A bidirectional DC-DC converter for renewable energy systems

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Abstract. To improve the energy quality, most of the renewable energy systems include an energy storage element charged by the bidirectional DC-DC converter. This paper proposes the bidirectional DC-DC converter which employs the two bridge configuration resonant class-E converters on the both sides of the isolating transformer. The low side converter is controlled as step up and the high side converter is controlled as step down. The proposed system is characterized by good dynamic properties and high efficiency because the converter transistors are switched in ZVS conditions. A theoretical analysis to provide relations for system design, and the laboratory model investigations to validate the system characteristic are given in the paper.

Key words: bidirectional, isolated, energy storage system, DC-DC converter.

1. Introduction

The essential part of the renewable energy system is a storage element [1–6]. The storage element gathers the energy fluctuations and enables to improve the system dynamic properties. A chemical battery or a super capacitor, used as a typical energy storage element, are characterized by the low nominal DC voltage value. To charge and discharge the storage element, the bidirectional DC-DC converter is used. The DC-DC converter often ensures an electrical isolation between low voltage and high voltage parts of the system, and then the transformer is used. In order to feed the transformer a DC power must be converted into AC power and next rectified to DC power. To minimize the transformer size, weight and cost, the frequency of the AC power should be as high as possible. The frequency increase is limited by the transistor conduction and switching losses. It should be noticed that the main source of the power dissipation is the low voltage side converter because it conducts a high current. So, the main effort of the research is directed to the low voltage converter efficiency. The first proposal of the bidirectional DC-DC converter system was a DAB (dual active bridge) converter [7]. The DAB converter consists of the two voltage-fed inverters at each side of the transformer. The energy flow value and direction were controlled by the phase-shifting angle of the both inverters. The main drawback of the DAB converter is that it does not accept a high difference between voltages of low and high sides of transformer, because then the current stress and losses caused by the circulating current become to high. Additionally this system does not ensure ZVS conditions of the transistors switching process in a wide range of the voltages variations. Other solution of the bidirectional DC-DC converter system [8] consists of a current-fed (boost) inverter at a low voltage side and a voltage-fed (buck) inverter at a high voltage side. The drawback of this system is the high voltage spikes provoked by the transformer leakage inductance when the boost converter is switched. The trans-former leakage inductance can be used as a useful element in the resonant converters [9]. In the paper [10] a bridge configuration class-E buck resonant converter is proposed. The bridge configuration class-E boost resonant converter was proposed in [11]. The class-E converters guarantee ZVS switching conditions for converter transistors in the whole operating range and apart from that do not generate the parasitic oscillations which invoke the voltage spikes. On the basis of both class-E converters mentioned above a bidirectional class-E DC/DC converter is discussed.

2. Topology, control principle and modes of operations

The proposed converter topology is shown in Fig. 1. To the energy flow from the low to the high voltage side, the boost converter (L) is controlled and the high side converter (H) is not controlled but operates as a rectifier. To the energy flow into the opposite side the buck converter (H) is controlled and the low side converter (L) operates as a rectifier. The main problem of this solution is the use of the same resonant circuit elements for the both directions of the energy flow. As the authors' theoretical investigation shows, such a situation is impossible and an additional capacitor must be used when the system operates in the buck mode. This capacitor C is joined by the additional switch shown in Fig. 1.

