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A Novel Quasi-Resonant Snubber-Assisted ZCS-PWM DC-DC Converter with High Frequency Link

Khairy Fathy[*] and Soon-Kurl Kwon[†]

[†][*]Department of Electrical Engineering, Kyungnam University, Masan, Korea

ABSTRACT

In this paper, a novel type of auxiliary switched capacitor assisted edge resonant soft switching PWM resonant DC-DC converter with two simple auxiliary commutation lossless inductor snubbers is presented. The operation principle of this converter is described using the switching mode equivalent circuits. This newly developed multi resonant DC-DC converter can regulate its DC output AC power under a principle of constant frequency edge-resonant soft switching commutation by an asymmetrical PWM duty cycle control scheme. The high frequency power regulation and actual power characteristics of the proposed soft switching PWM resonant DC-DC converter are evaluated and discussed. The operating performances of the newly proposed soft switching inverter are represented based on simulation results from an applications point of view.

Keywords: DC-DC converter, series capacitor compensated transformer leakage inductance, auxiliary lossless snubbing inductor, switched capacitor, zero current soft switching, and auxiliary edge resonant snubber

1. Introduction

Advanced developments in a variety of soft switching PWM DC-DC power converter circuits with or without a high frequency transformer link for the purpose of improving their actual efficiency, minimizing power density in volumetric size and weight, and achieving higher performances as high quality waveforms with quicker responses have actively been introduced. In addition, the current ringing and voltage surge caused by parasitic circuit component and high di/dt and dv/dt dynamic stresses in the power semiconductor switches are more significant in accordance with high frequency switching pulse modulation. Some circuit topologies with soft switching pulse modulation controlled voltage source full bridge inverter type DC-DC converters with a high frequency transformer have been developed so far and evaluated for telecommunication DC feeding power plants, automotive power supplies and new energy-related power conditioners.

In this paper, a novel circuit topology of a voltage source soft-switching multi resonant ZCS DC-DC converter with constant frequency PWM control strategy using active auxiliary quasi-resonant lossless inductor snubbers and switched capacitor snubbers is newly proposed. Additional outstanding practical features are also presented. The operating principle of the proposed edge resonant snubber assisted DC-DC converter topology incorporating ZCS-PWM control scheme is illustrated and

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[†] Corresponding Author: soonkurl@kyungnam.ac.kr
Tel: +82-55-249-2633, Fax: +82-55-248-2228, Kyungnam Univ.
[*] Dept. of Electrical Eng., Kyungnam Univ.

evaluated on the basis of operation mode waveforms and equivalent circuits of each mode according to simulation results. The effectiveness of this high frequency ZCS DC-DC inverter using IGBTs is substantially proved. The voltage source type ZCS DC-DC converter and its modifications match the practical operating requirements mentioned previously. The proposed ZCS PWM scheme is able to regulate its output DC power under a constant frequency asymmetrical PWM control strategy and under soft-switching operation conditions.

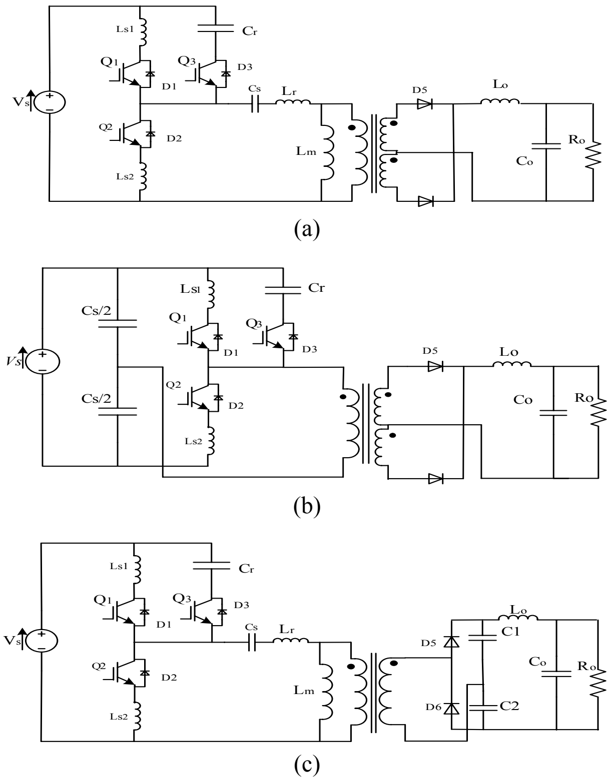
2. Proposed ZCS PWM DC-DC Converter with Active Edge Resonant Snubber

