Analysis and Design of a Current-fed Two Inductor Bi-directional DC/DC Converter using Resonance for a Wide Voltage Range

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Abstract – In this paper, a current-fed two-inductor bi-directional DC/DC converter using resonance (CF-TIBCR) and its design method are proposed. The CF-TIBCR has characteristics of low current ripple and a high current rating because of two separated inductors. Also, it achieves zero voltage switching for all switches and zero current switching for switches of a low voltage stage by using the resonant tank. Besides, a voltage spike problem in conventional current-fed converters is solved without the need for an additional snubber or clamping circuits. As a result, the CF-TIBCR features high step-up and high efficiency. Since the proposed converter has difficulty achieving the soft-switching condition when the converter requires the low voltage transfer ratio, a method that varies the number of resonant cycles is adopted to extend the output voltage range with satisfying the soft-switching condition. The principles of the operation characteristics are presented with a theoretical analysis, and the proposed converter is verified through results of an experiment using a laboratory prototype.

Keywords: Current-fed DC/DC converter, Zero voltage switching (ZVS), Zero current switching (ZCS), Resonance, Wide voltage range

1. Introduction

Recently, battery, photovoltaics (PV) and fuel-cells (FC) have received much attention as sources of energy that can solve the problems of environmental pollution and energy exhaustion. These types of energy sources are characterized by low voltage and high current output. Therefore, DC/DC converters for these power sources are needed to achieve a high step-up characteristic, low current ripple and galvanic isolation [1-3]. The current-fed two-inductor boost converter (CF-TIBC), which is derived from the duality principle in 1993 by using a transformer-coupled half-bridge converter, is suitable for these applications [4, 5]. The CF-TIBC has inherent high reliability and a step-up characteristic, and it can obtain a high input current rating and low input current ripple because the input current flows into the two separated inductors [4-16].

However, the CF-TIBC has several drawbacks when using the battery applications. Firstly, the CF-TIBC is not capable of charging a battery due to a unidirectional converter. Battery applications, such as an energy storage system (ESS) and electric vehicles (EVs) can require a bi-directional power flow to charge or to discharge a battery. Some research has contributed to the operation of the CF-TIBC using two opposite directions; this has involved replacing diodes with active switches [13-20].

The other problem of the conventional CF-TIBC leads to a high voltage spike when the switches are turned off. The voltage spike occurs due to the reverse recovery current of secondary diodes and unavoidable transformer leakage inductance; this is the reason why the conventional CF-TIBC is limited to a switching frequency and power rating. To address these problems, additional snubbers or active clamp circuits have been researched [6-8, 21]. However, these methods lead to rising production cost and complications of the circuit and deteriorating reliability of the system.

In this paper, a current-fed two-inductor bi-directional DC/DC converter using resonance (CF-TIBCR) is proposed as shown in Fig. 1. The proposed converter is mainly composed of two stages, which are a low voltage (LV) and a high voltage (HV) stage separated by the transformer. The diodes of the HV stage are replaced with the MOSFET switches. Thus, it is possible to conduct a bi-directional operation. Using the resonant components of the LV stage, the switches of the LV stage are satisfied with a zero voltage switching (ZVS) condition and a zero current switching (ZCS) when the switches are turned-on and

Fig. 1. Schematic of the proposed CF-TIBCR

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turned-off, respectively [9-16]. The switches of the HV stage also achieve ZVS. Therefore, the voltage spike problem is eliminated and system efficiency can be increased. The output voltage of the proposed converter is determined by the switching frequency, the resonant frequency, and the number of the resonant cycles. When the CF-TIBCR requires a low voltage transfer ratio, it is hard to satisfy the soft-switching condition. Therefore, a method of varying the number of the resonant cycles is adopted to increase the output voltage range and this makes soft switching possible within the entire operating range.

An introduction of the converter and a description of the operation modes and principles are presented in Section 2. Section 3 explains characteristics of the CF-TIBCR according to the number of the resonant cycles, and the design method of the resonant component. Then, experimental results for a wide voltage range and load variation using a 300W laboratory prototype are demonstrated in Section 4 in order to verify the proposed converter and its design method.

