A Novel Half-Bridge Asymmetrical ZCS-PWM DC–DC Converter with High Frequency-Link

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Keywords: half-bridge DC–DC converter, HF inverter, current doubler rectifier, ZCS-PWM, active edge resonant snubber, asymmetrical duty cycle, constant switching frequency, series transformer resonance

A novel high-frequency transformer-linked soft switching DCDC converter is proposed in this study.

Figure 1 shows the circuit configuration of the DC-DC converter proposed here. And, ideal operation waveforms of the DC-DC converter are illustrated in Fig. 2.

In the high-voltage primary-side inverter, an active snubber composed by an auxiliary switch Q3, a resonant capacitor C_r , and Zero Current Switching (ZCS) inductive snubber L_r , is added into the high main switch Q1. By using the edge resonance due to the active snubber, soft switching operation can be achieved in Q1 and Q3 by ZCS mode. Since the zero current transitions can be attained with less sensitivity to the current level through the power devices, the soft switching operations are achieved for the wide range of output power. On the other hand, the low side main switch Q2 can operate in ZCS mode with the aide of L_{r2} and the transformer parasitic parameter series resonance.

The converter operation and characteristics are analyzed by computer simulation. Moreover, the soft switching operation are verified by experiments using its prototype system. The measured waveforms of the active snubber are shown in Fig. 3. As shown here, ZCS turn-on and ZVZCS turn-off commutation are verified by the experimental results. The design guideline for the active snubber and related resonant circuit parameter with the gate signal generation sequence are also indicated in details.

Fig. 1. Asymmetrical active snubber-assisted ZCS-PWM DCDC converter.

Fig. 2. Ideal operation-waveforms of proposed DC-DC converter.

Fig. 3. Measured waveforms of active switches and resonant capacitor.

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A novel zero current soft-switching (ZCS)-PWM cell-assisted half-bridge DC–DC converter topology with a high frequency link is proposed in this paper. The newly-proposed DC–DC converter consists of a PWM-controlled single-ended half-bridge high frequency (HF) inverter and a current doubler rectifier linked with a HF transformer. In order to attain the wide range of ZCS-PWM operation in the primary-side HF inverter, an active edge resonant snubber cell composed by a switched capacitor and a lossless inductor is adopted in the half-bridge leg, providing ZCS commutation for a wide range of output power. The operation characteristics of the DC–DC converter proposed here are described, and its feasibility data is demonstrated and evaluated with simulation and experimental results.

Keywords: half-bridge DC–DC converter, HF inverter, current doubler rectifier, ZCS-PWM, active edge resonant snubber, asymmetrical duty cycle, constant switching frequency, series transformer resonance

1. Introduction

The latest developments of high frequency isolated DC–DC converters specified for low voltage/large current output applications have been one of key issues for establishing automotive power systems as well as telecommunication and information equipments and energy storage devices-interfaced power conditioner⁽¹⁾. In particular, most of PWM DC–DC converters with current doubler rectifier have begun to be one of the most promising circuit topologies suitable for this type of power conversion in terms of a high power density, low-profile, and its easy-to-implement control scheme⁽²⁾.

As the soft-switching scheme for those types of DC–DC converters, Zero Voltage Soft-Switching (ZVS) has been adopted owing to the less additional passive components. However, the ZVS commutation based on the edge-resonance with lossless capacitors in parallel with the switching power devices is significantly dependent on the current level through power devices. This property causes severe limitation of the soft switching operation under light load condition⁽³⁾. On top of that, IGBT with MOS-gate controlled bipolar mode characteristics are generally not suitable

for the ZVS scheme because of the tail current transition at its turn-off commutation. As a solution for the soft switching limitations mentioned above, ZCS is more effective for IGBT-based DC–DC converters.

In this paper, the newly-proposed lossless Active Edge-Resonant Snubber (AERS)-assisted ZCS scheme that attains more stable ZCS operation using PWM is to be presented. By adopting the ZCS snubber in the half-bridge HF inverter of the DC–DC converter, soft switching commutation at a main and an auxiliary IGBT switch of the half-bridge leg can be realized by the asymmetrical duty cycle control. In addition, ZCS operation can be performed in the other main IGBT switch by the series transformer resonance. As a result, ZCS can be achieved in a wide range of load variation under a constant frequency PWM control strategy in this DC–DC converter.

