

Bond Graph Modelling and Simulation of Buck ZCS Quasiresonant DC-DC Power Converter

Shaik Hussain Vali, Ganesh Vulasala

Abstract: Paper Zero current switching (ZCS) is one of the two resonant topologies in which the switching takes place while the current through the switch is zero. The focus of this work is on modeling a Buck Zero current switching (ZCS) Quasiresonant DC-to-DC converter using a domain independent modeling approach which is bond graph modeling approach. Development of the large signal model, steady state model and small signal AC bond graph models of the converter will be presented. Further the models are simulated in MATLAB/SIMULINK and the obtained results are verified with the results obtained by direct simulation of the converter in PSIM.

Keywords : Bond graphs, Buck Converter, modeling, Quasiresonant, Zero current switching.

I. INTRODUCTION

The customers of electrical utilities demand a high quality power in terms of supply voltage and supply frequency. The customer is demanding the power supply in various forms and various magnitudes with higher efficiencies and reduced weight. The power electronic design engineer is forced to go for various options to meet the requirements of the society. Several types of converters are emerged [1]. Before the invention of power semiconductor devices, the engineers had no option other than linear regulator which are having poor efficiency. Later on, Pulse width modulated (PWM) converters are designed [2]. The efficiency of the converters is very good while operating in either ON state or OFF state. But during the change of the state of the switches, the converters are having poor efficiency. Apart from the lower efficiency, the PWM converters are having drawbacks in terms of harmonic distortion, switching stress and electromagnetic interference (EMI) problems. The chief reason for these problems is the shapes of voltage profile and current profiles during change of states of the converter which are rectangular in nature. To make the profiles smooth, additional resonant components are added to the switches. This is basic step in quasiresonant DC-DC converters. They work either in zero voltage switching (ZVS) conditions or zero current switching (ZCS) conditions [3]-[4] depends on the topology.

Modeling of any physical system is necessary in order to design accurately. There are several modeling methods for power electronic converters. Modeling of power electronic systems using bond graphs [5]-[7] is a novel idea, because

bond graph approach has the advantage of multi domain applications. The quasiresonant DC-DC converters (both isolated and non-isolated) are having different domains in it such as electrical domain, magnetic domain with reactive and filter components and thermal domain with cooling arrangements. Therefore, the bond graph approach has the scope to model quasiresonant DC-DC converters.

II. INTROCUION TO BOND GRAPH

Unlike the past generations, the engineer of this generation has to deal with variety and complex systems. The complex systems are multi domain systems. There is a need for unification of the different systems with a single concept. The bond graph representation [5]-[7] is a tool to unify. Bond graphs represent the interconnection of different elements of system with lines. These lines are called as bonds. These lines have directions and names. Every line is associated with an effort and a flow. The product of effort and flow gives the power. The power or the energy is the common variable for all types of domains. Even though the effort and flow are different for different domains, power is common variable to all systems. In case of magnetic domain, magneto motive force and magnetic flux are the effort and flow of magnetic domains. When the magnetic domain need to integrate with electric domain, power is common for both domains irrespective of the corresponding efforts and flows. Causality is important while assigning the directions. The bond graphs should maintain the causality. After the completion of bond graphs, state equations are derived using the basic working principles of the domains. The number of state variables is equal to the number of energy elements present in the system. An appendix is provided at the end of paper [5]-[7].

The power electronic converters, multiple domains are present. Bond graph modeling is suitable to apply [8]-[10]. The concept of switched power junctions (SPJ) [11] is used to model power converters because the state of the converter alters with the change in switch positions. For power electronic converters, three models are to be developed which are large signal model, steady state bond graph model and small signal AC models. The bond graph technique unifies all the three models [12]. Quasiresonant DC-DC converters are one of the types of power electronic converters which mainly works on the principle of resonance. The bond graph technique is suitable to apply on quasiresonant DC-DC converters.

Revised Manuscript Received on October 05, 2019.

