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Bond Graph Modelling and Simulation of Boost ZVS Quasiresonant DC-DC Power Converter

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Abstract: *Here, a Boost Zero voltage switching (ZVS) Quasiresonant DC-DC power converter is modeled using bond graph modeling technique. The three important models of the converter which are large signal model, steady-state model and small signal AC bond graph models of the Boost ZVS Quasiresonant converter will be offered. The bond graph model is to be simulated in MATLAB/SIMULINK and the simulated waveforms are compared with that of PSIM simulated waveforms.*

Keywords: *Bond graphs, boost converter, Modelling, Quasiresonant, Zero voltage switching*

I. INTRODUCTION

The modern day power supply systems are demanding the following qualities from the designer which are superior quality, higher efficiency, hardware smallness and Quality, efficiency, compactness, reliability and higher values of power density [1]. In bygone days, linear voltage regulators were being used. But they have some disadvantages such as power dissipation in the form of heat and massive system. Later days, Pulse width modulated (PWM) converters [2] are developed. They are mainly used in small and medium quantities of power applications. The main advantages of these systems are increased efficiency due to reduced conduction and blocking losses. The reactive components such as filter inductor, filter capacitor and the transformer elements also benefit to the efficiency factor. But these converters are facing certain problems such as suffering power loss during switching transients; switching stresses while switching, electromagnetic interference problems (EMI) and harmonics due to the non sinusoidal switching voltages and currents. Most of these problems can be solved with the help of quasiresonant DC-DC converters. An LC resonant circuit is added to the switches of PWM converters which results in quasiresonant DC-DC converters. The classification of these converters depends on whether voltage or current is going to be zero while switching and are the ZVS-(zerovoltage switching) or ZCS –(zerocurrent switching) [3-4].

The fundamental step in the practical design of any system is its modeling. Using a suitable modeling technique, the system is modeled and later it is simulated. There are several modeling methods which are suitable for some physical systems. Bond graph modeling technique [5-7] is the most suitable for multi-domain systems. It was majorly used to model non-electrical systems. The main reason to choose bond graph technique to model the quasiresonant converter is the presence of magnetic domain (reactive components), thermal domain (heat sink design) apart from the electrical domain in this converter.

II. BOND GRAPH MODELLING TECHNIQUE

The vital part of bond graph modeling technique is drawing the suitable bond graph for the physical system chosen [5-7]. Bond graphs are composed of half arrowed lines with suitable labels and suitable signs called bonds. The signs give the flow directions of power or energy of the bonds. Irrespective of the system type (electrical, mechanical, thermal … etc), the bond graphs remain same if the working is analogous to various systems. The bond graphs do not depend on system type. It only depends on the relationship between excitation and response. With this advantage, the complex multi-domain systems are developed into a simple bond graph. Maintaining the causality is the final step in completing the graph. After drawing complete graph, using the laws pertaining to excitation and response junctions the state equations can be obtained. Depending on the order of the system, the equal number of state variables and in turn state equations are determined. An appendix in this matter is provided at the end [5-7].

Power supplies in general and quasiresonant converters in specific are multi domain systems (with the involvement of reactive components and cooling arrangements) are suitable for the exploration of bond graph technique. These techniques were successfully applied to switched mode power converters (SMPCs) [8-10]. In SMPCs, the circuit alters with change in switch positions alternatively. Switched power junctions (SPJ) [11] are used to model this switch position alteration. After drawing an appropriate bond graph, the state equations can be derived using Kirchoff's law. After developing the large signal model of the converter, the remaining two models are developed using the steps [12]. Similar procedure is followed in developing the model for quasiresonant converters.

III. CONVERTER MODELLING

The circuit diagram for the Boost ZVS quasiresonant DC-DC converter [13] is shown in Fig.
1.

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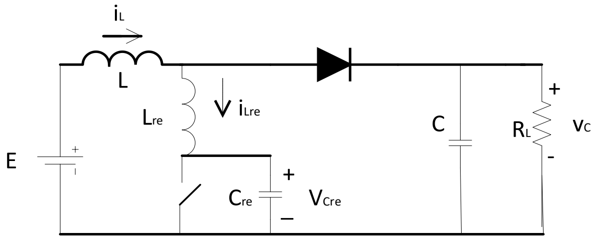

Fig. 1. Boost ZVS Quasiresonant DC-DC Converter

The bond graph models using steps [12] for the converter in the four modes of operations of the converter: when both the switch and diode are ON, when both the switch and diode are OFF and when any one of the switch and diode are On and the other is OFF are developed and are shown in Fig. 2(a) - 2(d).