In the first place of this paper, the circuit configuration, operation principle and analysis of the proposed DC–DC converter topology are described. In the next place, the ZCS operation of this DC–DC converter is verified with simulation and experimental results, and finally the operating performances of the DC–DC converter are evaluated from an experimental point of view.

2. Circuit Description

Figure 1 shows the proposed DC–DC converter configuration. Here, E_d represents the input supply DC voltage. This circuit topology derives from the single ended push-pull inverter developed by Miura et al⁽⁴⁾⁽⁵⁾. This DC–DC converter topology can be expressed by another circuit configuration as illustrated in Fig. 2 with the similar operation mechanism.

Besides the main switch $Q_1(S_1/D_1)$, the high side part of

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Fig. 1. Proposed AERS-assisted ZCS-PWM half-bridge DC-DC converter with current doubler rectifier.

Fig. 2. Alternative circuit configuration of proposed DC-DC converter.

the half-bridge leg is comprised of the ZCS-assisted inductor L_{r1} , the resonant lossless capacitor C_r actively switched by the auxiliary switch $Q_3(S_3/D_3)$, and all of them operate as an active snubber for Q_1 . In the low side part of the leg, the other ZCS-assisted inductor L_{r2} is inserted in series with the other main switch $Q_2(S_2/D_2)$. Moreover, the resonant and power factor-correcting capacitor C_s , which can cut the DC component of the HF inverter current, is inserted in series with L_s that includes the equivalent leakage inductance L_k of the HF transformer. By utilizing the transformer-parasitic parameters(L_k, L_m)-based series resonance with L_s and C_s , ZCS operation can be performed in Q_2 as well. Since the ZCS turn-on commutation in Q_2 is essentially assisted by L_s , the inductive snubber L_{r2} in series with Q_2 can be small compared to L_{r1} .

The AERS-assisted ZCS-PWM DC-DC converter proposed here has some remarkable advantageous properties over the conventional Pulse Frequency Modulation (PFM) ZCS DC-DC converter:

- (i) constant high frequency switching PWM operation.
- (ii) wider zero current soft switching region.
- (iii) optimized parameters of high frequency transformer and output filter.
- (iv) current overlapping mode soft commutation between Q_1 and Q_2 by L_{r1} and L_{r2} , which contributes to reverse recovery-less commutation.

3. Operation Principle

3.1 Switching Mode Operation The key waveforms of the proposed DC-DC converter are depicted in Fig. 3. In addition, its switching mode transitions and equivalent circuits during switching one cycle are illustrated in Fig. 4 under condition of $L_m \gg L_s$.

Fig. 3. Voltage and current waveforms of ZCS-PWM DC-DC converter during switching one cycle with 45% duty cycle.

The operation circuit modes during the switching one-cycle, which are divided into the eleven steps, are explained below:

- Mode 1 [t_0-t_1], <high-side main switch turn-on mode>: While D_2 of Q_2 is now conducting after turn-off commutation of D_2 , S_1 of Q_1 is turned on. Then, the switch current i_{Q1} softly increases with the aid of L_{r1} , hereby the ZCS mode turn-on of S_1 can be achieved.
- Mode 2 [t_1-t_2], <active snubber resonant mode>: Edge-resonance due to L_{r1} and C_r begins after D_2 is cut off at the time t_1 , and then D_3 of the auxiliary switch Q_3 delivers the resonant current circulating in the AERS cell. Consequently, the resonant capacitor voltage v_{cr} begins to be charged reversely.

i_{Q1} during the turn-on transition interval of Q_1 ($t_{0-2} \approx t_{1-2}$) is expressed by

$$i_{Q1}(t) = \frac{v_{cr}(t_1)}{Z_{q1}} \cdot \sin \omega_{o1}t + i_p(t), \dots \dots \dots (1)$$

where, $\omega_{o1} = 1/\sqrt{L_{r1}C_r}$, $Z_{q1} = \sqrt{L_{r1}/C_r}$, and $v_{cr}(t_1)$ represents the capacitor voltage across C_r at t_1 .

