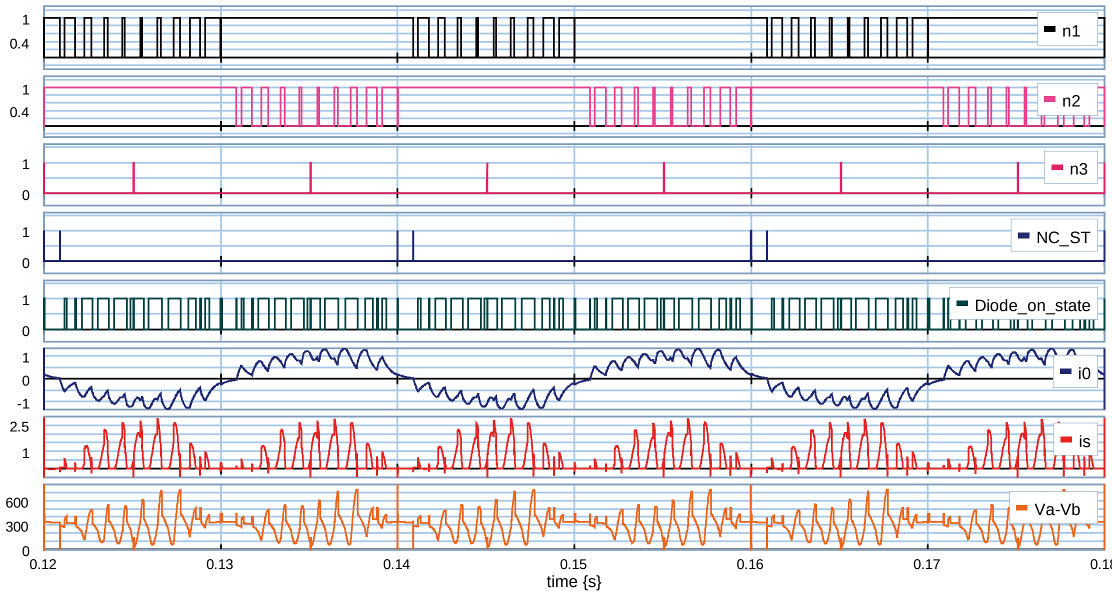

Figure 14: simulation response to external and internal events

Figure 15 presents a zoom of Figure 14 to better show the switching between modes. In the selected time window only the standard voltage vectors are applied and when the diode is in off-state, the current i_s is equal to zero. Also it can be noted, as indicated with vertical doted lines in the upper part of this figure, when the system passes from *Active_2* mode to *Open_1* and *Open_2* to *Active_1*.

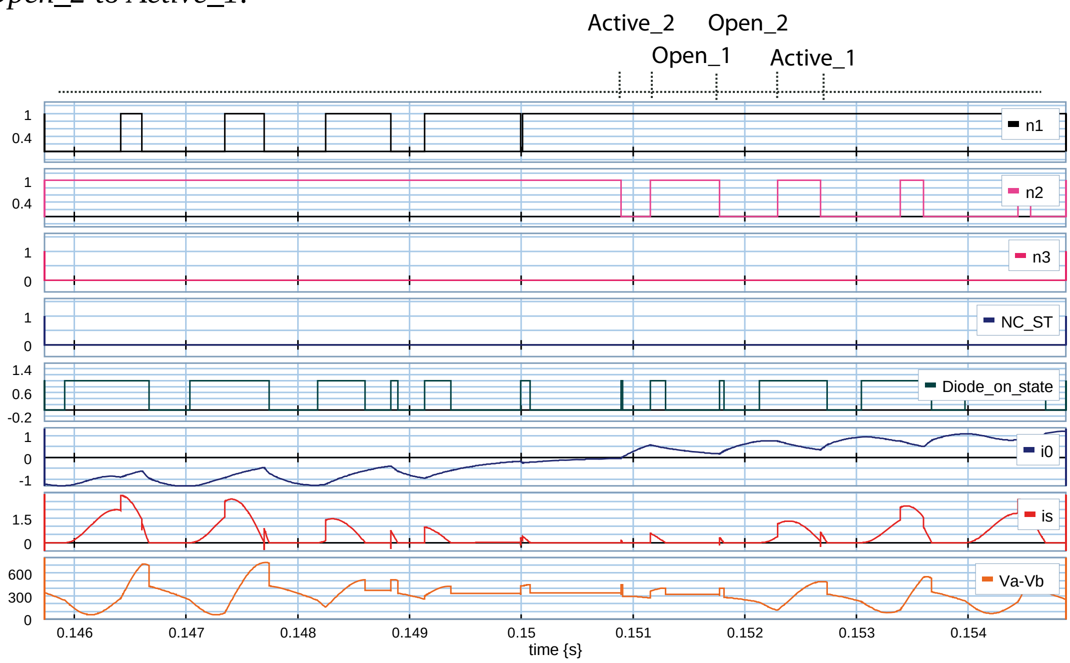

Figure 15: switching between modes when standard voltage vectors are applied.