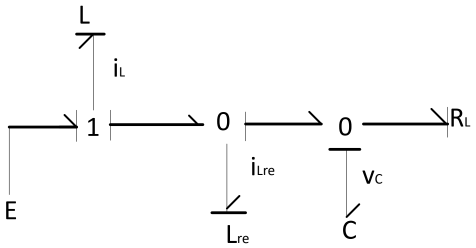

Fig. 2(a). Bond graph model of Boost ZVS Quasiresonant DC-DC converter (ON switch & ON Diode)

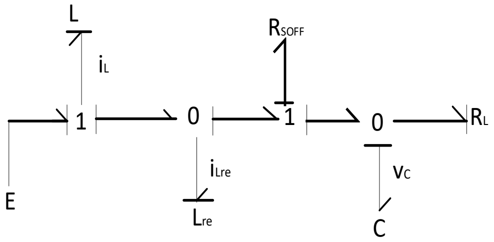

Fig. 2(b). Bond graph model of Boost ZVS Quasiresonant DC-DC converter (ON switch & OFF Diode)

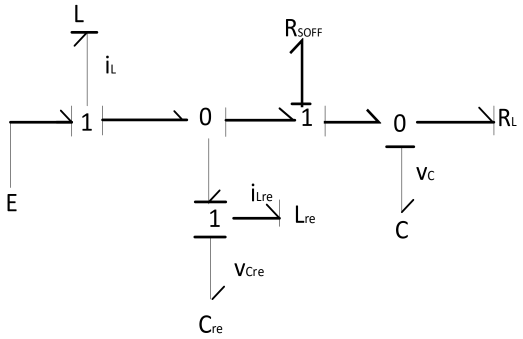

Fig. 2(c). Bond graph model of Boost ZVS Quasiresonant DC-DC converter (OFF switch & OFF Diode)

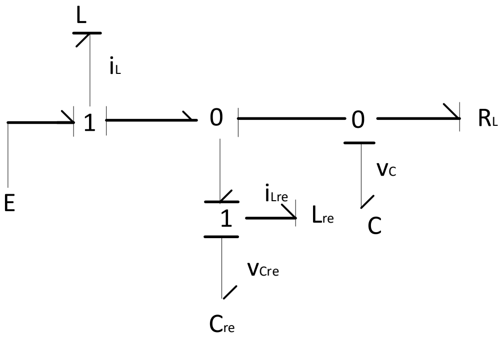

Figure 2(d). Bond graph model of Boost ZVS Quasiresonant DC-DC converter (OFF switch & ON Diode)

The entire large signal model of the converter is derived after combining all the modes and is shown in Fig. 2(e).

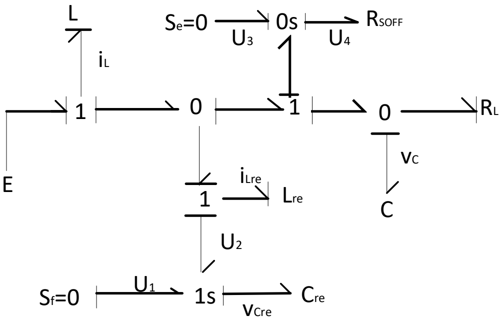

Fig. 2(e). Large signal Bond graph model of Boost ZVS Quasiresonant DC-DC converter

The large signal model is further modified into steadystate and small signal ac bond graph models by following the due steps [12]. The developed models are drawn and shown in Fig. 2(f) and 2(g).