The converter system is controlled by the transistors control pulse frequency change, maintaining a constant brake between pulses, as a consequence the transistor control pulse width is controlled. The minimal value of the control frequency corresponds to the maximal transistor control pulse width and the maximal value of the energy flow. As we can see in Fig. 2 the transistor control pulse width of the buck converter can be changed from the minimal value (maximal frequency) to the half control period value (minimal frequency). One branch control pulses cannot overlap.
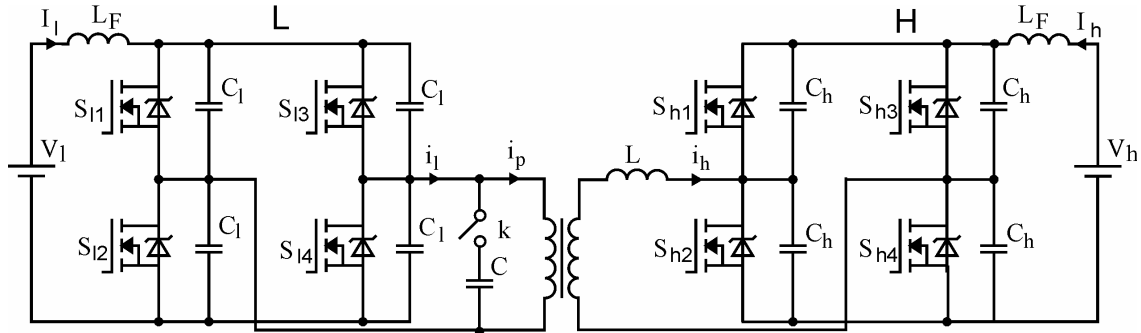
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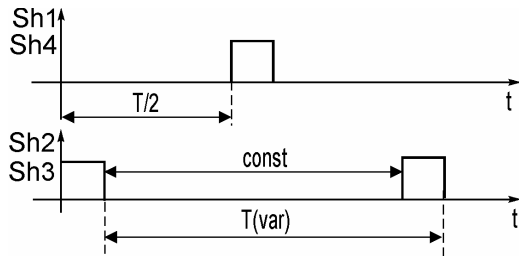Fig. 1. Proposed bidirectional DC-DC converter topology

Fig. 2. The control pulses of buck converter (H) transistors

The boost transistors control pulses width (frequency) which is controlled within the range when control pulses of the one converter leg overlap (Fig. 3).
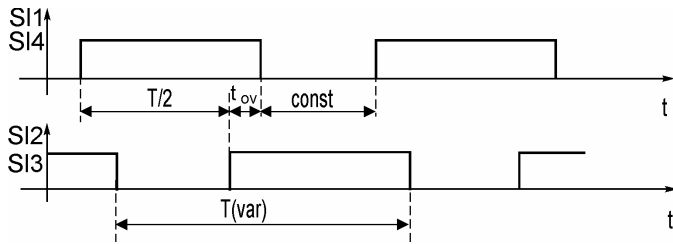

Fig. 3. The control pulses of boost converter (L) transistors

The both converters are designed for the so called an optimal operation point. The optimal operation point corresponds to the minimal pulse width (maximal frequency) of the buck converter and to the maximal pulse width (minimal frequency) of the boost converter. During the optimal operation the converter current flows through the transistors or a parallel placed capacitor. Transistors current waveforms have only positive value, so the internal transistors' body, diodes, do not participate in the current flow.

3. Steady state analysis and design guidelines

3.1. The buck operation principle. The characteristic waveforms of the buck mode of the optimal operation point are shown in Fig. 4.

Assuming that the converter (H) input current I_h is constant and the converter output i_h has sinusoidal shape and due to the converter configuration symmetry, the converter leg current can be expressed as:

$$i_h = \frac{I_m}{2} \sin \omega t + \frac{I_h}{2}, \tag{1}$$

where I_m is the amplitude of the high side transformer current.

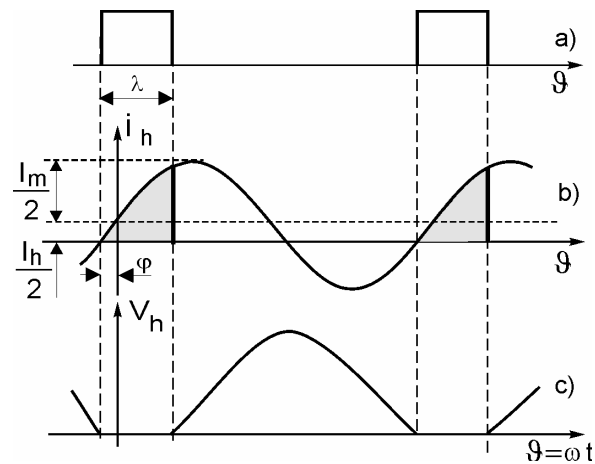Fig. 4. The waveforms for the buck optimal operation point (minimal value of transferred energy). a) transistor control pulse, b) transistor current. c) transistor voltage

The part of this current charges and discharges the capacitor C_h from zero voltage to zero voltage, so in accordance with Fig. 4 the following equation is fulfield:

$$\int_{\lambda-\varphi}^{2\pi-\varphi} \left(\frac{I_m}{2} \sin \omega t + \frac{I_h}{2} \right) d(\omega t) = 0, \tag{2}$$

where λ is the width of control pulse and $\sin \varphi = \frac{I_h}{I_m}$.