Figure 16 is a zoomed version of Figure 14, to better show how the switched system passes from *Open_2* to not controlled *shoot-through_1* and then to *Active_1* mode. Note that, when the not controlled shoot-through vector is applied, the values of i_s and $V_a - V_b$ are zero, validating the control laws implemented on the residual sinks.

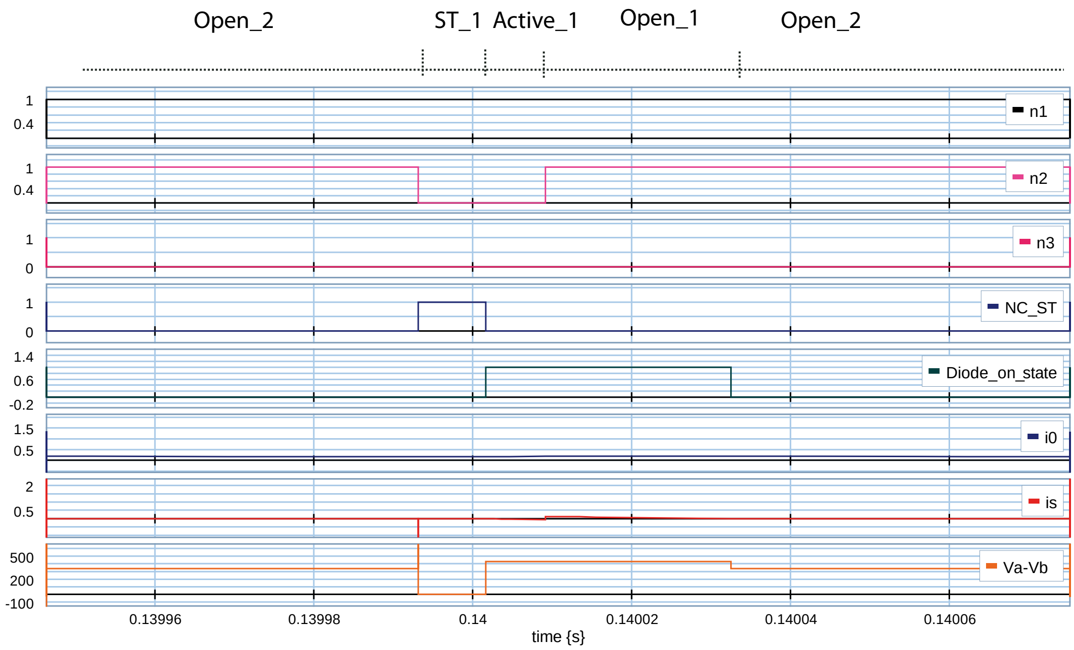

Figure 16: zoom of Figure 14, not controlled Shoot-through vector

Figure 17 shows a time window of the controlled shoot-through vector. The system passes from *Active_1* to *shoot-through_1* mode due to the fact that before the commutation $u_C > \frac{U_S}{2}$ and, when the switched system tries to enter in *shoot-through_2* mode, generates a current impulse of negative sign that is limited by the diode D.