- Mode 3 [t_2-t_3], <steady-state power injection mode>: After D_3 is reversely-biased and cut-off at t_2 , the input power is supplied from E_d to the load R_o through S_1 .

The low-side output filter diode L_{o2} in the current doubler is forward-biased before the end of this mode in the case of large duty cycle.

- Mode 4 [t_3-t_4], <auxiliary switch turn-on mode>: Prior to the turn-off of S_1 , S_3 of the auxiliary switch Q_3 in the AERS cell is turned on. Then, the current i_{Q3} through Q_3 softly increases with edge-resonance due to L_{r1} and C_r , thereby soft commutation of Q_3 in a turn-on state can be performed by ZCS.

Fig. 4. Switching mode-transitions and equivalent circuits during switching one-cycle under condition of $L_m \gg L_s$.

i_{Q1} in this mode is expressed as below:

$$i_{Q1}(t) = \frac{v_{cr}(t_3)}{Z_{q1}} \cdot \sin \omega_{o1}(t - t_3) - i_p(t), \dots \dots (2)$$

$$i_{Q1}(t_3) \approx I_{pp}, \dots \dots \dots (3)$$

where $v_{cr}(t_3)$ and I_{pp} represent the capacitor voltage across C_r at t_3 and the peak value of the transformer primary current i_p in this mode, respectively.

- Mode 5 [t_4-t_5], <high-side main switch turn-off mode>: Commutation of i_{Q1} from S_1 to D_1 naturally completes owing to the resonance continuing from the previous operation mode. During this interval, S_1 is turned off, thereby Zero Current and Zero Voltage Switching (ZCZVS) mode turn-off operation can be completely achieved in Q_1 .

i_{Q1} in this mode is also given by Eq. (2).

- Mode 6 [t_5-t_6], <series transformer resonant mode>: While the input power is transferred through S_3 , i_{Q3} decreases gradually in accordance with resonance due to

C_r , C_s and L_s . i_{Q3} during this interval is written by

$$i_{Q3}(t) = \frac{E_d}{Z_{q3}} \cdot \sin \omega_{o3}(t - t_5), \dots \dots \dots (4)$$

$$\omega_{o3} = \frac{1}{\sqrt{L_s \cdot \frac{C_r C_s}{C_r + C_s}}},$$

$$Z_{q3} = \sqrt{\frac{L_s(C_r + C_s)}{C_r C_s}},$$

$$i_{Q3}(t_5) = i_p(t_5) = \frac{v_{cr}(t_3)}{Z_{q1}} \sin \omega_{o1}(t_5 - t_3), \dots \dots \dots (5)$$

- Mode 7 [t_6-t_7], <auxiliary switch turn-off mode>: Commutation of i_{Q3} from S_3 to D_3 can attain owing to the series resonance continuing from the pervious mode. The gate signal to S_3 is removed during this interval, then ZCZVS mode turn-off commutation can be achieved in Q_3 . The transformer secondary current reverses its direction, consequently the rectifier diode D_{o1} in the current doubler is reversely biased and cut off before the end of this mode.
- Mode 8 [t_7-t_8], <low-side main switch turn-on mode>: While D_3 is conducting, S_2 of Q_2 is turned on at t_7 . Then, the current i_{Q2} through Q_2 softly increases with the aid of L_s and L_{r2} , thereby ZCS mode turn-on commutation can be achieved in Q_2 . In this mode, the current commutation from Q_3 to Q_2 completes.
- Mode 9 [t_8-t_9], <inverter current circulating mode>: The transformer primary current i_p freewheels in the closed circuit including S_2 and the transformer primary winding while the input power is supplied to the load through the current doubler rectifier. At the same time, series resonance due to C_s , L_{r2} and L_s with the transformer parasitic parameters generates.

In this mode, the current i_{Q2} through Q_2 is written by

$$i_{Q2}(t) = \frac{v_{cs}(t_8)}{Z_{q2a}} \cdot \sin \omega_{o2}(t - t_8), \dots \dots \dots (6)$$

$$\omega_{o2} = \frac{1}{\sqrt{(L_s + L_{r2} + N_T^2 L_{o1}) C_s}},$$

$$Z_{q2a} = \sqrt{\frac{L_s + L_{r2} + N_T^2 L_{o1}}{C_s}},$$

$$i_{Q2}(t_8) \approx 0, \dots \dots \dots (7)$$

where $v_{cs}(t_8)$ is the voltage across C_s at t_8 .

