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Switched junctions in bondgraph for modelling power electronic systems

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Abstract

Modelling of switched-mode power electronic systems using bondgraph is difficult because of lack of switch element in the bondgraph. To overcome this problem, we propose the concept of switched junctions. Here, the dominant junction variable is switched to emulate the practical switch. A few switched-mode power converters are modelled and simulated to demonstrate the efficacy of using the switched junctions.

Keywords: Switched junctions, bondgraphs, modelling, power electronics.

1. Introduction

Bondgraph is a system modelling technique. It has been used extensively in modelling interconnected interacting physical systems.[1–3] Bondgraphs not only allow the modelling of systems for analysis and simulation, but also are a powerful tool for automatic computer programming. Bondgraphs were invented by Henry Paynter to overcome the inherent drawbacks of block diagrams for servo controls and simulation problems. They consider both energy and signal exchanges between the components of a system. For systems where power and efficiency play a major role, bondgraph modelling method is very convenient.

Bondgraphs have been used primarily for modelling dynamical systems where there is continuous energy or power flow through all the components of the system. They do not inherently support modelling of switched power systems like switched-mode power converters and inverters. To overcome this problem, two approaches have generally been used: (i) macromodelling the power switches using inductances, capacitances and resistances;[4] and (ii) using modulated transformers and gyrators with modulation index being either 1 or 0, depending on the state of the power switch.[5] The first approach poses no problem in modelling power electronic systems wherein the components are operating in the linear region. However, for switched power electronic systems, the time constants of the macromodels of the power switch will be in the order of μs and the simulation time will be in the order of seconds. This will make the system a very stiff one and lead to simulations which may take days to finish. In the second approach, wherein modulated transformers or gyrators may be used to represent power switches, the very nature of the effort–flow relationship may get altered. This approach controls either the effort or the flow of the power switch. As a consequence, the model is not a correct representation of the physical system in most cases.

In order to overcome the above-stated problems, this paper proposes an extension to the conventional bondgraph junction. In this paper, the concept of a switched junction is proposed which is a generalization of the conventional bondgraph junction. Section 2 lays the foundation for the concept of switched junctions. Section 3 elucidates the application of switched junctions to modelling of switched-mode power converters.

2. Switched junctions

The 0- and 1-junctions are the multiports used in bondgraph. They are defined according to Thoma[1], and Karnopp and Rosenberg[3]. The 0-junction is defined as

$$\sum_k f_k = 0, \text{ where } f_k \text{ is the flow in the } k\text{th bond of the 0-junction, and}$$

$$e_k = e_{0j},\ \forall k, \text{ where } e_{0j} \text{ is the 0-junction effort.} \qquad \text{(def. 1)}$$

There is only one flow causal bond at the junction which will determine the junction effort, e_{0j}. The 1-junction is defined as

$$\sum_k e_k = 0, \text{ where } e_k \text{ is the effort in the } k\text{th bond of the 1-junction, and}$$

$$f_k = f_{1j},\ \forall k, \text{ where } f_{1j} \text{ is the 1-junction flow.} \qquad \text{(def. 2)}$$

There is only one effort causal bond at the junction which will determine the junction flow, f_{1j}.

The 0- and 1-junctions, as defined by def. 1 and def. 2, respectively, are for continuous power flow through the system. To handle switched power flow through the system, def. 1 and def. 2 are extended to the switched junctions. The *switched* 0-*junction* is defined as

$$\sum_k f_k = 0, \text{ where } f_k \text{ is the flow in the } k\text{th bond of the 0-junction, and}$$

$$e_k = e_{0j},\ \forall k, \text{ where } e_{0j} \text{ is the 0-junction effort.}$$

If e_i and f_i are the effort and flow, respectively, of the ith flow causal bond of the switched 0-junction and u_i is the causal switch of the ith flow causal bond, then

$$e_{0j} = u_i \cdot \begin{bmatrix} u_1 & u_2 & \cdots & u_n & u_{n+1} & \cdots \end{bmatrix} \cdot \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_i \\ e_{i+1} \\ \vdots \end{bmatrix} \quad u_i \cdot u_n = \begin{matrix} 0 & i \neq n \\ 1 & i = n \end{matrix}, \text{ and}$$

$$f_i = 0 \text{ if } u_i \cdot u_n = 0. \qquad \text{(def. 3)}$$

Note that def. 3 reduces to def. 1 when there is only one flow causal bond at the 0-junction.