2. Steady-state Analysis

The LV stage of the CF-TIBCR consists of the main inductors (L_{m1} and L_{m2}), the switches (S_{B1} and S_{B2}), the anti-parallel diodes (D_{SB1} and D_{SB2}) and the resonant components (L_r , C_{SB1} and C_{SB2}). The HV stage switches ($S_{F1} \sim S_{F4}$) are combined with the resonant capacitances ($C_{SF1} \sim C_{SF4}$) and the anti-parallel diodes ($D_{SF1} \sim D_{SF4}$). L_H indicates the filter inductor to reduce the current ripple on the HV stage. TR is the high frequency transformer. A number of assumptions are needed to perform a simple analysis;

- 1) The main inductance, the filter inductance and the filter capacitance are significantly large. Therefore, the currents and voltages of the input and output are constant and ripple-free in one switching period.
- 2) The magnetizing inductance of TR is infinitely larger than L_r . Thus, the magnetizing inductance does not affect the resonance.
- 3) The parasitic impedance, such as line impedance, switch conduction resistance, and transformer winding capacitance, are all neglected in the analysis.

Fig. 2 shows the key waveforms of the CF-TIBCR. The duty ratio of the LV stage switches gate signal G_{SB} is larger than 50% for the continuous flow of the main inductor currents. Also, the LV stage switches are controlled as shifting the phase of the gate signals which have a difference of 180 degrees. Thus, no interval exists in which both switches are turned off. According to the number of the resonant cycles, the proposed converter is operated as a one-cycle mode or a two-cycle mode as shown in Fig. 2(a) and (b). To satisfy the soft-switching condition, the LV

Fig. 2. Key waveforms of the CF-TIBCR in (a) the one-cycle mode and (b) the two-cycle mode

stage switches should be turned-on at the end of the resonance in both operating modes. In case of the HV stage switches, they are turned-on when the LV stage switches are turned-off with dead time to satisfy the ZVS condition in the HV stage.

A switching cycle can be divided into eight intervals according to the resonant current. Since the same intervals symmetrically occur in each leg, only four intervals are analyzed (i.e., interval 1 to 4) in this paper.

Interval 1 ($t_0 \leq t < t_1$): At t_0 , the resonances between L_r and $C_{SF1} \sim C_{SF4}$ are finished. In addition, the current flowing through the switch S_{B1} (i.e., i_{SB1}) starts to flow through the anti-parallel diode D_{SB1} in this interval. Thus, the voltage of switch S_{B1} during interval 1 is zero. The voltage of the transformer in the LV stage V_{T1} is applied across the

resonant inductor L_r . Therefore, i_{Lr} starts to increase linearly, which can be described as:

$$i_{Lr}(t) = \frac{V_H}{n_T L_r} t + i_{Lr}(t_0) \quad (1)$$

where $i_{Lr}(t_0)$ is the initial resonant current at t_0 and n_T is the transformer turns ratio. When i_{SB1} reaches zero, this interval ends. Using (1), the time interval $T_{M1}(t_0, t_1)$ can be expressed as:

$$T_{M1} = \frac{L_r \Delta i_{SB,M1}}{V_{T1}} = \frac{n_T L_r |i_{Lr}(t_0) + I_{Lm1}|}{V_H} \quad (2)$$

where $\Delta i_{SB,M1}$ is an increment of $i_{SB1}(t)$, which is the difference between $i_{Lr}(t_0)$ and I_{Lm1} .

Interval 2 ($t_1 \leq t < t_2$): In this interval, the resonance occurs in the LV stage. At t_1 , the current i_{SB1} reaches zero, and starts to flow into the C_{SB1} . Since the V_{T1} is applied across L_r , the maximum voltage of V_{SB1} (i.e., V_m) is twice that of V_{T1} . Using the above assumptions, i_{Lr} and voltage across the LV stage switch V_{SB1} can be calculated as:

$$i_{Lr}(t) = \frac{V_{T1}}{Z_{NL}} \sin \omega_{rL}(t - t_1) - I_{Lm} \quad (3)$$

$$V_{SB1}(t) = V_{T1} \cos \omega_{rL}(t - t_1) - V_{T1} \quad (4)$$

where ω_{rL} is the angular resonant frequency, and Z_{NL} is the characteristic impedance between L_r and C_{SB1} . The resonance ends when switch S_{B1} is turned-on. To satisfy the ZVS condition, S_{B1} should be turned-on when V_{SB1} reaches zero. Therefore, the time interval $T_{M2}(t_1, t_2)$ is relative to the resonant period T_{rL} and the number of the resonant cycles n_r .