Shaik Hussain Vali, Research Scholar, Department of Electrical Engineering, Jawaharlal Nehru Technological University, Anantpur, India. Email: hussainvali4@gmail.com

Ganesh Vulasala, EEE department, JNTUA College of Engineering, Pulivendula, India. Email: ganivg@gmail.com

III. MODELING OF CONVERTER

The circuit of the Buck ZCS quasiresonant DC-DC converter [13] is given in Fig.1

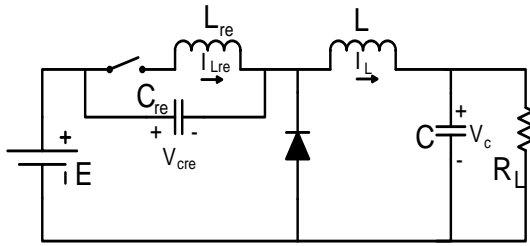


Fig 1. Buck ZCS Quasiresonant DC-DC Converter

The bond graph models [12] for the converter shown in fig. 1. are developed individually by taking all the possible switching positions of the switch and diode. There are four possible switch positions which are turning ON of both switch and diode, turning OFF of both switch and diode and only one of the switch or diode is ON where as the other is OFF. The bond graphs for all these possibilities are drawn and shown in figures from 2(a)- 2(d).

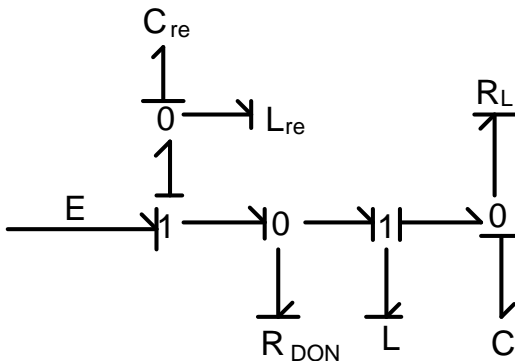


Fig. 2(a). Bond graph model of Buck ZCS Quasiresonant DC-DC converter (ON switch & ON Diode)

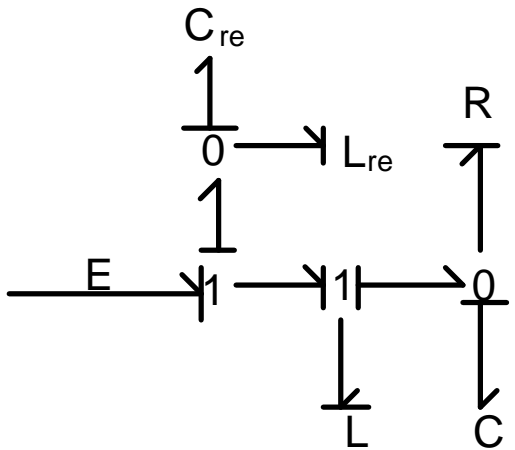


Fig. 2(b). Bond graph model of Buck ZCS Quasiresonant DC-DC converter (ON switch & OFF Diode)

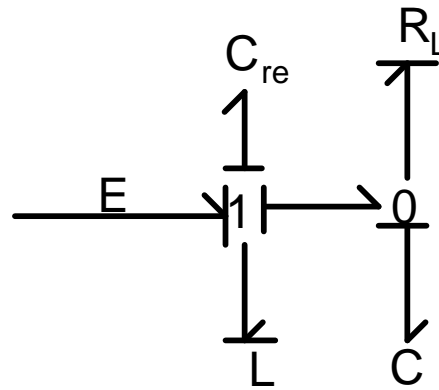


Fig. 2(c). Bond graph model of Buck ZCS Quasiresonant DC-DC converter (OFF switch & OFF Diode)

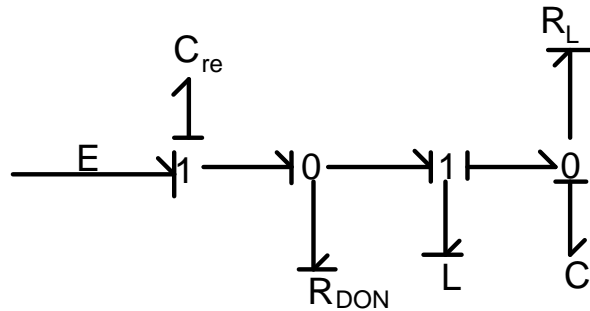


Fig. 2(d). Bond graph model of Buck ZCS Quasiresonant DC-DC converter (OFF switch & ON Diode)

After drawing the graphs individually, they are combined into a large signal bond graph model of the converter, which is shown in Fig. 2(e).