2.1 Circuit Configuration

Fig. 1 shows the newly developed multi-resonant ZCS-SEPP PWM DC-DC converter circuit using the latest trench gate IGBTs and operating with a constant frequency PWM control strategy. This voltage-fed ZCS PWM modified half bridge DC-DC converter circuit consists of the following: two main switches of reverse conducting IGBTs Q1(SW1/D1) and Q2(SW2/D2), a single auxiliary switch Q3(SW3/D3) in series with auxiliary edge-resonant switched capacitor Cr as an active snubber in parallel with Q1 and LS1, two ZCS-assisted lossless inductor snubbers LS1, LS1 connected in series with the main switches Q1 and Q2, power factor compensated series load resonant capacitor Cs, high frequency centre-tapped transformer and DC filter. The Lo- Co output filter is connected in parallel with the DC load that used to smooth out the DC output voltage. The proposed ZCS-PWM DC-DC converter is configured by a few circuit components and power semiconductor devices as three active control switches are used. Fig. 1(b) indicates a modified half-bridge ZCS-PWM DC-DC converter with high frequency link. Fig. 1(c) Single ended push-pull ZCS PWM DC-DC power converter with a voltage doubler rectifier.

2.2 Gate Pulse Timing Sequences

The high frequency AC rectified output power of the proposed DC-DC converter circuit, can be continuously regulated by a constant frequency asymmetrical PWM (duty cycle) control scheme under a condition of zero current soft switching commutation. The gate voltage pulse timing PWM sequences for the active switches Q_1, Q_2, and the auxiliary switch Q_3 are represented schematically in Fig. 2. The main active switch Q_1 is firstly switched on during the period of time T_{on1} and before the main switch Q_1 is turned off by a time of T_o. On the other hand, the auxiliary switch Q_3 is turned on for a period $T_{on3,}$ inserting an overlapping time of T_o between the switches Q_1 and Q_3. In other words, the operation of the auxiliary switch Q_3 is synchronized to the main switch Q_1. It is turned on just before the instant that the main switch Q_1 is due to be turned off. Then, the main switch Q_2 is turned on after turning off the auxiliary switch Q_3 with a dead time of $T_{d1.}$ The main switch Q_1 is again switched on after a dead time T_{d2} as another period starts, as depicted in Fig. 2.



(a)

(b)

(c)

Fig. 1 (a) Single ended push-pull ZCS PWM DC-DC power converter with high frequency link

(b) Half-bridge ZCS-PWM DC-DC converter with high frequency link

(c) Single ended push-pull ZCS PWM DC-DC power converter with voltage doubler rectifier

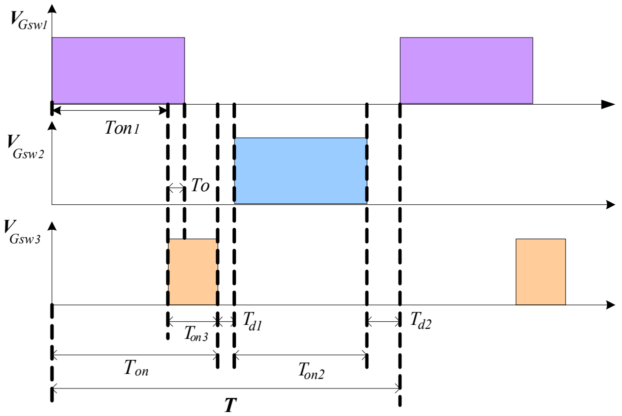


Fig. 2 Proposed PWM gate pulse timing sequences for main and auxiliary switches

2.3 Duty factor as Control Variables

By adjusting the constant frequency asymmetrical PWM control variable, the duty cycle, which is defined as the sum of the conduction time T_{on1} of the main active switch Q_1 and conduction time T_{on3} of the auxiliary switch Q_3 to the total switching period operating time T of the high frequency switching mode, of the proposed high frequency ZCS-PWM inverter can regulate its high frequency output power continuously under a condition of zero current soft switching. The conduction time T_{on1} of the main active switch Q_1 can be controlled while keeping the conduction time T_{on3} of the auxiliary switch Q_3, the overlapping time T_o and the dead time T_{d1} constants. As a control variable, the duty cycle D is defined as

$$D = T_{on} / T \tag{1}$$

$$T_{on} = T_{on1} + T_{on3} - T_o \tag{2}$$

The proposed ZCS PWM DC-DC converter with two lossless inductor snubbers for ZCS assistance and a single switched capacitor can not only be controlled by the constant frequency asymmetrical PWM technique for high power settings, but can also be controlled by a constant high frequency pulse density modulation (PDM) technique at low power settings under ZCS condition. In addition, by using a dual mode hybrid control of the asymmetrical PWM and PDM at a constant high frequency, soft switching operating range can be effectively expanded from high power to low power settings.