$$T_{M2} \approx T_{rL} n_r = 2\pi n_r \sqrt{L_r C_{SB1}} \quad (5)$$

Interval 3 ($t_2 \leq t < t_3$): Since switch S_{B1} is turned-on at t_2 , the current i_{SB1} , which is the difference between i_{Lr} and I_{Lm} , flows through the switch S_{B1} . Similarly to the interval 1, i_{Lr} is linearly increased because V_{T1} is applied across L_r . Therefore, i_{Lr} can be expressed as (6).

$$i_{Lr}(t) = \frac{V_H}{n_T L_r} (t - t_2) - i_{Lr}(t_2) \quad (6)$$

This interval ends when the HV stage is turned-off. In the steady state, the difference between the increment of i_{Lr} in interval 1 and 3 is the input current I_L . The time interval $T_{M3}(t_2, t_3)$ can be calculated as (7).

$$T_{M3} = \frac{L_r \Delta i_{SB,M3}}{V_{T1}} = -\frac{L_r \{i_{Lr}(t_0) - I_{Lm}\}}{V_{T1}} \quad (7)$$

Interval 4 ($t_3 \leq t < t_4$): The resonances between L_r and the HV stage resonant capacitors ($C_{SF1} \sim C_{SF4}$) occur in interval 4. In this interval, i_{Lr} is divided into two resonant routes. The voltage across the HV stage switch V_{SF} and i_{Lr} can be described as:

$$i_{Lr}(t) = i_{Lr}(t_3) \cos \left\{ \frac{\omega_{rH}}{n_T} (t - t_3) \right\} + \frac{V_H}{Z_{NH}} \sin \left\{ \frac{\omega_{rH}}{n_T} (t - t_3) \right\} \quad (8)$$

$$V_{SF}(t) = \frac{V_H}{2} \cos \left\{ \frac{\omega_{rH}}{n_T} (t - t_3) \right\} - \frac{i_{Lr}(t_3) Z_{NH}}{2} \sin \left\{ \frac{\omega_{rH}}{n_T} (t - t_3) \right\} + \frac{V_H}{2} \quad (9)$$

where Z_{NH} is the characteristic impedance and ω_{rH} is the angular resonant frequency between L_r and C_{SFx} in the HV stage. Because calculating time of interval 4 using (9) is complicated, an approximated interval 4 (i.e., $T_{rH,a}$) can be calculated using (10). It can be derived by assuming that the resonant inductance L_r is significantly larger than the resonant capacitances in the HV stage.

$$T_{rH,a} = \frac{2n_T C_{SF} V_H}{i_{Lr}(t_3)} \quad (10)$$

To achieve the ZVS condition in the HV stage, sufficient time is required to discharge the energy in the HV stage capacitors. Thus, the dead time of the HV stage switches d_D should be larger than the calculated value of $T_{rH,a}$.

When the CF-TIBCR operates in the buck operation, the gate signals remain the same. Thus, the operation modes including the equations of voltage and current are similar to a boost operation. All switches also have a soft-switching condition in the buck operation. Therefore, a mode analysis of the buck operation is omitted in this paper.

The voltage transfer ratio in the boost and buck operation ($G_{V,BST}$ and $G_{V,BK}$) can be solved as (11) and (12) respectively, by equating input and output energy.

$$G_{V,BST} = \frac{n_T f_r}{n_r f_{sw}} \quad (11)$$

$$G_{V,BK} = \frac{n_r f_{sw}}{n_T f_r} \quad (12)$$

As shown in (11) and (12), the output voltage of the proposed converter is determined by the number of resonant cycles and a ratio of the switching frequency to resonant frequency.

3. Design of the CF-TIBCR

The operating range of the CF-TIBCR is affected according to the resonant components because the duty

ratio for satisfying soft-switching condition is restricted by the resonant components. Also, system efficiency mainly depends on the resonant components, since they mainly affect the peak current of the switches. Thus, we consider the available duty ratio and peak current according to the resonant components to achieve both soft-switching and increasing the operating range. In this paper, we use the basic system parameters where the rated power P_{rate} is 300W, the low voltage is $24V_{\text{dc}}$, the range of the high voltage is $200\sim 380V_{\text{dc}}$ and the transformer turns ratio is two.