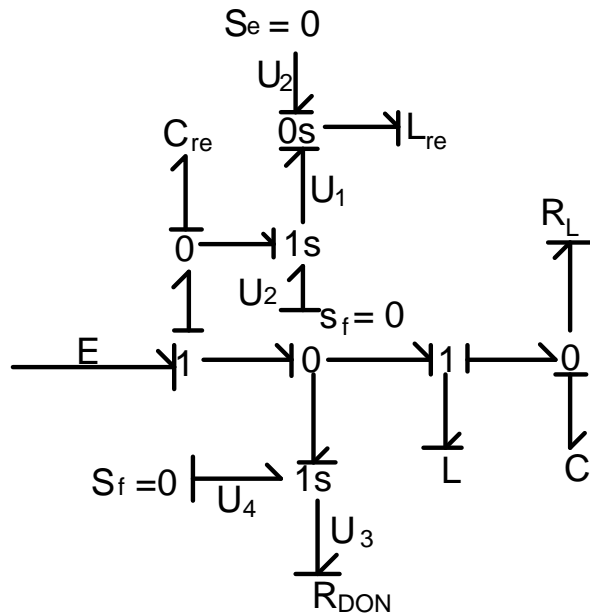


Fig. 2(e). Large signal Bond graph model of Buck ZCS Quasiresonant DC-DC converter

With the help of large signal model developed, the steady state model and small signal ac bond graph models for the converter are developed and drawn by following the reduction steps [12] and are shown in Fig. 2(f) and 2(g) respectively.

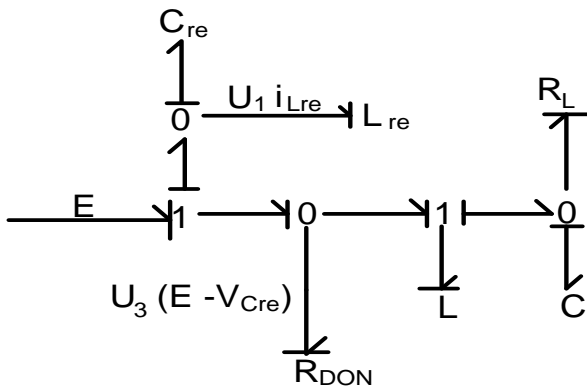


Fig. 2(f). Steady state Bond graph model of Buck ZCS Quasiresonant DC-DC converter

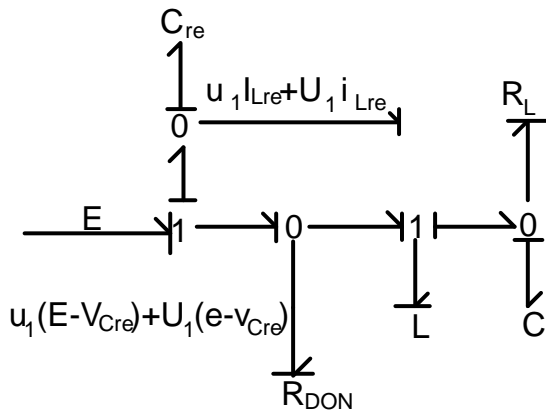


Fig. 2(g). Small-signal AC Bond graph model of Buck ZCS Quasiresonant DC-DC converter

There is important to note a situation when the diode goes into ON state. The supply voltage 'E' and the resonant capacitor will come in parallel connection when the diode goes to ON state. In this situation, the bond graph cannot have causality. To maintain the exact causality, a small resistor R_{DON} is used on behalf of ON state diode. This R_{DON} is drawn in Fig. 2(a) and 2(d). After completing the graphs, the state equations can be derived with the help of Kirchoff's laws and Ohm's law. The state variables are the integral causal variables of inductors and capacitors which are i_L , i_{Lre} , v_C and v_{Cre} . The state equations for the steady state model as in Fig. 2(f) are derived and shown from (1) to (4).