- Mode 10 [t_9-t_{10}], <secondary side commutation mode>: The transformer primary current i_p decreases gradually with the series resonance sustaining from the previous mode. As a result, D_{o1} begins to be forward biased, so that the secondary winding of the HF transformer is shorted. In this mode, i_{Q2} is given by

$$i_{Q2}(t) = \frac{v_{cs}(t_9)}{Z_{q2b}} \cdot \sin \omega_{o2}'(t - t_9), \dots\dots\dots (8)$$

$$\omega_{o2}' = \frac{1}{\sqrt{(L_s + L_{r2})C_s}},$$

$$Z_{q2b} = \sqrt{\frac{L_s + L_{r2}}{C_s}},$$

where $v_{cs}(t_9)$ is the capacitor voltage of C_s at t_9 .

- Mode 11 [t_{10} - t_{11}], <low-side main switch turn-off mode>: Commutation of i_{Q2} from S_2 to D_2 naturally completes. The gate signal to S_2 is removed during this interval, thereby ZCZVS mode turn-off commutation can be achieved in Q_2 . i_{Q2} during this mode is also given by Eq. (8).

The transformer secondary current reverses its direction, and the rectifier diode D_{o2} is reversely biased and cut off. At t_{11} , S_1 is turned on by ZCS as at t_0 , then this converter operation returns to Mode 1. Note that soft commutation between Q_1 and Q_2 can be performed by the devices-current overlapping mode due to L_{r1} and L_{r2} .

3.2 Gate Pulse Pattern for Asymmetrical PWM Duty Cycle The gate pulse timing sequences for all the switches and the schematic diagram of the gate pulses generator are illustrated in Figs. 5(a) and (b), respectively⁽⁶⁾. Here, duty cycle D which is defined in Eq. (9), is adjusted for output voltage or power regulation:

$$D = \frac{T_{on}}{T_s}, \dots\dots\dots (9)$$

where T_{on} corresponds to the combined on-period of Q_1 and Q_3 , and T_s represents the switching one-period.

In order to achieve the ZCS operation properly, the controllable range of the asymmetrical duty cycle D is determined by

$$\frac{\pi \sqrt{L_{r1}C_r}}{T_s} < D < D_{max}, \dots\dots\dots (10)$$

where D_{max} denotes the maximum duty cycle, and it is smaller than 0.5.

The on-period T_{on3} of S_3 can be fixed in a constant value. In T_{on3} , the overlapped on-period T_a of S_1 and S_3 can be estimated from the resonance period during Mode 4 and Mode 5 as follows:

$$T_a \approx \frac{\pi \sqrt{L_{r1}C_r}}{2}, \dots\dots\dots (11)$$

Furthermore, the remaining time interval T_b , utilized for the ZCZVS turn-off commutation of S_3 , can be specified by

$$T_b \approx \pi \sqrt{L_s \cdot \frac{C_r C_s}{C_r + C_s}}, \dots\dots\dots (12)$$

4. Design Method of Circuit Parameters

In the first step, the switching frequency f_s ($= 1/T_s$) is

(a) Gate pulse timing sequences based on asymmetrical PWM scheme

(b) Schematic diagram of gate pulse generator

Fig. 5. Asymmetrical PWM duty cycle control scheme for Proposed DC-DC converter.

decided from the series resonant frequency f_r of the conventional ZCS DC-DC converter topology without the AERS cell and inductive snubbers (L_{r1} and L_{r2}), under the condition of $f_s < f_r$.

4.1 Design Consideration for AERS The inductance of the ZCS-assisted inductor L_{r1} can be determined with the series inductor L_s from di_p/dt rate in Mode 3 as defined below:

$$\frac{di_p}{dt} \approx \frac{I_{pp}}{DT_s} = \frac{v_L}{L_{r1} + L_s}, \dots\dots\dots (13)$$

where v_L represents the voltage drop across L_{r1} and L_s , and this voltage can be determined from the ratio to the input supply voltage E_d . The other ZCS-assisted inductor L_{r2} can be small compared to L_{r1} because ZCS turn-on commutation in Q_1 is assisted by L_s as well.