The *switched* 1-*junction* is defined as

$$\sum_k e_k = 0, \text{ where } e_k \text{ is the effort in the } k\text{th bond of the 0-junction, and}$$

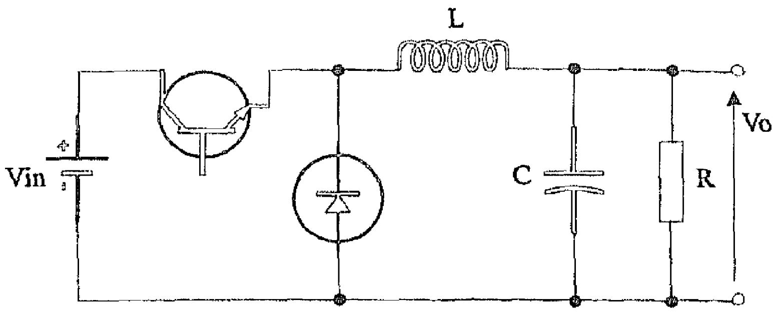


FIG. 1. Buck converter.

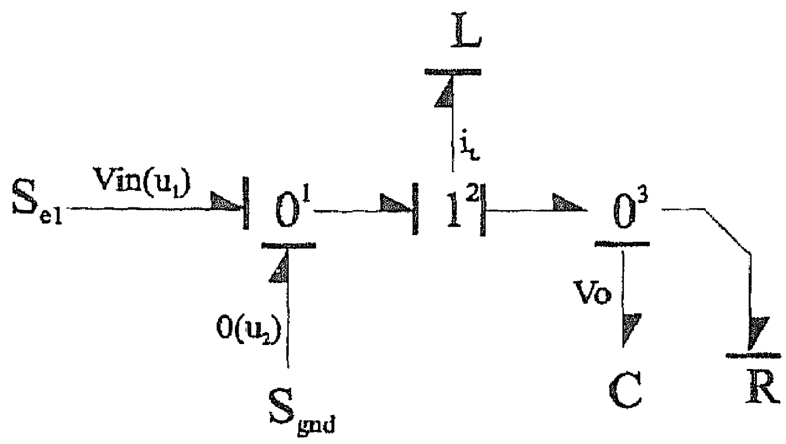


FIG. 2. Bondgraph model for buck converter.

$f_k = f_{1j}$, $\forall k$, where f_{1j} is the 1-junction flow.

If e_i and f_i are the effort and flow, respectively, of the ith effort causal bond of the switched 1-junction and u_i is the causal switch of the ith effort causal bond, then

$$f_{1j} = u_i \cdot \left[u_1\ u_2 \cdots u_n\ u_{n+1}\ \cdots\right] \cdot \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_i \\ f_{i+1} \\ \vdots \end{bmatrix} \quad u_i \cdot u_n = \begin{matrix} 0 & i \neq n \\ 1 & i = n \end{matrix}, \text{ and}$$

$$e_i = 0 \text{ if } u_i \cdot u_n = 0. \tag{def. 4}$$

Note that def. 4 reduces to def. 2 when there is only one effort causal bond at the 1-junction.

3. Application of switched junctions in switched-mode power converters

The concept of switched junctions explicated in Section 2 is applied for the switched-mode power converters in this section. The bondgraph models for the buck, boost, buck–boost and the full-bridge converter configuration are illustrated in Fig. 1 through 8. Figure 1 shows the buck converter configuration. The corresponding bondgraph model is shown in Fig. 2. The 0^1-junction is a switched junction. Its effort is given according to def. 3 as

$$e_{01} = u_i \cdot \left[u_1\ \ u_2\right] \cdot \begin{bmatrix} V_{in} \\ 0 \end{bmatrix} \quad u_i = u_1 \text{ during } DT \text{ and } u_i = u_2 \text{ during } (1-D)T, \tag{1}$$

where D is the duty cycle and T the switching period of the switch. Therefore, during the period DT, the 0^1-junction effort is V_{in} and is 0 during $(1-D)T$. The flow in the bonds attached to 0^1-junction is determined by the 1^2-junction. The remaining portion of the bondgraph has conventional meaning as given in Thoma,[1] and Karnopp and Rosenberg.[3]

Figure 3 shows the boost converter and the corresponding bondgraph model is shown in Fig. 4. The 0^2-junction is a switched junction. Its effort is given according to def. 3 as

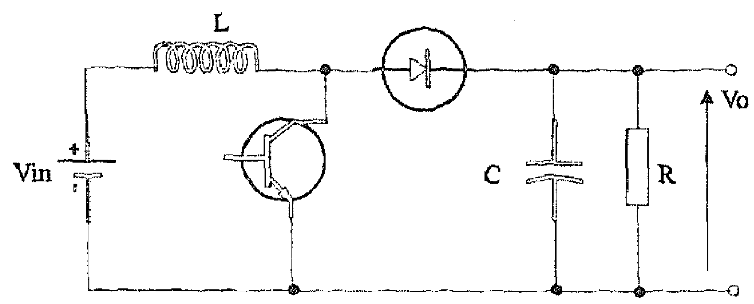


FIG. 3. Boost converter.