$$v_{Lre} = U_1 v_{Cre} \quad (1)$$

$$v_L = -v_0 + U_4 (E - v_{Cre}) \quad (2)$$

$$i_{Cre} = i_L + U_3 \left(\frac{E - v_{Cre}}{R_{don}} \right) - U_1 i_{Lre} \quad (3)$$

$$i_C = i_L - \frac{v_0}{R_L} \quad (4)$$

IV. SIMULATED WAVEFORMS

Consider the values, $E = 28$ V, $L = 560$ μ H, $C = 0.01116$ μ F, $R = 11.2$ Ω , $f_s = 1$ MHz, $D = 0.5$, $L_{re} = 1.59$ μ H and $C_{re} = 4$ nF. The simulation results in MATLAB/SIMULINK using the toolbox [14] are represented in Fig. 3(a) to 3(f).

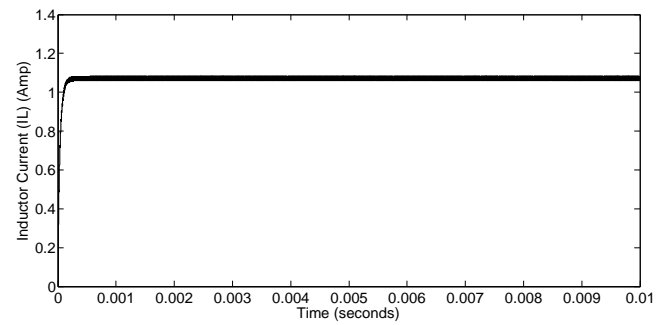


Fig. 3(a) Inductor Current (I_L) – Buck ZCS Quasiresonant DC-DC Converter

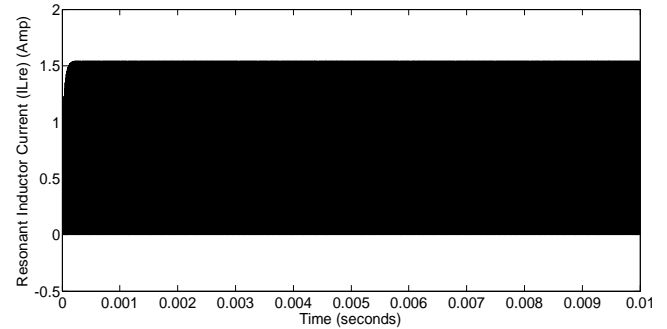


Fig. 3(b) Resonant Inductor Current (I_{Lre}) – Buck ZCS Quasiresonant DC-DC Converter

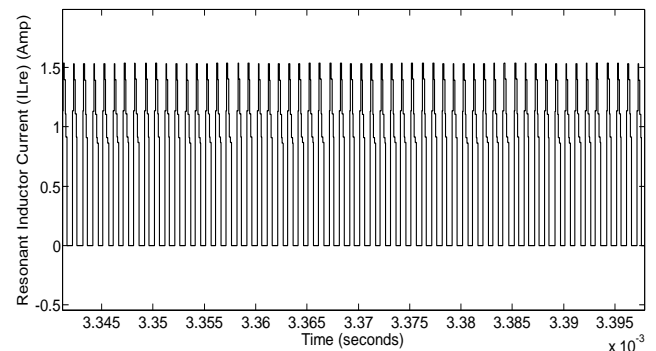


Fig. 3(c) Resonant Inductor Current (I_{Lre}) – Buck ZCS Quasiresonant DC-DC Converter

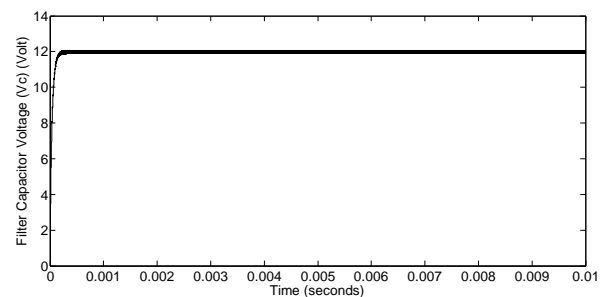


Fig. 3(d) Filter Capacitor Voltage (V_c) – Buck ZCS Quasiresonant DC-DC Converter