The characteristics of the resonant peak current based on C_r are illustrated in Fig. 6. As can be seen in those curves, when C_r is less than the optimized value C_{ro} the turn-off commutation of the main switch Q_1 is in a hard switching mode. Meanwhile, the resonant peak current becomes excessive when C_r is much larger than C_{ro} . In this case, the conduction losses due to the edge resonance increases.

In order to ensure the ZCZVS mode turn-off commutation of the main switch Q_1 in the AERS cell, the peak value of the edge-resonant current through Q_1 during its turn-on commutation should be larger than the transformer primary current

Fig. 6. Characteristics of resonant peak current through main switch vs. capacitance of lossless snubbing capacitor.

prior to its turn-off commutation. From Fig. 3 and Eqs. (1)–(3), this condition can be expressed by

$$\frac{v_{cr}(t_3)}{Z_{q1}} > i_p(t_3) \approx I_{pp} \dots \dots \dots (14)$$

Then, the resonant characteristics impedance Z_{q1} of the AERS cell is designed by

$$Z_{q1} = \sqrt{\frac{L_{r1}}{C_r}} < \frac{v_{cr}(t_3)}{I_{pp}} \dots \dots \dots (15)$$

where I_{pp} is simply obtained from the HF transformer current at $D = D_{max}$. Accordingly, C_r can be determined by

$$C_r > \frac{L_{r1} I_{pp}^2}{v_{cr}(t_3)^2} \dots \dots \dots (16)$$

The resonant capacitor voltage $v_{cr}(t_3)$ is smaller than input voltage E_d due to the existence of the capacitor voltage across C_s . In addition, circulating current within the AERS cell increases while the HF transformer current decreases. Therefore, $v_{cr}(t_3)$ increases in accordance with reduction of the duty cycle. Thus, the required capacitance of the resonant snubbing capacitor C_r can be determined in Eq. (16) by setting the minimum voltage of $v_{cr} < E_d$.

4.2 Design Consideration for Output Filter Inductors

For attaining a high power density in the DC–DC converter treated here, the current doubler rectifier should be designed to operate by continuous conduction mode (CCM) in a large duty cycle region. Accordingly, once the current ripple in the output filter inductor is decided, the inductances of L_{o1} and L_{o2} can be temporarily designed.

In addition to this, there should be a special consideration to the upper side inductor L_{o1} for the ZCZVS turn-off commutation on Q_2 . Figs. 7(a) and (b) illustrate the simplified equivalent circuits for Mode 9 and Mode 10 prior to the ZCZVS turn-off in Q_2 ⁽⁷⁾. Note that the leakage inductance of the transformer secondary winding is referred to the primary side of the HF transformer and included in L_s .

In order to ensure the ZCZVS turn-off in Q_2 , the corresponding term t_{8-10} defined below should be included in the on-period $T_{on2} (\approx (1 - D)T_s)$ of Q_2 :

Fig. 7. Simplified equivalent circuits of proposed DC–DC converter for Mode 9 and 10: (a) Mode 9 ($V_{o'} = DE_d$), (b) Mode 10.

Table 1. Circuit parameters of simulation DC–DC converter model.

Parameter & symbol	value & unit
Power rating P_o	1.7 kw
Switching frequency f_s	50 kHz
Input supply DC voltage E_d	300 V
Output voltage V_o	42 V
Rated output current I_o	40 A
Transformer turn ratio $N_T (= N_p/N_s)$	2/1
Transformer magnetizing inductance L_m	2 mH
Series inductance with leakage inductance L_s	7.0 μ H
ZCS-assisted lossless inductors L_{r1}/L_{r2}	2.0 μ H/1.2 μ H
Series resonant capacitor C_s	250 nF
Snubbing resonant capacitor C_r	70 nF
Output filter inductors L_{o1}, L_{o2}	15 μ H
Output filter capacitor C_o	100 μ F

$$t_{8-10} = \pi \left(\sqrt{(L_{r2} + L_s + N_T^2 L_{o1}) \cdot C_s} / 2 + \sqrt{(L_{r2} + L_s) \cdot C_s} \right) < (1 - D)T_s \dots \dots \dots (17)$$

As a result, the inductance of L_{o1} can be specified in more detail by Eq. (17). In this current doubler rectifier, L_{o1} and L_{o2} are set to the same value for simplifying the design procedure.