From the above equation we can find the relation between the converter input and output currents as a function of the transistor control pulse width.

$$\frac{I_m}{I_h} = \sqrt{1 + \left(\frac{\sin \lambda + \pi \left(2 - \frac{\lambda}{\pi} \right)}{1 - \cos \lambda} \right)^2}. \tag{3}$$

Then the instantaneous value of capacitor C_h voltage can be expressed as:

$$v_h = \frac{1}{\omega C_h} \int_{\lambda-\varphi}^{\omega t} \left(\frac{I_m}{2} \sin \omega t + \frac{I_h}{2} \right) d(\omega t) =$$

$$= \frac{I_m}{2\omega C_h} \left[\cos(\lambda - \varphi) - (\lambda - \varphi) \sin \varphi + \omega t \sin \varphi - \cos \omega t \right]. \tag{4}$$

In the steady state operation, the mean value of capacitor C_h voltage is equal to the half value of the high voltage V_h

$$\frac{V_h}{2} = \frac{1}{2\pi} \int\limits_{\lambda-\varphi}^{2\pi-\varphi} v_h d\left(\omega t\right). \tag{5}$$

So, we can find the equation to calculate the desired value of the capacitance C_h

$$C_h = \frac{I_m}{2\pi\omega V_h} \left\{ (2\pi - \lambda)\left[\cos\left(\lambda - \varphi\right) - (\lambda - \varphi)\sin\varphi\right] + \right.$$
$$\left. + \frac{1}{2}\sin\varphi\left(2\pi - \lambda\right)^2 + \sin\lambda \right\}. \tag{6}$$

To find the desired capacitance C value we introduce the following procedure. If the capacitor C voltage waveform is sinusoidal and has amplitude V_m then the rectifier (L) input current i_l rms value can be calculated as:

$$I_{lr} = \sqrt{\left(k_T \cdot I_m\right)^2 - \left(\omega C' V_m\right)^2}, \tag{7}$$

where k_T – the transformer turns ratio, C' – the substitute capacitance results from parallel connected capacitors $C' = C + C_l + C_l$.

On the other hand, in accordance with the resonant converters analysis method [12] the rectifier (L) input can be substituted by the resistance which value results from the transferred power value $P_{\min}$. Therefore, the RMS value of the current I_l is given by:

$$I_{lr} = \frac{\sqrt{2}P_{\min}}{V_m}. \tag{8}$$

In the steady state operation the rectifier output voltage value is equal to the battery voltage V_l and, because of sinusoidal shape of the rectifier input voltage, the following equation is fulfilled:

$$V_m = \frac{2}{\pi}V_l. \tag{9}$$

Using Eqs. (7)–(9) we can find the desired capacitance C' value

$$C' = \frac{2}{\omega\pi V_l}\sqrt{k_T^2 I_m^2 - \frac{16 P_{\min}^2}{\pi^2 V_l^2}}. \tag{10}$$

The capacitance C_l value and the inductance L value should be the same for the both direction of the energy flow therefore they will be calculated for the boost operation mode.

3.2. The boost operation principle. The direction of the energy flow from the low voltage to the high voltage sources is called the boost operation mode. In this mode the converter (L) is controlled and converter (H) operates as rectifier. The system design concerns the optimal operation point when the maximal energy value is transferred and the transistors control pulses have a maximal width and overlap. This operation mode was discussed deeply in the paper [11], and now only the guideline for its design is presenting. Relation between input I_l and output i_l converter $[L]$ currents was expressed in [11] as:

$$\frac{I_l}{I_{lm}} = \frac{1 + \cos\left(\dfrac{2t_{0v}}{T}\pi\right)}{\pi\left(1 - \dfrac{2t_{0v}}{T}\right)}, \tag{11}$$

where I_{lm} – the converter (L) output current amplitude, t_{0v} – control pulse overlap, T – control period. When we assume that the optimal operation point corresponds to $\dfrac{2t_{0v}}{T} = 0.26$ then $\dfrac{I_l}{I_{lm}} = 0.725$ and capacitance C_l can be calculated as:

$$C_l = 8.866 \cdot 10^{-3}\frac{T I_{lm}}{V_l}. \tag{12}$$

The last desired element, the resonant circuit inductance L value can be calculated using following equation:

$$1.1T = 2\pi\sqrt{2C_h L}. \tag{13}$$

Described Eqs. (6), (10), (12), (13) are sufficient basis for the converter design.