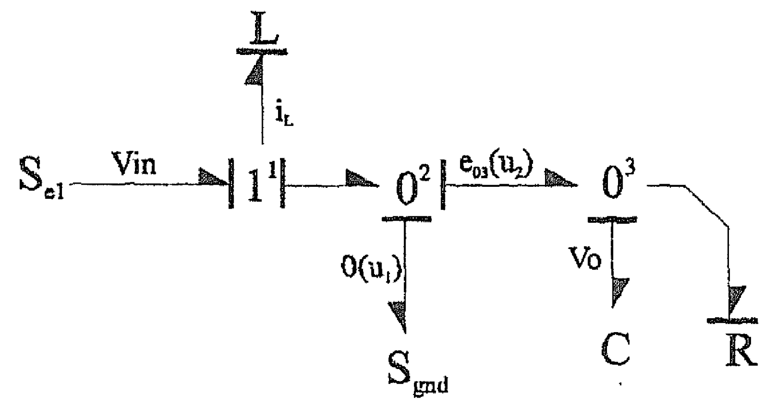


FIG. 4. Bondgraph model for boost converter.

$$e_{02} = u_i \cdot [u_1 \ u_2] \cdot \begin{bmatrix} 0 \\ V_0 \end{bmatrix} \quad u_i = u_1 \text{ during } DT \text{ and } u_i = u_2 \text{ during } (1 - D)T. \tag{2}$$

During the period DT, the 0^2-junction effort is 0 and during $(1 - D)T$, it is V_0. The flow in the bonds attached to 0^2-junction is determined by the 1^1-junction. The remaining portion of the bondgraph has conventional meaning as given in Thoma,[1] and Karnopp and Rosenberg.[3]

Figure 5 shows the buck–boost converter and the corresponding bondgraph model is shown in Fig. 6. The 0^1-junction is a switched junction. Its effort is given according to def. 3 as

$$e_{01} = u_i \cdot [u_1 \ u_2] \cdot \begin{bmatrix} V_{in} \\ -V_0 \end{bmatrix} \quad u_i = u_1 \text{ during } DT \text{ and } u_i = u_2 \text{ during } (1 - D)T. \tag{3}$$

During the period DT, the 0^1-junction effort is V_{in} and during $(1 - D)T$, it is $-V_0$. The flow in the bonds attached to 0^1-junction is determined by the inductor L. The remaining portion of the bondgraph has conventional meaning as given in Thoma,[1] and Karnopp and Rosenberg.[3]

Figure 7 shows the full-bridge converter and its corresponding bondgraph model is shown in Fig. 8. The 0^2- and 0^3-junctions are switched junctions. Their efforts are given according to def. 3 as

$$e_{02} = u_i \cdot [u_1 \ u_2] \cdot \begin{bmatrix} V_{in} \\ 0 \end{bmatrix} \quad u_i = u_1 \text{ during } DT \text{ and } u_i = u_2 \text{ during } (1-D)T. \tag{4}$$

$$e_{03} = u_i \cdot [u_1 \ u_2] \cdot \begin{bmatrix} 0 \\ V_{in} \end{bmatrix} \quad u_i = u_1 \text{ during } DT \text{ and } u_i = u_2 \text{ during } (1 - D)T. \tag{5}$$

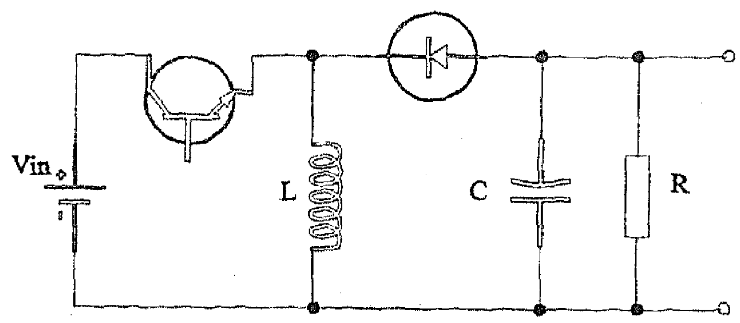


FIG. 5. Buck–boost converter.