5. Simulation Analysis and Evaluations

5.1 Circuit Parameter Design Procedure The converter operation is analyzed with the computer-aided simulation. The circuit parameters of the simulation DC–DC converter model are indicated in Table 1. In this table, the circuit parameters are designed as follow:

- (i) <Switching frequency and duty cycle control range>: Switching frequency f_s is designed for 50 kHz, and the controlled range of the asymmetrical duty cycle is set between 0.25 to 0.45.
- (ii) <Circuit parameters in AERS>: By setting di_p/dt to 1 A/ μ s, the ZCS-assisted inductor L_{r1} is determined to 2.0 μ H from Eq. (13) with an example of practical leakage inductance in a HF transformer. Then, the snubbing capacitor C_r is designed for 70 nF based on Eq. (16) with $v_{cr} = 100$ V, $I_{pp} = 15$ A.
- (iii) <Period from Mode 8 to Mode 10, and output filter inductor>: The on-period of Q_2 is determined from $(1 - D)T_s = 11 \mu$ s, where D is specified to 0.45. Then, L_{o1} can be set to 15 μ H from t_{8-10} which meets Eq. (17). This inductance of L_{o1} can also meet the current ripple rate di_{Lo}/dt set by 3 A/ μ s.

(a) $D = 0.45$ (b) $D = 0.25$

Fig. 8. Simulation waveforms of AERS-assisted ZCS-PWM DC–DC converter: (from top to bottom) i_{Q1} & v_{Q1} , i_{Q2} & v_{Q2} , i_{Q3} & v_{Q3} , i_p & v_x , and DC output current I_o .

In this simulation, the input and output DC voltages are set in 300 V and 42 V respectively by considering that the DC–DC converter proposed here can be applied to POL (Point of Load) converter in an electric power train architecture of the promising hybrid vehicles.⁽¹⁾

5.2 ZCS Operation Characteristics The simulated voltage and current waveforms of the proposed DC–DC converter are shown in Fig. 8. This simulation analysis was carried out by two duty cycles $D = 0.45$ and 0.25 under an open loop control strategy. For each duty cycle setting, ZCS in turn-on and ZCZVS in turn-off commutation can be observed in all the main and auxiliary switches.

The output voltage and power characteristics on the duty cycle under the open loop control strategy are provided in Fig. 9. For this simulated converter model, the complete ZCS commutation can be ensured in Q_1 – Q_3 from the full load ($R_o = 1.0\Omega$) to 50% ($R_o = 2.0\Omega$) load. In the region lower than 50% load, the turn-off commutation of Q_2 becomes a hard switching mode while the complete ZCS operations of Q_1 and Q_3 are still achievable by the AERS cell.

The ZCS operating ranges and characteristics of the DC–DC converter with closed loop control schemes (constant voltage/constant current conditions) are shown in Figs. 10 and 11.

Furthermore, the characteristic curves described in Figs. 9 to 11 indicate that the AERS-assisted ZCS scheme and its circuit topology are effective and the DC–DC converter can operate stably under wide load variation by the asymmetrical PWM duty cycle control processing.

For the input supply voltage variation, it is also confirmed

(a) P_o vs. D with parameter R_o (b) V_o vs. D with parameter R_o

Fig. 9. Open loop control characteristics in steady state.

that the ZCS commutations can always be performed in all the switches when Eq. (14) can be met.

6. Experimental Verification

The ZCS commutation and operating characteristics of the proposed circuit are investigated in experiments with its prototype. The prototype design specifications and the experimental set-up are indicated in Table 2.

The switching frequency is decided from the series resonant-frequency of the DC–DC converter prototype, and the other specifications such as the HF transformer maximum frequency, in this case 60 kHz. In this experiment, the DC input supply voltage E_d is set to 200 V because of performance limitation of the DC power supply. Moreover, the gate pulse signals are generated using a FPGA board by an open-loop control scheme.