3.1 Duty Ratio to satisfy Soft-switching

The turn-off time of the LV stage switches should include the resonant period and the interval of current flowing through the anti-parallel diode to achieve the ZVS conditions. Since the LV stage switches are controlled by overlapping, a duty of the LV stage switches d_{SB} should be within the range of 0.5 to 1. In this Section, the lower limit of 0.6 and the upper limit of 0.9 are employed, considering the switch transition times. The duty ratio to satisfy a soft switching condition for the LV switches is calculated as (13), which is represented as $d_{\text{SB,BST}}$ or $d_{\text{SB,BK}}$ according to the operation mode.

$$\begin{aligned} d_{\text{SB,BST}} &= \frac{3}{4} - \frac{n_r f_{\text{sw}}}{2f_r} + \frac{n_r^2 f_r L_r |I_H|}{2n_r V_H} + d_D \\ d_{\text{SB,BK}} &= \frac{3}{4} - \frac{n_r f_{\text{sw}}}{2f_r} - \frac{n_r^2 f_r L_r |I_H|}{2n_r V_H} + d_D \end{aligned} \quad (13)$$

Figs. 3(a) and (b) illustrate d_{SB} with varying L_r and C_{SBx} in the boost operation. The peak current of the LV switches increases as the resonant inductance decreases or V_H increases. It leads to reduce duty ratio because T_{M1} , which is the time of current flowing through the anti-parallel diode, is increased. As shown in Fig. 3(a), $d_{\text{SB,BST}}$ can

exceed the upper duty limit when the output voltage is lower at the same load condition because T_{M1} is reduced by decreasing of the slope of i_{Lr} . Fig. 3(b) shows the required $d_{\text{SB,BST}}$ at an output voltage of $200V_{\text{dc}}$. In terms of the output power, the required $d_{\text{SB,BST}}$ of a high output power condition is higher than that of a low output power condition. Since the increment of input current makes the peak current of the switches higher, T_{M3} , which is the time of current flowing through the switches S_B , becomes longer at the same inductance. As shown in Figs. 3(a) and (b), the duty ratio of the two-cycle mode is lower than that of the one-cycle mode because T_{M2} (*i.e.*, total resonant period) is increased although T_{M1} is decreased. Therefore, when the converter is operated in the one-cycle mode in which the output voltage is low and the power condition is high, it is hard for $d_{\text{SB,BST}}$ to satisfy the duty consideration rather than the other conditions.

Figs. 4(a) and (b) depict $d_{\text{SB,BK}}$ curves with varying L_r and C_{SBx} in the buck operation. As L_r increases, T_{M3} decreases because T_{M1} and T_{M3} are reversed in comparison to the boost operation. Thus, $d_{\text{SB,BK}}$ rapidly decreases in a low V_H condition due to the decrement of the slope i_{Lr} as shown in Fig. 4(a). In contrast to the boost operation, the higher output power makes T_{M1} longer because of the increasing negative switch current. Thus, the turn off time, which is the sum of T_{M1} and T_{M2} , is required more for a high output power condition as shown in Fig. 4(b). Although T_{M2} is increased in the two-cycle mode, the duty ratio of the two-cycle mode is higher than that of the one-cycle mode because the T_{M1} is significantly decreased. Therefore, the low input voltage and high power condition in the one-cycle mode can make $d_{\text{SB,BK}}$ exceed the lower duty limit similarly to the boost operation.

In both operation modes, the required duty is also affected by variation of V_L . Since the required duty is determined by the voltage transfer ratio as (13), the lower V_L makes decrease the f_{sw} in the same V_H condition, and

Fig. 3. Duty ratio of the LV stage switches to satisfy the soft switching condition according to (a) output voltage and (b) load condition in the boost operation

it results increasing of the required duty. As a result, the resonant components should be designed, considering that d_{SB} does not exceed the duty limit considering the conversion ratio and load condition.

3.2 Switch peak current

When designing the proposed converter, it is important to consider the peak voltage and current in order to avoid device failure. High peak current can reduce system efficiency, because it increases the root mean square (RMS) value of the current. In the steady state, $i_{SB,pk}$ in the boost operation can be calculated as (14), determined by (6) and (13).

$$i_{SB,pk} = \frac{V_H}{4n_T L_r} \left(\frac{1}{f_{sw}} - \frac{2n_T}{f_{res}} \right) + \frac{P}{2V_L} \quad (14)$$

In the buck operation, $i_{SB,pk}$ is a negative value with the same magnitude as that in the boost operation. Fig. 5

shows $i_{SB,pk}$ waveforms of LV stage switches when $V_H=380V$ according to L_r and C_{SBx} . Since the resonant inductance determines the slope of the i_{SB} for the whole switching period, $i_{SB,pk}$ is dramatically increased at a lower resonant inductance and higher V_H condition. As output power increases, the peak current increases due to longer T_{M3} . In both operations, the two-cycle mode has a larger peak value in comparison to the one-cycle mode.