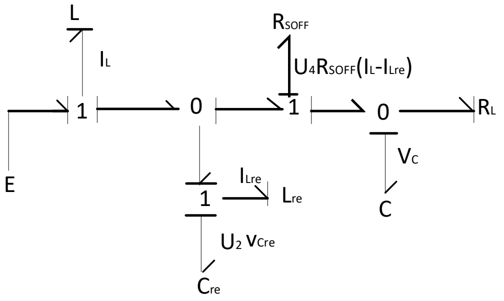

Fig. 2(f). Steady state Bond graph model of Boost ZVS Quasiresonant DC-DC converter

When the diode of the circuit is in OFF mode, the filter inductor is forced to come in series with the resonant inductor. It makes two different states equal each other which violate the basic kirchoff's current law. To overcome this problem, the OFF state of the diode is represented with a large resistance (RSOFF). With this representation, the causality of bond graph is restored. This large resistance (RSOFF) is shown in two modes of operation as in Fig. 2(b) and 2(c).

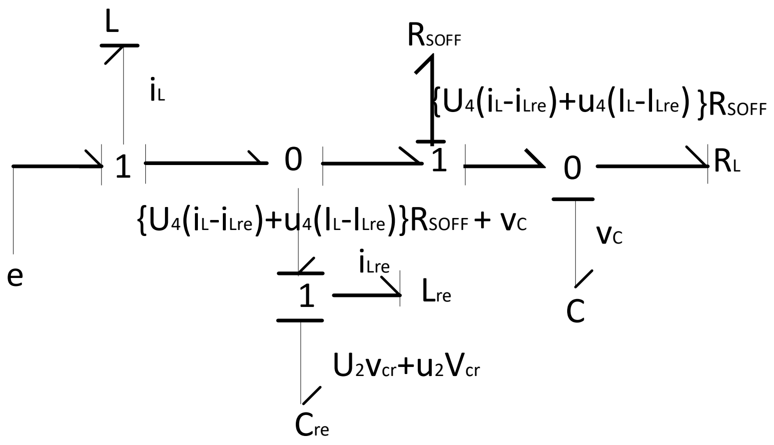

Fig. 2(g). Small-signal AC Bond graph model of Boost ZVS Quasiresonant DC-DC converter

The number of state variables is four. Out of which, two are the currents in filter inductor and resonant inductor. The remaining two are the voltages across filter capacitor and resonant capacitor. The state equations are formed by applying kirchoff's laws at the junctions of the steady state model in Fig. 2(f). The equations are represented by the (1) to (4).

$$v_{Lre} = v_0 - U_2 v_{Cre} + U_4 (i_L - i_{Lre}) R_{soff} \qquad (1)$$

$$v_L = E - v_0 - U_4 (i_L - i_{Lre}) R_{soff} \qquad (2)$$

$$i_{Cre} = U_2 i_{Lre} \qquad (3)$$

$$i_C = U_3 (i_L - i_{Lre}) - \frac{v_0}{R_L} \qquad (4)$$

IV. SIMULATION WAVEFORMS

The model developed is simulated in MATLAB/SIMULINK with the help of a toolbox [14] for the values, E = 156 V, L = 9.156 mH, C = 0.61 µF, R = 400 Ω, fs = 1 MHz, D = 0.61, Lre = 10.656 µH and Cre = 437.8 pF. The results obtained are shown in Fig. 3(a) to 3(f).

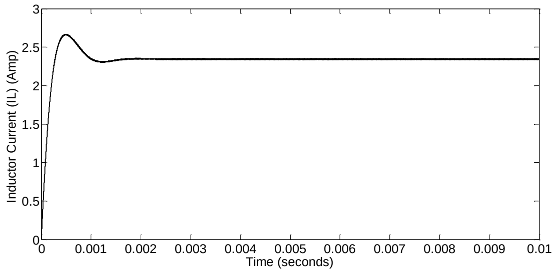

Fig. 3(a). Inductor Current (IL) – Boost ZVS Quasiresonant DC-DC Converter

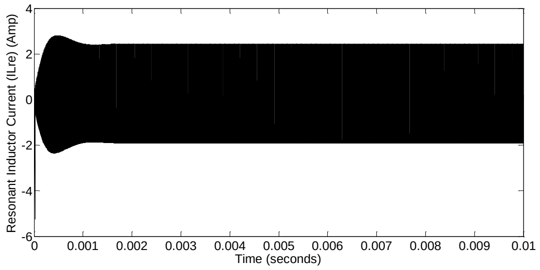

Fig. 3(b). Resonant Inductor Current (ILre) – Boost ZVS Quasiresonant DC-DC Converter