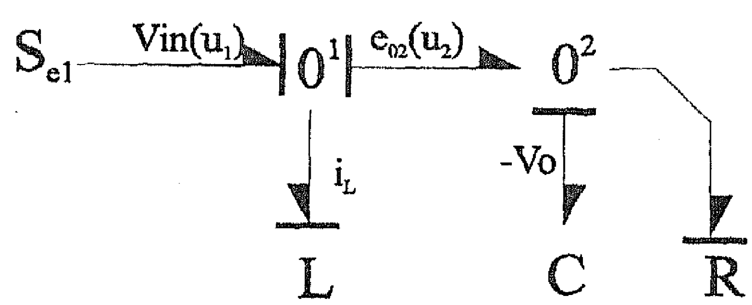


FIG. 6. Bondgraph model for buck–boost converter.

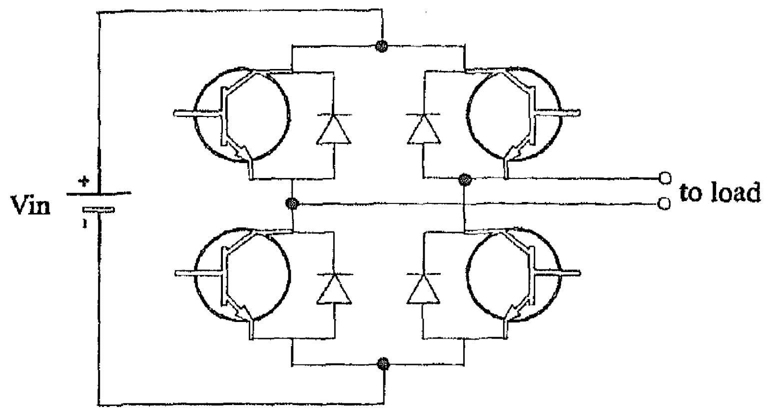


FIG. 7. Full-bridge converter.