The steady-state operating waveforms of the AERS cell with the low-side main switch under the duty cycle $D = 0.45$ are shown in Fig. 12. From the observed waveforms, the ZCS commutation between the main and auxiliary switches can be confirmed as well as the ZCS-PWM assisted snubber operation of the switched capacitor. The series-resonant frequency depends on the values of the output filter inductors L_{o1} , L_{o2} in the current doubler rectifier, so the conduction period of the anti-parallel diode D_2 in Q_2 also changes with the output filter inductance.

Switching voltage and current waveforms of Q_1 – Q_3 under the duty cycle $D = 0.45$ are shown in Figs. 13–15, respectively. The ZCS turn-on and the ZCZVS turn-off commutation of each switch are observed in each switching waveform. Thus, the feasibility of the proposed DC–DC converter topology and the soft switching scheme are verified in principle.

Fig. 10. Constant output-voltage closed loop control characteristics in steady state: $V_o = 42$ V.

Fig. 11. Constant output-current closed loop control characteristics in steady state: $I_o = 40$ A.

The measured actual converter efficiency attains 96% in the ZCS-PWM HF inverter with the AERS cell ⁽⁴⁾⁽⁵⁾. Thereby, an actual efficiency of the ZCS-PWM DC-DC converter proposed here can be estimated at 92%–93% with the load current $I_o = 40$ A and the voltage drop across secondary-side rectifier power devices $V_f = 0.6$ V.

7. Conclusions

The HF-link half-bridge soft switching DC-DC PWM converter with the switched capacitor and lossless inductor-based Active Edge Resonant Snubber AERS cell has been presented in this paper. The operation principle of the DC-DC converter was described and its basic performance was evaluated on the soft switching operation for a wide output power range with the asymmetrical PWM duty cycle control strategy.

In order to discuss the feasibility study of the proposed DC-DC converter, the simulated waveforms were demonstrated, and the essential switching operation of the DC-DC converter with the AERS cell has been verified using its prototype. From the simulation and experimental results, it has been clarified that the proposed DC-DC converter is suitable for large voltage step-down POL DC-DC converters with soft switching commutations under a wide load variation.

Besides the automotive-related application as mentioned in this paper, this soft switching PWM DC-DC converter will be able to be applied widely into electric power trains such as intermediate bus converters in information and telecommunication power supplies.

Table 2. Design specifications and circuit parameters of experimental prototype converter.

Parameter & symbol	value & unit
Power rating P_o	1.2 kw
Switching frequency f_s	35 kHz
Input supply DC voltage E_d	200 V
Output voltage V_o	30 V
Rated output current I_o	40 A
Transformer turn ratio $N_T (= N_p/N_s)$	5/2
Transformer magnetizing inductance L_m	2.0 mH
Series inductance with leakage inductance L_s	8.3 μ H
ZCS-assisted lossless inductors L_{r1}/L_{r2}	4.5 μ H/4.0 μ H
Series resonant capacitor C_s	150 nF
Snubbing resonant capacitor C_r	50 nF
Output filter inductors L_{o1}, L_{o2}	20 μ H
Output filter capacitor C_o	100 μ F
Resistive load R_o	0.75 Ω

· $Q_1/Q_2, Q_3$: MITSUBISHI CM50DU-24H (two sets).

· D_{o1}, D_{o2} : SanRex FRS200BA60 (discrete).

Fig. 12. Steady-state operating waveforms of AERS-assisted ZCS-PWM DC-DC converter (i_{Q1} : 10 A/div, i_{Q2} : 10 A/div, i_{Q3} : 10 A/div, v_{cr} : 250 V/div, time: 4.0 μ s/div).

Fig. 13. Switching voltage and current waveforms in Q_1 ($v_{ce(Q1)}$: 250 V/div, i_{Q1} : 10 A/div, time: 4.0 μ s/div).

More detailed experimental evaluations on conversion efficiency, loss analysis and EMI level reduction of this ZCS-PWM DC-DC converter are to be discussed in the next research work.

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Fig. 14. Switching voltage and current waveforms in Q_2 ($v_{ce(Q2)}$: 250 V/div, i_{Q2} : 10 A/div, time: 4.0 μ s/div).

Fig. 15. Switching voltage and current waveforms in Q_3 ($v_{ce(Q3)}$: 100 V/div, i_{Q2} : 10 A/div, time: 2.0 μ s/div).

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