3.3 Load condition

There is a maximum output power for the proposed converter to be able to satisfy the soft-switching condition (i.e., $P_{ss,max}$) depending on f_{sw} related with V_H . If the output power of the converter is lower than $P_{ss,max}$, T_{M1} exists because of the negative value of $i_{SB}(t_0)$. However, $i_{SB}(t_0)$ is larger than zero when the converter requires more power than $P_{ss,max}$. In this case, interval 1 does not exist throughout the whole switching period, and the resonant voltage does not reach zero. This leads to the failure of

Fig. 4. Duty ratio of the LV stage switches to satisfy the soft switching condition according to (a) output voltage and (b) load condition in the buck operation

Fig. 5. Peak current of the LV stage switches according to the output power condition at $V_H=380V_{dc}$ condition

Fig. 6. Maximum output power to satisfy the soft-switching condition according to the resonant components

Fig. 7. Design examples of the resonant components considering $i_{SB,pk}$, d_{SB} and $P_{ss,max}$ conditions in (a) the one-cycle mode and (b) the two-cycle mode

the ZCS and ZVS. $P_{ss,max}$ can be calculated as (15) according to the resonant components, and it is depicted when voltage is low. This is the worst case for design and is shown in Fig. 6.

$$P_{ss,max} = \frac{2\pi n_r V_H^2}{n_r^2 Z_{NL}} \left(0.5 - \frac{n_r f_{sw}}{f_{res}} - 2d_D \right) \quad (15)$$

If the resonant components are used in the region where the required output power is larger than $P_{ss,max}$, the converter cannot achieve a soft-switching conditions. Thus, L_r and C_{SBx} should be selected to fall within the region where the rated output power is lower than $P_{ss,max}$. As shown in Fig. 6, the higher characteristic impedance Z_{NL} and the one-cycle mode can cause a decrease in the $P_{ss,max}$. These factors make it difficult to satisfy the soft-switching conditions.

3.4 Selection of the resonant components

The converter operating the two-cycle mode is more

Fig. 8. Operating range of the proposed converter in each resonant cycle mode at full load condition

advantageous in the low voltage range because d_{SB} and $P_{ss,max}$ conditions, which satisfy the limits, widen although $i_{SB,pk}$ is higher. Thus, the resonant components are designed to satisfy both operation modes, which are the one-cycle mode in the high voltage range and the two-cycle mode in the low voltage range.

In this paper, the converter is operated as the one-cycle mode within the range from $250V_{dc}$ to $380V_{dc}$, and the two-cycle mode under $250V_{dc}$. If the range of operating switching frequency is set between 25kHz and 80kHz, the selection regions of the resonant components, which satisfy the above conditions, according to the operation mode are described as Fig. 7 using Figs. 3-6. There are four condition lines, representing the peak current limit, the $P_{ss,max}$ condition, and the duty limits of each mode. The soft-switching condition is not satisfied when the resonant components are selected under the $P_{ss,max}$ condition line. Also, selection of the resonant components on the left side of the peak current limit line causes $i_{SB,pk}$ to become higher than 40A, which is the limit value. The trajectories of the resonant components related to switching frequency, which are the upper and lower frequency limits. Consequently, the resonant components should be designed to fall within the selection area bounded by the peak current limit, the $P_{ss,max}$ condition line, and the upper/lower switching frequency limits in each operation mode. In this paper, $L_r=33.5\mu H$ and $C_{SB}=10nF$ are chosen from the selection area to satisfy the limit conditions in both resonant cycle modes. In this case, the operation range of the converter is shown in Fig. 8. According to V_H , the number of the resonance n_r is decided, and the required duty ratio d_{SB} is calculated to secure the time of the resonance depending on n_r .

4. Experimental Results

To verify the proposed converter and its design method,

a 300W laboratory prototype was built and tested. PQ4040 PL-7 and PQ3535 PL-7 core are used as the transformer and the resonant inductor, respectively. The transformer turns ratio is two. The proposed converter use TMS320F28335 (Texas Instrument) DSP-based digital controller, and FCH76N60NF (Fairchild Semiconductor) as the LV and HV stage switches. Also, all tests were measured using the LECROY WaveSurfer 24MXs. The system parameters are given in Table 1.