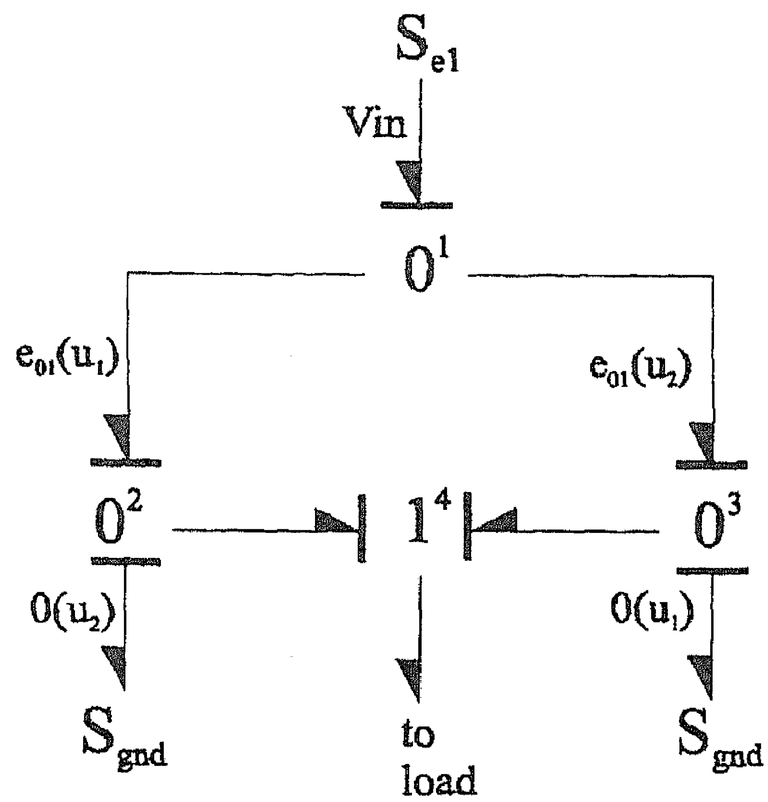
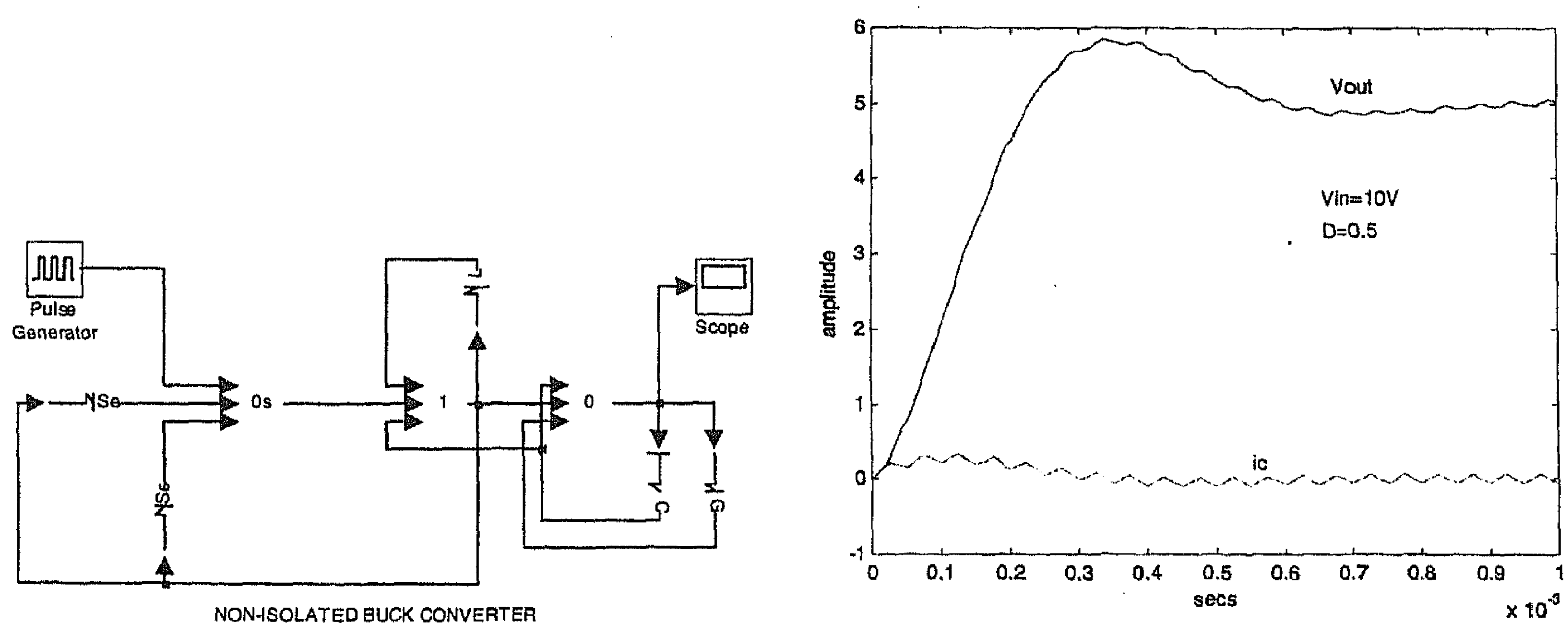


FIG. 8. Bondgraph model for full-bridge converter.

Equations (4) and (5) define the efforts at the two switched junctions. The flow in the bonds attached to switched junctions is determined by the 1^4-junction.

4. Simulation results

The circuits discussed in the previous sections have been modelled in bondgraph and simulated in the MATLAB/SIMULINK environment. A bondgraph toolbox has been developed which is used for simulation of all bondgraph-modelled systems. Figure 9(a) shows the bondgraph model of the buck converter and Fig. 9(b) the waveforms probed at the output which show the output voltage and the capacitor current. In Fig. 9(a), the 0s represents the switched junction. The input voltage applied is 10 V and a duty ratio of 50% is used. The output voltage is



(a) (b)

FIG. 9(a). Bondgraph model of buck converter and (b) simulation results of output voltage and capacitor current.

seen to settle to 5 V. Both the transient and steady-state responses are as per theoretical calculations.

5. Conclusion

Modelling switched-mode power electronic systems using bondgraph poses difficulties. This is because there is no switch element in bondgraph. To overcome this problem, either macro-models of power switches or power switches represented by modulated bondgraph elements are used. The former method leads to very stiff systems and the latter switches either the flow or effort variable losing control on the other variable. To overcome the problem of modelling switched systems, this paper proposes the concept of switched junctions. This proposal is a generalization of the existing definition of bondgraph junctions. With this extension, the bondgraph modelling capabilities are extended even to switched power electronic systems. These extended bondgraph modelling capabilities are demonstrated on a few switched power converter configurations.

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