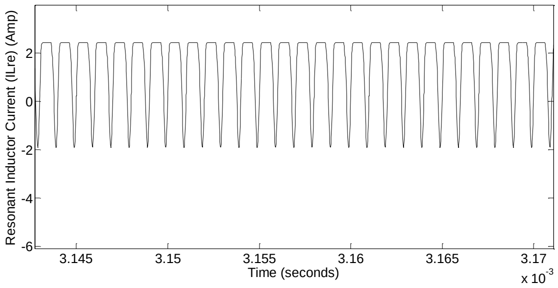

Fig. 3(c). Resonant Inductor Current (ILre) – Boost ZVS Quasiresonant DC-DC Converter

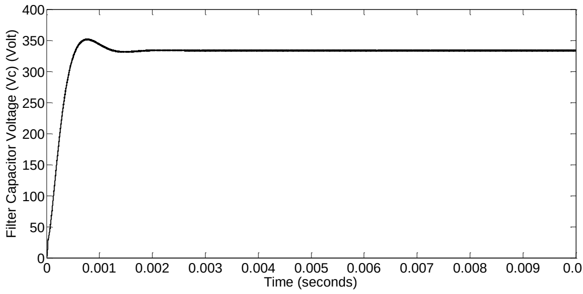

Fig. 3(d). Filter Capacitor Voltage (Vc) – Boost ZVS Quasiresonant DC-DC Converter

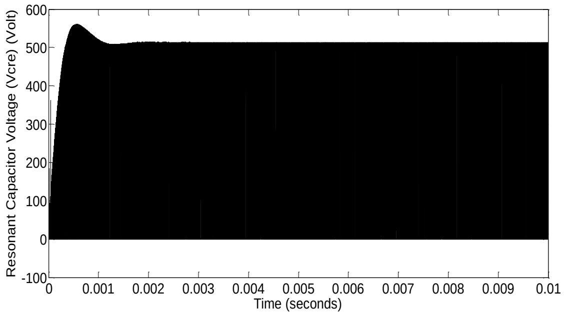

Fig. 3(e). Resonant Capacitor Voltage (Vcre) – Boost ZVS Quasiresonant DC-DC Converter

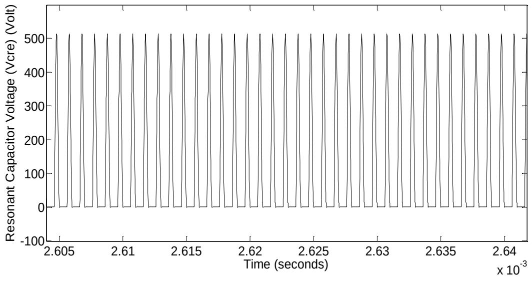

Fig. 3(f). Resonant Capacitor Voltage (Vcre) – Boost ZVS Quasiresonant DC-DC Converter

The results obtained after simulation in PSIM are shown in Fig. 4(a) to 4(f)

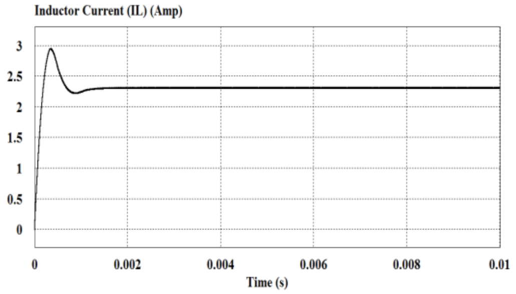

Fig. 4(a). Inductor Current (IL) – Boost ZVS Quasiresonant DC-DC Converter

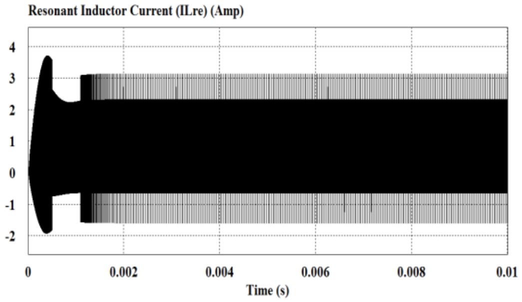

Fig. 4(b). Resonant Inductor Current (ILre) – Boost ZVS Quasiresonant DC-DC Converter