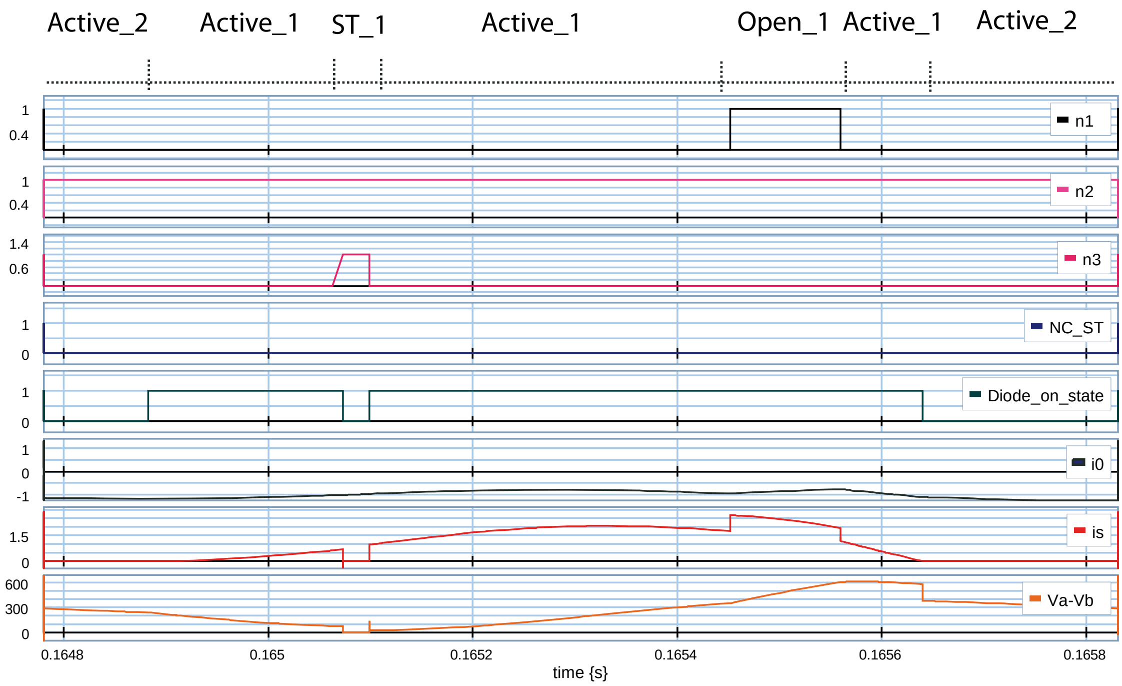

Figure 17: zoom of Figure 14, controlled shoot-through vector

Figure 18 shows the states of the switched system and the source current i_s to show the periodicity of the solution. Note that the voltage across the capacitors are always greater than $\frac{U_S}{2}$.

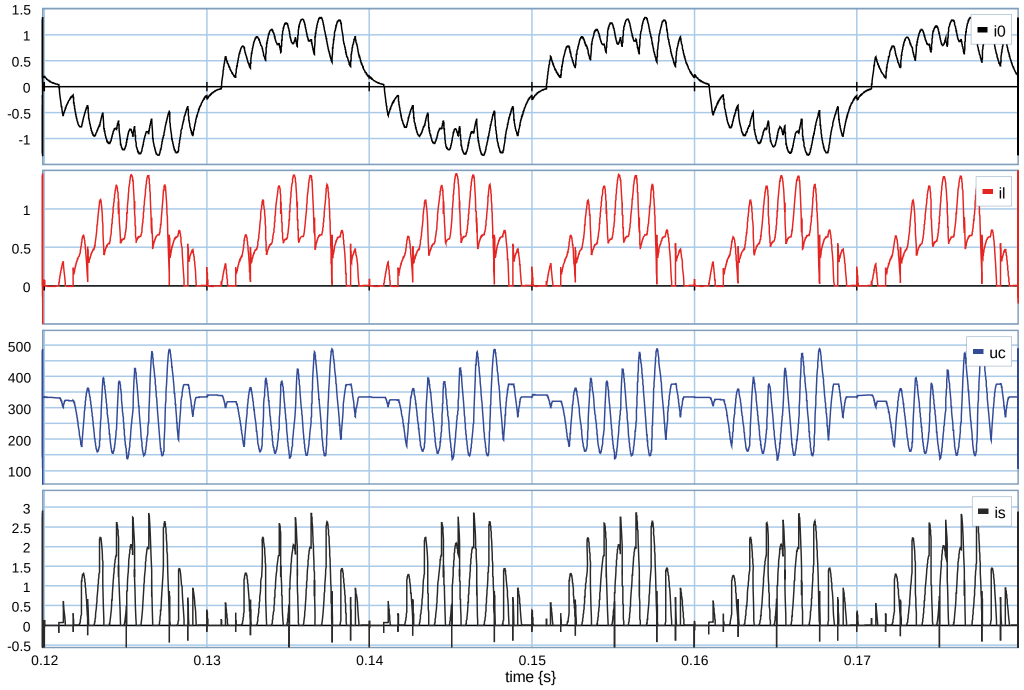

Figure 18: State variables and source current.

As a final comment about the simulation responses, special care has to be taken to generate the appropriate time events for the PWM signal, in order to perform a correct simulation process. This is due to the fact that 20sim is not an event oriented simulation software.