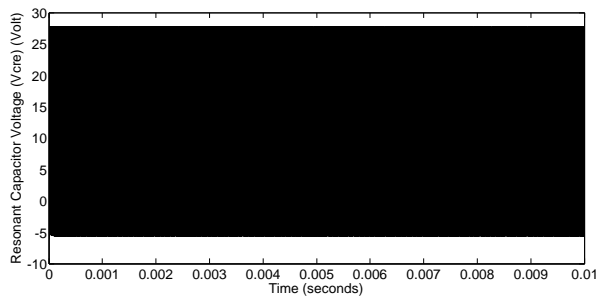


Fig. 3(e) Resonant Capacitor Voltage (Vcre) – Buck ZCS Quasiresonant DC-DC Converter

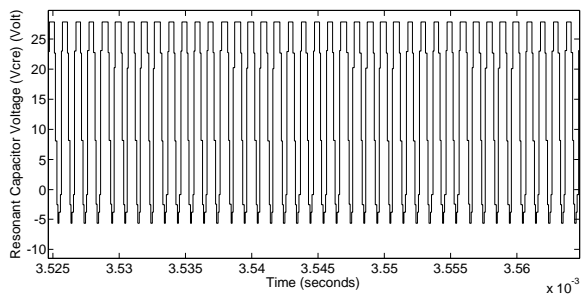


Fig. 3(f) Resonant Capacitor Voltage (Vcre) – Buck ZCS Quasiresonant DC-DC Converter

The simulation results for the same values in PSIM software are shown in Fig. 4(a) to 4(f).

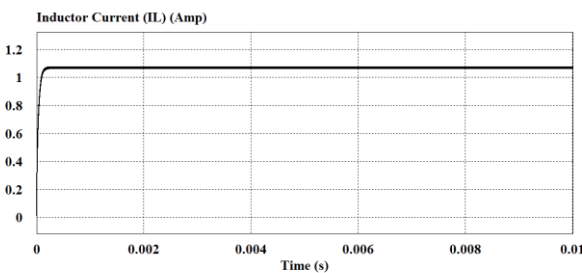


Fig. 4(a) Inductor Current (IL) – Buck ZCS Quasiresonant DC-DC Converter

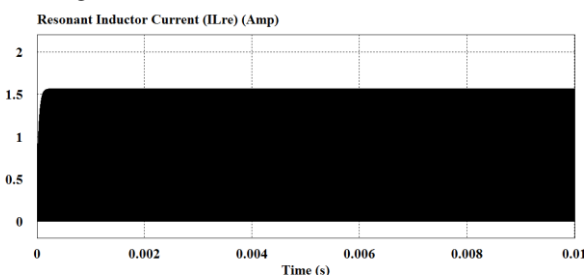


Fig. 4(b) Resonant Inductor Current (ILre) – Buck ZCS Quasiresonant DC-DC Converter

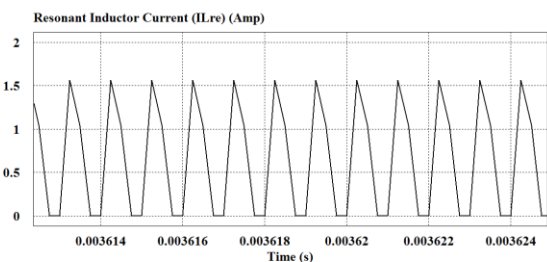


Fig. 4(c) Resonant Inductor Current (ILre) – Buck ZCS Quasiresonant DC-DC Converter