Figs. 9-12 show the key waveforms when the converter is operated in the boost operation with varying output

Table 1. Parameters of the prototype converter

Parameter	Symbol	Value	Unit
Low voltage	V_L	24	V
High voltage	V_H	200~380	V
Power rating	P_{rate}	300	W
Switching frequency	f_{sw}	20~80	kHz
Main inductance	L_m	1	mH
Resonant inductance	L_r	33.5	μ H
Resonant capacitance in the LV stage	C_{SB}	10	nF
Resonant capacitance in the HV stage	C_{SF}	1	nF
Transformer turns ratio	n_T	2

Fig. 9. The key waveforms of the CF-TIBCR at $200V_{dc}$ output voltage in the two-cycle mode of the boost operation

Fig. 11. The key waveforms of the CF-TIBCR at $250V_{dc}$ output voltage in the one-cycle mode of the boost operation

Fig. 10. The key waveforms of the CF-TIBCR at $250V_{dc}$ output voltage in the two-cycle mode of the boost operation

Fig. 12. The key waveforms of the CF-TIBCR at $380V_{dc}$ output voltage in the one-cycle mode of the boost operation

voltages at full load condition. Since the turns ratio of the transformer is two, the peak voltage of the switches is the same as the output voltage. If the output voltage is lower than $250V_{dc}$, the converter using the designed resonant components cannot achieve the soft-switching condition in the one-cycle mode because the converter does not satisfy the $P_{ss,max}$ condition. Therefore, the converter should be operated in the two-cycle mode when the output voltage is lower than $250V_{dc}$. As shown in Figs. 9 and 10, the LV stage switches achieve ZVS turn-on and ZCS turn-off conditions in the two-cycle mode. The peak currents of the switches are measured at 17.95A and 26.02A, whose calculated values by (14) are 18.05A and 28.08A, respectively. These errors are caused by the parasitic components, such as the switch on-resistance, the forward voltage drop of the anti-parallel diode and the power loss of the magnetic components. Figs. 11 and 12 show that the converter is operated in the one-cycle mode that satisfies the soft-switching conditions. Using the one-cycle mode has the advantage of having a lower peak current value than the two-cycle mode in the same output voltage condition. For example, the switch peak current is measured at 15.20A when the converter has an output voltage of $250V_{dc}$, which is almost 60% of the value of the converter operating in the two-cycle mode at the same

output voltage.

Figs. 13-16 are the key waveforms of the converter, which is operated in the buck operation that varies the input voltage and has a fixed output voltage of $24V_{dc}$. In contrast with the boost operation, i_{SB} is smaller than i_{Lr} by I_{Lm} , and T_{M1} becomes longer than T_{M3} in the buck operation because of the negative value of I_{Lm} . Therefore, the maximum magnitude of the switch current occurs at t_0 . In the low input voltage range, the converter is operated in the two-cycle mode to satisfy a duty limit condition as shown in Figs. 13 and 14. Similarly to the boost operation, the converter operating in the one-cycle mode has the advantage of the lower peak current when the input voltage is higher than $250V_{dc}$ as shown in Figs. 14 and 15. However, a magnitude of the negative peak current in the buck operation increases in the higher output voltage condition because of increment of T_{M1} . Therefore, the maximum negative current of the switches is measured by $-38.7A$ at condition of the highest input voltage although the converter operates in the one-cycle mode as shown in Fig. 16. Also, a lower switching frequency is needed in the same resonant cycle mode along with increases in the input voltage.

In both operation modes, there are errors of duty ratio

Fig. 13. The key waveforms of the CF-TIBCR at $200V_{dc}$ input voltage in the two-cycle mode of the buck operation

Fig. 14. The key waveforms of the CF-TIBCR at $250V_{dc}$ input voltage in the two-cycle mode of the buck operation

between the calculated value using (13) and the used value in the experiment. The main reason is parasitic impedance on the current path, which decreases the slope and peak value of the switch current. It cannot enable the switch voltage to be equal to zero at the end of the resonance.

When the resonant mode is transferred, the operation switching frequency is varied by change of n_r according to (11) or (12). Also d_{SB} is changed depending on the output voltage. For example, if the output voltage reference exceeds $250V_{dc}$ in the boost operation, the operating frequency is decreased to almost half value of the switching frequency in one-cycle mode by the voltage controller. The duty ratio of the LV stage switches is also changed according to the switching frequency. Fig. 17 shows the experimental results when the resonant mode is changed. During the transient time, the output voltage is not exactly same as its reference value. In this case, the LV stage switches achieve the ZCS condition but it cannot satisfy the ZVS condition, because the duty ratio is not enough to secure the time for the resonance. Therefore, there are some distortions in the voltage of the switch and current flowing through the resonant inductor as shown in Fig. 18.