4. Experimental verification

The proposed bidirectional DC-DC converter prototype was built and tested in experimental circuit shown in Fig. 5.

The accumulator $V_l = 50$ V was used as low voltage sources (storage element). As the high voltage $V_h = 300$ V source was used DC motor coupled with AC motor transferred energy to the grid 3×230 V. The converter circuit parameters are summarized in Table 1.
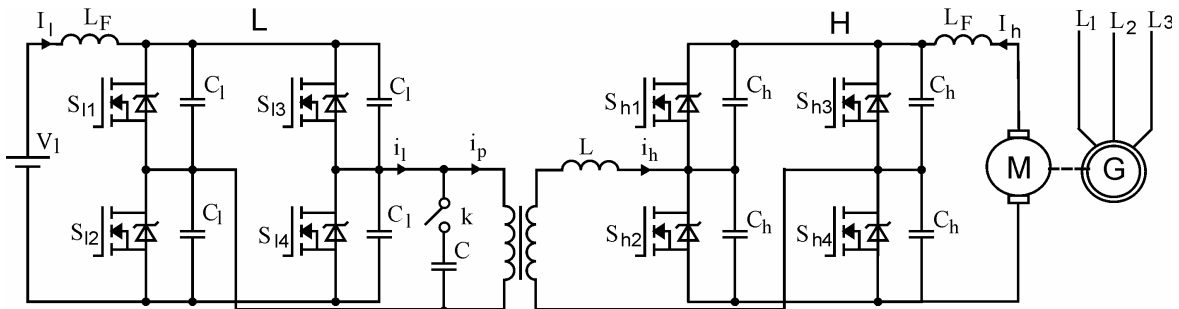

Fig. 5. Experimental circuit of the bidirectional DC-DC converter test

Table 1
Circuit parameters of the DC-DC converter

Rated power	300 W÷1.5 kW
Converter transistors	IRFP4227PBF (boost) IXFN32120 (buck)
Transformer core material	Nanocristalline Toroidal Cores VITROPERM 500 F
Transformer turn ratio	$k_T = 3$
Resonant inductance	$L = 16.5\ \mu H$
Resonant capacitances	$C_l = 32$ nF $C_h = 15.7$ nF
Additional capacitance	$C = 140$ nF
low side input inductance	$L_F = 200\ \mu H$
high side input inductance	$L_F = 200\ \mu H$
control frequency range	200 kHz÷300 kHz

The relevant waveforms show the characteristic point of operations. The optimal operation point when the maximal energy value is transferred from the accumulator to the grid is presented in Fig. 6.
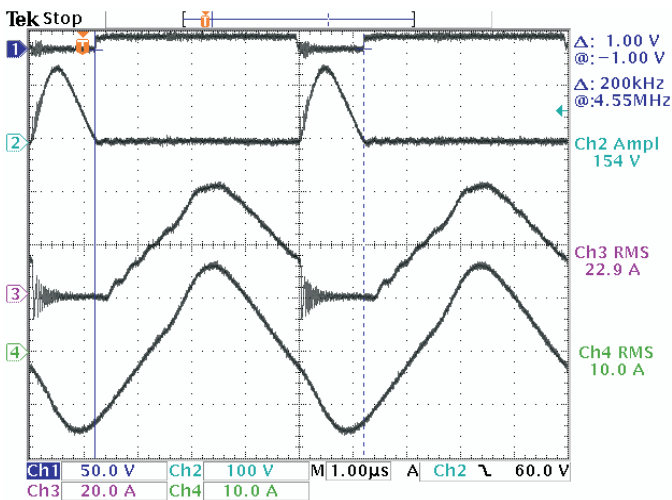