Quasiresonant DC-DC Converter

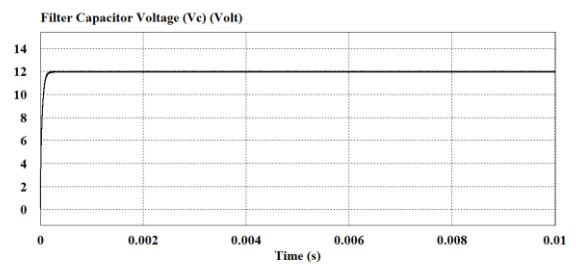


Fig. 4(d) Filter Capacitor Voltage (Vc) – Buck ZCS Quasiresonant DC-DC Converter

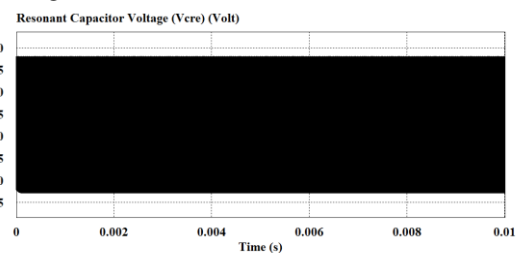


Fig. 4(e) Resonant Capacitor Voltage (Vcre) – Buck ZCS Quasiresonant DC-DC Converter

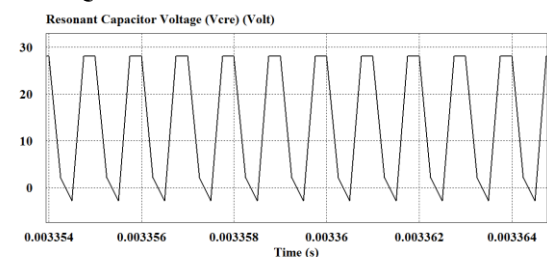


Fig. 4(f) Resonant Capacitor Voltage (Vcre) – Buck ZCS Quasiresonant DC-DC Converter

V. TABULATION OF RESULTS

The results got both in MATLAB/SIMULINK and PSIM for buck ZCS Quasiresonant DC-DC converter is shown in Table 1. The modeling results are approximately same as that of the results in PSIM.

Table I. Simulated Results – Buck ZCS Quasiresonant DC-DC Converter

S.No.	Variable	MATLAB/SIMULINK	PSIM
1	Steady Value of Inductor Current (IL) (Amp)	1.05	1.05
2	Peak Value of Resonant Inductor Current (ILre) (Amp)	1.5	1.55
3	Steady value of filter capacitor voltage (Vc) (Volt)	12	12
4	Peak Value of Resonant Capacitor Voltage (Vcre) (Volt)	33	31

VI. CONCLUSION

Using the technique of bond graph modeling, Buck ZCS Quasiresonant DC-DC converter is modeled. From large signal bond graph model of the converter, the steadystate bond graph and the small signal AC bond graph models of the Buck ZCS Quasiresonant converter are developed. The models are simulated in MATLAB/SIMULINK. The results obtained in SIMULINK are verified with the results obtained in PSIM software. Therefore, the developed model can be used to integrate with the application model of the converter without difficulty. It can be used in other domain applications also.

APPENDIX

Bond graphs and equations for the graph junctions:

0-junction:

Fig. 5 below shows a 0-junction. It has four bonds. The efforts of all bonds are same. That effort is decided by the effort of one bond, which is called effort decider. In this bond graph, bond 1 is the effort decider. So, the efforts of the remaining bonds 2-4 are same as the effort of effort decider bond. Whereas the flow at bond 1 is decided by the flows at remaining bonds. Assume e_1, e_2, e_3 and e_4 are the efforts of bonds 1-4 respectively. Assume f_1, f_2, f_3 and f_4 are the flows of bonds 1-4 respectively. In equation form

$$e_2 = e_1$$

$$e_1 = e_3$$

$$e_1 = e_4$$

$$f_1 - f_2 = f_3 + f_4$$

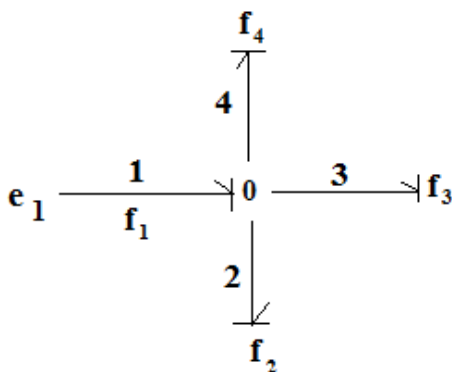


Fig.5. 0-junction

1-junction:

Fig. 6 below shows a 1-junction. It has four bonds. The flows of all bonds are same. That flow is decided by the flow of one bond, which is called flow decider. In this bond graph, bond 1 is the flow decider. So, the flows of the remaining bonds 2-4 are same as the flow of flow decider bond. Whereas the effort at bond 1 is decided by the efforts at remaining bonds. In

equation form

$$f_2 = f_1$$

$$f_3 = f_1$$

$$f_4 = f_1$$

$$e_1 = e_2 + e_3 + e_4$$

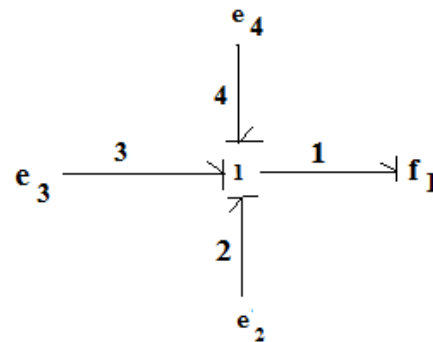


Fig.6. 1-junction

Switched Power Junctions:

Conventionally the bond graphs have two junctions. They are 0-junction and 1-junction. The bonds connected to 0-junction all have same value of efforts. The bonds connected to 1-junction all have same value of flows. In dynamic systems where there is a possibility for sudden change in the state of the system, the efforts of 0-junctions and the flows of 1-junction are not constant. Their values depend on the system state. The values are switched from one to other. In this situation it is required to have other types of junctions. They are called switched power junctions. They are named 0s-junction and 1s-junction.

0s-junction:

Fig. 7 represents a 0s-junction. It has four bonds connected. Out of four, two bonds have the causal bars near junction. These two are effort deciders one at a time. Here, bonds 1 and 2 are effort deciders during U_1 and U_2 durations respectively. So, the efforts of the bonds 3 and 4 are decided by either the effort at bond 1 or the effort at bond 2. The flow of either bond 1 or bond 2 is equal to the algebraic sum of the flows at bonds 3 and 4 depends on the switched state U_1 or U_2 . The equations are

$$e_3 = U_1 e_1 + U_2 e_2$$

$$e_4 = U_1 e_1 + U_2 e_2$$

$$f_1 = U_1 (f_3 + f_4)$$

$$f_2 = U_2 (f_3 + f_4)$$

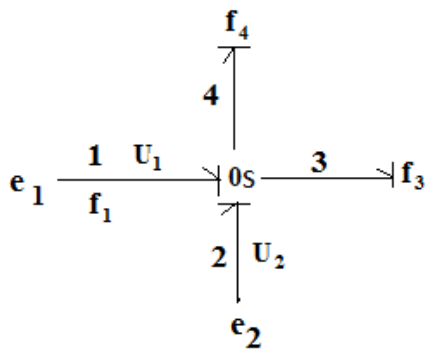


Fig.7. 0s-junction

1s-junction:

Fig. 8 represents a 1s-junction. It has four bonds connected. Out of four, two bonds have the causal bars away from junction. These two are flow deciders one at a time. Here, bonds 1 and 2 are flow deciders during U_1 and U_2 durations respectively. So, the flows of the bonds 3 and 4 are decided by either the flow at bond 1 or the flow at bond 2. The effort of either bond 1 or bond 2 is equal to the algebraic sum of the efforts at bonds 3 and 4 depends on the switched state U_1 or U_2 . The equations are

$$\begin{aligned} f_3 &= U_1 f_1 + U_2 f_2 \\ f_4 &= U_1 f_1 + U_2 f_2 \\ e_1 &= U_1 (e_3 + e_4) \\ e_2 &= U_2 (e_3 + e_4) \end{aligned}$$