Fig. 19 shows the efficiency curves of the proposed CF-

Fig. 15. The key waveforms of the CF-TIBCR at $250V_{dc}$ input voltage in the one-cycle mode of the buck operation

Fig. 16. The key waveforms of the CF-TIBCR at $380V_{dc}$ input voltage in the one-cycle mode of the buck operation

Fig. 17. The waveforms of the resonant mode transfer

Fig. 18. The enlarged waveforms during the transient time

Fig. 19. The efficiency of the proposed converter

TIBCR according to V_H . The maximum efficiency is measured at 95.1% in the boost operation. In the buck operation, it is also measured at 92.2%. In the same resonant mode, the efficiency decreases with increasing V_H . This is because the slope of i_{SB} during T_{M1} and T_{M3} , which causes higher RMS value of switch current, becomes steep as V_H increases. In terms of the resonant mode, the efficiency in the one-cycle is higher than that of the two-cycle mode, because of the smaller $i_{SB,pk}$ and the higher switching frequency in the one-cycle mode. In the buck operation, the efficiency is commonly lower than that of the boost operation because of the longer T_{M1} . That is why the errors of $i_{SB,pk}$ between the calculated value and the experimental result are higher than that of the boost operation.

5. Conclusion

This paper proposes a current-fed bi-directional DC/DC converter using resonance and its design method to extend the voltage range. The proposed converter has a high input current rating and low current ripple because the LV stage current is divided into two inductors. In addition, the converter provides a high voltage transfer ratio with a low transformer turns ratio. Using the resonant components, the proposed converter solves the voltage spike problem, and achieves ZVS and ZCS conditions for the LV stage switches and ZVS condition for the HV stage switches. Soft-switching that varies the voltage is achieved through the control of the switching frequency and duty ratio. To extend the voltage range, the method of changing the number of the resonance is adopted. Also, the design method for the proposed converter is derived by considering the duty, peak current and $P_{ss,max}$ conditions. The experiments using the 300W laboratory prototype in both the operation modes reveal good performance, which verifies the proposed method.

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References

- [1] Fontes, G., Turpin, C., Astier, S. and Meynard, T.A., "Interactions Between Fuel Cells and Power Converters: Influence of Current Harmonics on a Fuel Cell Stack," *IEEE Trans. Power Electronics*, vol. 22, no. 2, pp. 670-678, Mar. 2007.
- [2] Blaabjerg, F., Zhe Chen and Kjaer, S.B., "Power electronics as efficient interface in dispersed power generation systems," *IEEE Trans. Power Electronics*, vol. 19, no. 5, pp. 1184-1194, Sept. 2004.
- [3] Araujo, S.V., Torrico-Bascope, R.P. and Torrico-Bascope, G.V., "Highly Efficient High Step-Up Converter for Fuel-Cell Power Processing Based on Three-State Commutation Cell," *IEEE Trans. Industrial Electronics*, vol. 57, no. 6, pp. 1987-1997, Jun. 2010.
- [4] Wolfs, P. J., Ledwich, G. F., and Kwong, K. C., "The application of the duality principle to nonplanar circuits," *IEEE Trans. Power Electronics*, vol. 8, no.