Fig. 6. Characteristic waveforms of the boost optimal operation point , 1) transistor control pause, 2) transistor voltage, 3) transistor current, 4) the transformer high side current
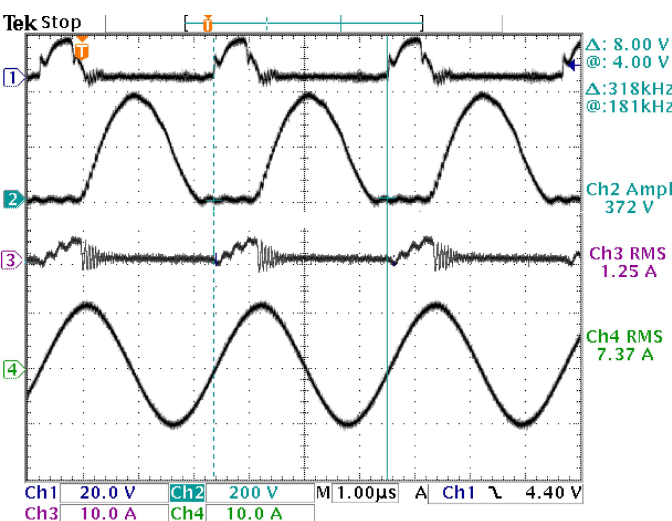

Fig. 7. Characteristic waveforms of the buck optimal operation point, 1) transistor control pause, 2) transistor voltage, 3) transistor current, 4) the transformer high side current

The next optimal operation point when the minimal power value is transferred from the grid to the accumulator is presented in Fig. 7.

For the both situations the transistor current waveforms have only positive value (the transistor body diodes do not participate in the current flow). The ZVS transistor switching process is evident because the transistors' current and voltage waveforms do not overlap. The transformer current has sufficiently sinusoidal waveforms, as we have assumed, during theoretical investigation. Oscillation visible on the transistor current and voltage waveforms results from the probes' locations. The current probe measured the transistor and its parasitic capacitance currents, it is located on the connection of the transistor with the external capacitor and it introduces a parasitic inductance. But, the bidirectional converter system input and output current are without any oscillations, that is important for the energy storage element exploitation.

When the transferred energy in boost directions has smaller than maximal value or the transferred energy in buck direction is higher than the minimal value, the converter operates in sub-optimal operation mode.
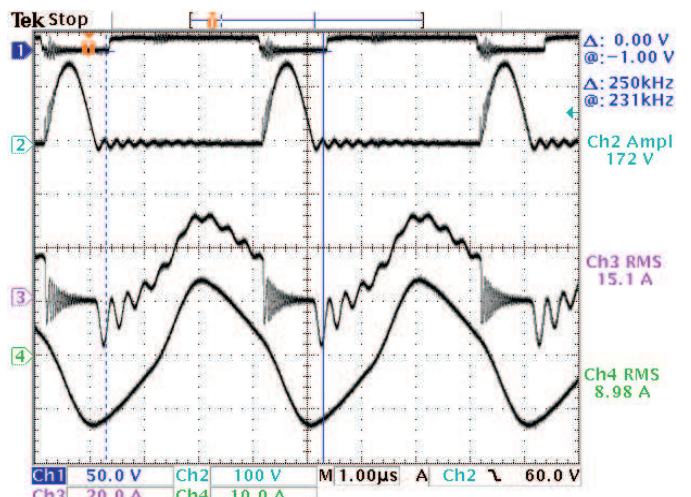

Fig. 8. Characteristic waveforms of the boost sub-optimal operation point, 1) transistor control pause, 2) transistor voltage, 3) transistor current, 4) the transformer high side current