5 CONCLUSIONS

In this work a fully Object Oriented BG-model of the Z-source inverter was presented with the following features: simultaneous representation of all operation modes in a unique SwBG model, one to one correspondence between physical phenomena and BG components, only-integral causality assignment in all its energy storage elements and a reduced numbers of SPJ.

Simulation responses demonstrate the good performance of the model in all its operation modes.

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REFERENCES

Allard, B., Helali, H., Lin, Ch., Morel, H., 1995. Power converter average model computation using the bond graph and Petri Net Techniques. *IEEE Power Electronic Specialist Conference*, pp. 830–836.

Asher, G., 1993. The robust modeling of variable topology circuits using bond graphs. *Proc. Int. Conf. on Bond Graph Modeling and Simulation*. San Diego, CA, pp. 126–131.

Borutzky, W., 2009. Bond graph model-based fault detection using residual sinks. *Proc. IMechE, Part I: Journal of Systems and Control Engineering*, Vol. 223, pp. 337-352, London: PEP.

Borutzky, W., 2004. Bond Graphs. "*A Methodology for Modelling Multidisciplinary Dynamic Systems*". Erlangen, San Diego: SCS Publishing House.

Broenink, J. and Wijbrans, K., 1993. Describing discontinuities in bond graphs. *Proceedings of International Conference on Bond Graph Modelling*. San Diego, CA, pp. 120–125.

Controllab Products B.V., 20-sim™, http://www.20sim.com/

Dauphin-Tanguy, G. and Rombaut, C., 1997. A Bond Graph Approach For Modeling Switching Losses of Power Semiconductor Devices. *Proc. Int. Conf. on Bond Graph Modeling and Simulation*. pp. 207-212.

Demir, Y. and Poyraz, M., 1997. Derivation of state and output equations for systems containing switches and a novel definition of switch using the bond graph model. *Journal of the Franklin Institute*. 3343 (2) 191–197.

Gajanayake, C.J. Vilathgamuwa, D.M. Poh Chiang Loh. 2005 *"Small-Signal and Signal-Flow-Graph Modeling of Switched Z-Source Impedance Network"*. Ieee. power electronics letters, Vol. 3, Nº. 3, September.

Help 20sim 4.1 Controllab Products B.V., 20-sim™, http://www.20sim.com/webhelp.html

Junco, S., Diéguez, G., Ramírez, F., 2007. On commutation modeling in Bond Graphs, *Proc. Int. Conf. on Bond Graph Modeling and Simulation,* San Diego, CA, pp. 12-19.

Karnopp, D. and Rosenberg, R., 1992. *System Dynamics. A Unified Approach*, 2nd ed., Wiley Interscience, New York.

Lin, H. and Antsaklis, P., 2007. Switching Stabilizability for Continuous-Time Uncertain Switched Linear Systems. *IEEE Transactions on automatic control*. Vol. 52, N°4, April 2007. pp 633-646.

Mosterman, P. and Biswas, G., 1995. Behaviour generation using model switching. A hybrid bond graph modeling technique. *Proc. Int. Conf. on Bond Graph Modeling and Simulation*, Las Vegas, pp. 177–182.

Mosterman, P. and Biswas, G., 1998. A theory of discontinuities in physical systems models. *Journal of the Franklin Institute*, 335B (3), 401–439.

Nacusse Matías, Sergio Junco, Alejandro Donaire 2008.*" Automatizando el modelado y simulación con Bond Graphs de sistemas físicos conmutados*". Mecánica Computacional Vol XXVII, págs. 3479-3494.

Nacusse Matías, Junco Sergio. 2010. "Automatic Handling of commutations in Bond Graph based Simulations of Switched systems". International Conference on Integrated Modeling and Analysis in Applied Control and Automation (IMAACA 2010). Fez, Marruecos. Octubre 2010. ISBN 2-9524747-6-1. pp. 27-35.

Peng, F. Z. 2003. *"Z-source inverter"*, IEEE Transaction in Industrial Applications, vol. 39, no. 2, pp.504 – 510.

Strömberg, J., Top, J., Söderman, U., 1993. Variable causality in bond graph caused by discrete effects. *Proc. Int. Conf. on Bond Graph Modeling and Simulation*, San Diego, CA, pp. 115–119.

Umarikar, A. and L. Umanand. 2005, *"Modelling of switching systems in bond graphs using the concept of switched power junctions"*, J. Franklin Institute, 342, 131-147.

Vázquez Sieber A. H. Haimovich and S. Junco. 2008. *"Modelado y simulación híbrida del inversor Z-source monofásico"*. En Congreso Argentino de Control Automático AADECA, Buenos Aires, Argentina.