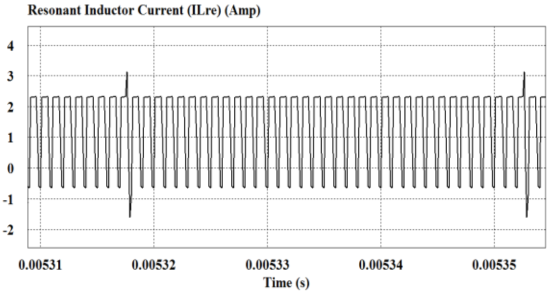

Fig. 4(c). Resonant Inductor Current (ILre) – Boost ZVS Quasiresonant DC-DC Converter

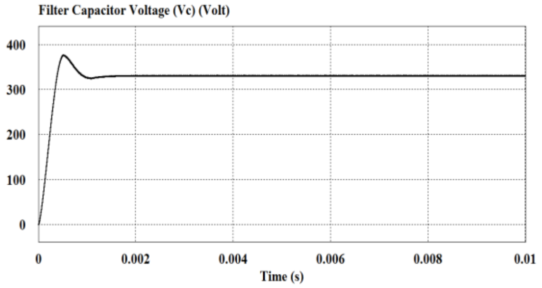

Fig. 4(d). Filter Capacitor Voltage (Vc) – Boost ZVS Quasiresonant DC-DC Converter

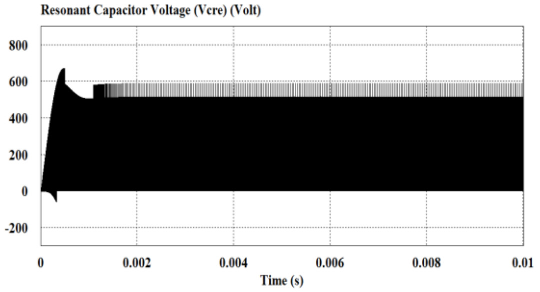

Fig. 4(e). Resonant Capacitor Voltage (Vcre) – Boost ZVS Quasiresonant DC-DC Converter

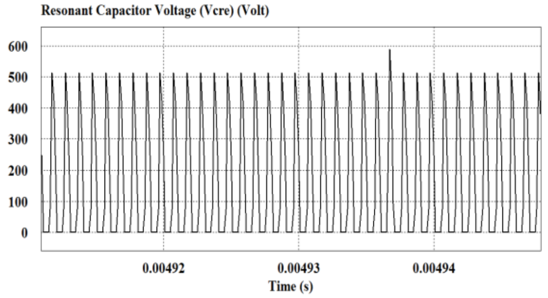

Fig. 4(f). Resonant Capacitor Voltage (Vcre) – Boost ZVS Quasiresonant DC-DC Converter

V. RESULTS TABULATION

The results are tabulated below in Table I and are compared that are resulted in MATLAB/SIMULINK and PSIM for the converter. They are found similar.

Table I. Simulated Results - Boost ZVS Quasiresonant DC-DC Converter

S.No.	Variable	MATLAB/SIMULINK	PSIM
1	Steady state Inductor Current (IL) (Amp)	2.3	2.3
2	Peak Resonant Inductor Current (ILre) (Amp)	3.6	3.3
3	Steady state filter capacitor voltage (Vc) (Volt)	330	325
4	Peak Resonant Capacitor Voltage (Vcre) (Volt)	510	505

VI. CONCLUSION

All the three bond graph models of boost ZVS Quasiresonant DC-DC converter which are steadystate model, large signal and small signal AC models are developed successfully. Using MATLAB/SIMULINK, the simulated results are obtained. The converter is simulated in PSIM directly. The results obtained in PSIM are successfully verified the bond graph model results. So, the developed model can be integrated to either the same domain or different domain application of boost ZVS quasiresonant DC-DC converter. Because the bond graph models are independent of domain.