The adequate waveforms are presented in Fig. 8 for the boost operation and in Fig. 9 for the buck operation.
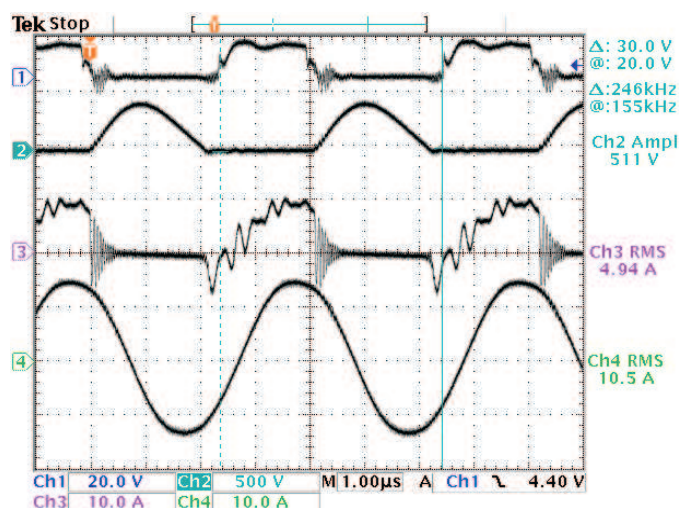
Fig. 9. Characteristic waveforms of the buck sub-optimal operation point, 1) transistor control pause, 2) transistor voltage, 3) transistor current, 4) the transformer high side current
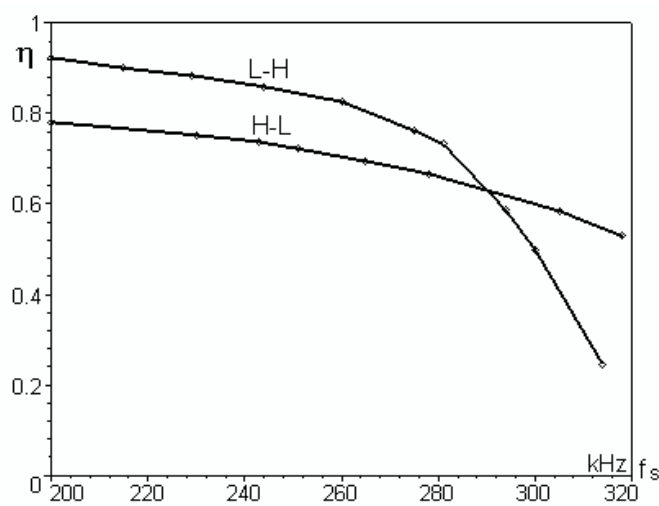

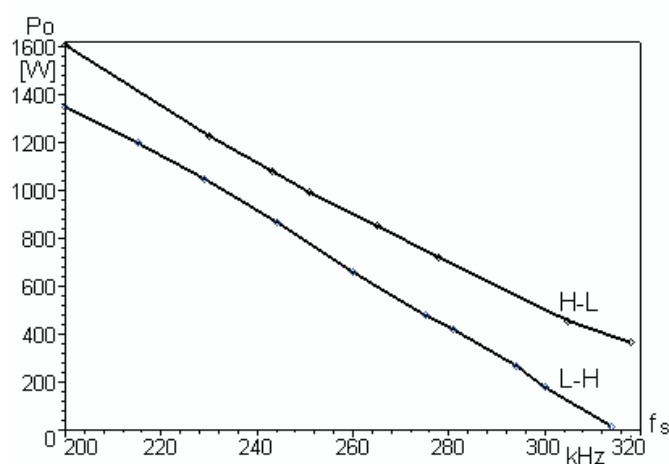Fig. 10. The power transferred efficiency, L-H – boost operation, H-L – buck operation

Fig. 11. The transferred power, H-L – buck operation, L-H – boost operation

The transistor current waveform has positive and negative value so the internal transistor body diodes participate in the current flow. Because the transistor current and voltage waveforms do not overlap, the ZVS conditions are fulfilled. As a consequence of the aforementioned conditions, the presented bidirectional DC-DC converter is devoid of the transistors switching power dissipation within the whole operation range, therefore it is marked by high efficiency.

Efficiency curves measured on the experimental setup are shown in Fig. 10 and the transferred power in Fig. 11.

Due to the high converter switching frequency (200 kHz÷300 kHz), the converter size and weight are minimized and dynamic properties are attractive.

5. Conclusions

This paper proposes the novel class E buck/ boost resonant bidirectional DC-DC converter for renewable energy system. Among important features of the presented converter topology are, low size, low weight and high dynamics because of the transistors ZVS switching process with high frequency. The converters employed in the system are current sourced. Therefore, the connection parasitic inductance are of no importance and system is environmentally friendly.

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