- 2, pp. 104-111, Apr. 1993.
- [5] Wolfs, P. J., "A current-sourced DC-DC converter derived via the duality principle from the half-bridge converter," *IEEE Trans. Industrial Electronics*, vol. 40, no. 1, pp. 139-144, Feb. 1993.
- [6] Sang-Kyoo Han, Hyun-Ki Yoon, Gun-Woo Moon, and Myung-Joong Youn, Yoon-Ho Kim and Kang-Hee Lee, "A new active clamping zero-voltage switching PWM current-fed half-bridge converter," *IEEE Trans. Power Electronics*, vol. 20, no. 6, pp. 1271-1279, Nov. 2005.
- [7] S. J. Jang, , Chung-Yuen Won, Byoung-kuk Lee and Jin Hur, "Fuel Cell Generation System With a New Active Clamping Current-Fed Half-Bridge Converter," *IEEE Trans. Energy Conversion*, vol. 22, no. 2, pp. 332-340, Jun. 2007.
- [8] Quan Li; Wolfs, P., "A Current Fed Two-Inductor Boost Converter With an Integrated Magnetic Structure and Passive Lossless Snubbers for Photovoltaic Module Integrated Converter Applications," *IEEE Trans. Power Electronics*, vol. 22, no. 1, pp. 309-321, Jan. 2007.
- [9] Ren-Yi Chen, Tsorng-Juu Liang, Jiann-Fuh Chen, Ray-Lee Lin and Kuo-Ching Tseng, "Study and Implementation of a Current-Fed Full-Bridge Boost DC-DC Converter With Zero-Current Switching for High-Voltage Applications," *IEEE Trans. Industry Applications*, vol. 44, no. 4, pp. 1218-1226, July-Aug. 2008.
- [10] Bo Yuan, Xu Yang, Xiangjun Zeng, J. Duan, J. Zhai and Donghao Li, "Analysis and design of a high step-up current-fed multiresonant DC-DC converter with low circulating energy and zero-current switching for all active switches," *IEEE Trans. Industrial Electronics*, vol. 59, no. 2, pp. 964-978, Feb. 2012.
- [11] Bo Yuan, Xu Yang, Donghao Li, Yunqing Pei, Duan, J., Zhai, J., "A Current-Fed Multiresonant Converter with Low Circulating Energy and Zero-Current Switching for High Step-Up Power Conversion," *IEEE Trans. Power Electronics*, vol. 26, no. 6, pp. 1613-1619, Jun. 2011.
- [12] Prasanna, P.R.; Rathore, A.K., "Analysis, Design, and Experimental Results of a Novel Soft-Switching Snubberless Current-Fed Half-Bridge Front-End Converter-Based PV Inverter," *IEEE Trans. Power Electronics*, vol. 28, no. 7, pp. 3219-3230, July 2013.
- [13] Pan Xuewei, A. K. Rathore and U. R. Prasanna, "Novel soft-switching snubberless naturally clamped current-fed full-bridge front-end-converter-based bidirectional inverter for renewables, microgrid, and UPS applications," *IEEE Trans. Industry Applications*, vol. 50, no. 6, pp. 4132-4141, Nov.-Dec. 2014.
- [14] Pan Xuewei and A. K. Rathore, "Novel bidirectional snubberless naturally commutated soft-switching current-fed full-bridge isolated DC/DC converter for fuel cell vehicles," *IEEE Trans. Industrial Electronics*, vol. 61, no. 5, pp. 2307-2315, May. 2014.
- [15] Pan Xuewei and A.K. Rathore, "Novel interleaved bidirectional snubberless soft-switching current-fed full-bridge voltage doubler for fuel-cell vehicles," *IEEE Trans. Power Electronics*, vol. 28, no. 12, pp. 5535-5546, Dec. 2013.
- [16] A.K. Rathore and U.R. Prasanna, "Analysis, design, and experimental results of novel snubberless bidirectional naturally clamped ZCS / ZVS current-fed half-bridge DC/DC converter for fuel cell vehicles," *IEEE Trans. Industrial Electronics*, vol. 60, no. 10, pp. 4482-4491, Oct. 2013.
- [17] S.W Lee, S.R Lee and C.H Jeon, "A New High Efficient Bi-directional DC/DC Converter in the Dual Voltage System," *Journal of Electrical Engineering & Technology*, vol. 1, no. 3, pp. 343-350, Sep. 2006.
- [18] Hua Bai and Mi, C., "Eliminate Reactive Power and Increase System Efficiency of Isolated Bidirectional Dual-Active-Bridge DC-DC Converters Using Novel Dual-Phase-Shift Control," *IEEE Trans. Power Electronics*, vol. 23, no. 6, pp. 2905-2914, Nov. 2008.
- [19] Biao Zhao, Qiang Song and Wenhua Liu, "Power Characterization of Isolated Bidirectional Dual-Active-Bridge DC-DC Converter With Dual-Phase-Shift Control," *IEEE Trans. Power Electronics*, vol. 27, no. 9, pp. 4172-4176, Sept. 2012.
- [20] Jiarong Kan, Shaojun Xie, Yu Tang and Yunya Wu, a "Voltage-Fed Dual Active Bridge Bidirectional DC/DC Converter With an Immittance Network," *IEEE Trans. Power Electronics*, vol. 29, no. 7, pp. 3582-3590, July 2014.
- [21] Radika. P, "A High Efficiency DC-DC Boost Converter with Passive Regenerative Snubber," *Journal of Electrical Engineering & Technology*, vol. 9, no. 2, pp. 501-507, Mar. 2014.

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