APPENDIX

Bond graphs and equations for the 1-junction & 0-junction:

0-junction:

Fig. 5 represents a 0-junction. One bond at the 0-junction, decides the effort. It is called effort decider bond. Remaining all bonds has the same effort. Here in the bond graph, bond 1 is the effort decider bond. So, the effort at remaining bonds 2-4 is same as that at bond 1. The flow at the bond 1 is determined by knowing the flows at the remaining bonds 2-4. In equation form

$$e_2 = e_1$$

$$e_1 = e_3$$

$$e_1 = e_4$$

$$f_1 - f_2 = f_3 + f_4$$

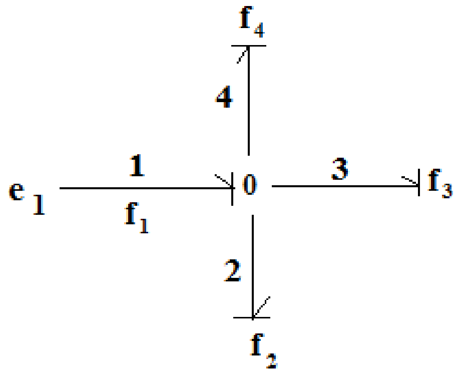

Fig.5. 0-junction

Here 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

1-junction:

Fig. 6 shows a 1-junction. At the 1-junction, the flow is determined by only one bond. It is called flow decider bond. Remaining all bonds has the same flow. Here in the bond graph, bond 1 is the flow decider bond. So, the flow at remaining bonds 2-4 is same as that at bond 1. The effort at the bond 1 is determined by knowing the efforts at the remaining bonds 2-4. In equation form

$$f_2 = f_1$$

$$f_3 = f_1$$

$$f_4 = f_1$$

$$e_1 = e_2 + e_3 + e_4$$

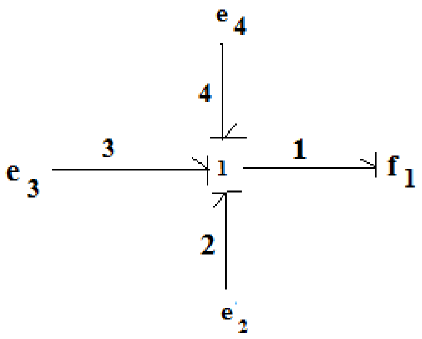

Fig.6. 1-junction

Switched Power Junctions:

In general, bond graphs are associated with two junctions namely 0-junction and 1-junction. The efforts of the bonds of 0-junction are decided by effort decider. The flows of the bonds of 1-junction are decided by flow decider. In power electronic systems where there is a continuous change in the states of the switches and diodes, the effort decider and the flow decider are not same for all states. To model this type of switches and diodes, switched power junctions are used. There are two types: 0s-junction and 1s-junction.

0s-junction:

Fig. 7 shows a 0s-junction. It is associated with four bonds. Out of four bonds, two have the causal bars near junction. They are the effort deciders. 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 determined 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

$$e_3 = U_1 e_1 + U_2 e_2$$

$$e_4 = U_1 e_1 + U_2 e_2$$
$$f_1 = U_1 (f_3 + f_4)$$
$$f_2 = U_2 (f_3 + f_4)$$

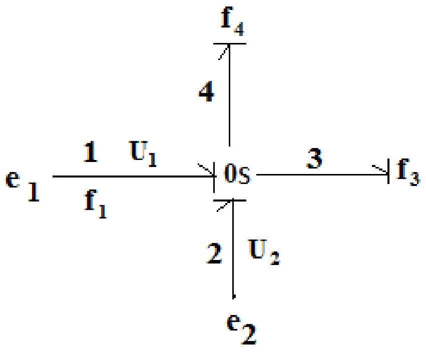

Fig.7. 0s-junction

1s-junction:

Fig. 8 shows a 0s-junction. It is associated with four bonds. Out of four bonds, two have the causal bars away from junction. They are the flow deciders. 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

$$f_3 = U_1 f_1 + U_2 f_2$$
$$f_4 = U_1 f_1 + U_2 f_2$$
$$e_1 = U_1 (e_3 + e_4)$$
$$e_2 = U_2 (e_3 + e_4)$$

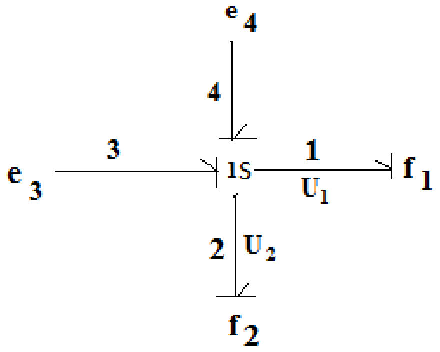

Fig.8. 1s-junction

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