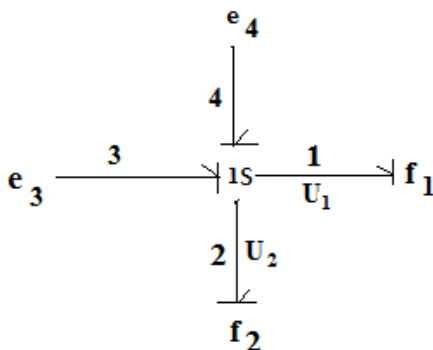


Fig.8. 1s-junction

REFERENCES

1. R. Severns, Modern DC-to-DC switchmode Power Converter Circuits: Van Nostrand Reinhold Electrical/Computer Science and Engineering Series, April 2014.
2. Marian K. Kazimeirczuk, PulseWidth Modulated DC-DC Power Converters, 2nd Edition, John Wiley & Sons, 2016.
3. KH.Liu, Ramesh Oruganti, and Fred CY Lee, "Quasiresonant converters: Topologies and characteristics," IEEE Transactions on Power Electronics, vol. PE-2, no. 1, pp. 62-71, Jan.1987.
4. G.Hua and F.C.Lee, "Softswitching techniques in PWM converters," IEEE Transactions on Industrial Electronics, Vol. 42, Issue: 6, pp. 595-603, Dec 1995.
5. Dean C. Karnopp, Donald L. Margolis and Ronald C. Rosenberg, System Dynamics: A Unified Approach, 2nd Edition, John Wiley & Sons, 1990.
6. A. Mukherji and R. Karmakar, Modeling and Simulation of Engineering Systems through BondGraphs, Alpha Science International Ltd, August 2000
7. W.Boretzky, G.D.Tanguy and J.U.Thoma, "Advances in bondgraph modeling-theory, software, applications," Journal of Mathematics and Computer in Simulation, volume.39, No: 5-6, pp. 465-475, Nov 1995.

8. R.Andouisi, A.Mami, G.D.Tanguy, M.Anabi, Bondgraph "Modeling and Dynamic Study of a Photovoltaic System Using MPPT Buck-Boost Converter," IEEE International Conference on Systems, Man and Cybernetics, vol. 3., page: 6, Oct. 2002.
9. Marisol Delgado and Hebert Sira-Remiraz, "A bondgraph approach to the modeling and simulation of regulated dc-to-dc power supplies," Simulation Practice and Theory, Vol. 6, Issue:7, pp. 631-646, Nov 1998.
10. Allerd.B., Hilale H., Lin.C.C. and Morell. H, "Power Converter average model computasion using the bondgraph and PetriNet Techniques," Proceedings of PESC '95 - Power Electronics Specialist Conference, pp. 830-836, 18-22 June1995.
11. A.C.Umarikar and L.Umanand, "Modeling of switching systems in bondgraphs using the concept of switched power junctions," Journal of the Frankline Institute, volume 342, Issue:2, pp.131-147, March 2005.
12. A.C.Umarikar and L.Umanand, "Modeling of switched_mode power converters using bondgraphs," IEE Proceedings - Electric Power Applications, volume 152, Issue.1, pp. 51-60, Jan 2005.
13. M.K. Kazimierczuk, "Steadystate analysis and design of a buck zero-current-switching resonant DC-to-DC converter," IEEE Transactions on Power Electronics, vol. 3, no. 3,pp. 286-296, Jul 1988.
14. A.C.Umarikar, T.Mishra and L.Umanand, "Bondgraph Simulation and Symbolic Extration tool box in MATLAB/SIMULINK," J. Indian Inst. Science (IISc), Vol. 86, No. 1, pp. 45-68, January-February 2006.

AUTHORS PROFILE



Shaik Hussain Vali, Research scholar in department of Electrical Engineering, Jawaharlal Nehru Technological University Anantapur, India. He completed his B.Tech in Electrical and Electronics Engineering and M.Tech in Machine drives and Power Electronics from JNTU Hyderabad, India and IIT Kharagpur, India respectively. His research interests include switched mode power supply design and renewable energy applications.



Ganesh Vulasala, Professor in department of Electrical and Electronics Engineering, Jawaharlal Nehru Technological University Anantapur College of Engineering, Pulivendula, India. He completed his B.Tech in Electrical and Electronics Engineering, M.Tech in Electrical Power systems and PhD in Electrical and Electronics Engineering from JNTU Hyderabad, SVU Tirupati and JNTU Anantapur respectively all from India. His research interests include Smart grid technologies and renewable energy applications.