3. Principle of Soft Switching Converter

At the beginning of each switching cycle, the high side main switch SW1 of Q_1 turns on, the resonant inductor Lr ensures ZCS by limiting the rate of the current rise.

After this time, the primary side energy is supplied to the load R in the secondary side circuit through the high frequency transformer HF-T. After the switch current i_{SW1} through SW_1 of Q_1 naturally commutates to the anti-parallel diode D_1 of Q_1 by quasi-resonance due to ZCS-assisted high side inductor snubber L_{S1}, in series with the switch Q_1, together with the auxiliary series leakage inductance primary side of the HF-T tuned capacitor C_s, the auxiliary switch SW_3 of Q_3 is turned on and the main switch SW_1 of Q_1 is turned off. As a result, a ZCS commutation at a turn-off switching mode transition can be achieved by a timing process in which the main switch SW1 of Q1 is arbitrarily turned off. In this mode, since an auxiliary resonant current i_{SW3} flows through the switch SW_3 of Q_3 and increases slowly, a ZCS commutation at a turn-on switching mode transition can be achieved for SW_3 of Q_3. After i_{SW3} is commutated to the anti-parallel diode D3 of Q3 by the resonance formed by Cr and Lr., leakage inductance of the transformer circuitry and series compensated capacitor Cs, a ZCS commutation at a turn-off switching mode transition can be performed by turning off SW3 of Q3. While the auxiliary switch SW_3 of Q_3 is conducting, the voltage v_{Q2} across the low side main switch SW_2 of Q_2 decreases towards zero. The low side main switch SW_2 of Q_2 is turned on as soon as the diode D_2 of Q_2 attains a reverse biasing state and begins to conduct naturally. While the diode D_2 continues conducting, the current flowing through D_2 of Q_2 is naturally commutated to SW_2 of Q_2. Therefore, a complete ZVS and ZCS (ZVZCS) hybrid commutation transition can be actually achieved for SW_2 of Q_2.

On the other hand, after the current i_{SW2} through the low side main switch SW_2 of Q_2 is naturally commutated to D_2 of Q_2 with the aid of a low side ZCS-assisted inductor snubber L_{S2}, and series tuned capacitor C_s, ZCS commutation at a turn-off switching mode transition can be performed by turning off the switch SW_2 of Q_2. While the diode D_2 of Q_2 is conducting, the D_2 is commutated by turning on the switch SW_1 of Q_1 when a second switching cycle starts. In this mode, a ZCS turn-on switching commutation can be realized with the aid of a ZCS-assisted inductor snubber L_{S1}. The proposed edge resonant snubber type ZCS PWM DC-DC converter offers a complete ZCS for all the main and auxiliary switches and achieves ZVZCS hybrid commutation at turn-on switching mode transition for the switch SW_2 of Q_2.

4. Operation Modes of Converter

The switching operation mode equivalent circuits of the proposed zero current soft switching DC-DC converter in steady state during one switching cycle are shown in Fig. 3. The current and voltage operating waveforms of each element and the relevant operating modes in steady state during one switching period are illustrated in Fig. 4.

For a duty cycle $D = 0.36$. This multi resonant high frequency soft switching DC-DC converter circuit includes eleven operating switching modes as shown in Fig. 3. The operation principle of the proposed zero current soft switching DC-DC converter circuit will be explained in the following by using the corresponding switching mode equivalent circuits, which are divided into twelve operational modes.

Mode 1 (t_o-t_1): A gating signal is applied to the main switch Q_1, while the quasi-resonant snubber capacitor starts to discharge through the snubber inductor and diode D_3 of Q_3 and the main switch Q1 is turned on. Then, the switch current I_{Q1} increases softly with a quasi resonance due to L_{r1} and C_{r1}, so the ZCS turn-on commutation of S1 is accomplished. At the same time, the primary current starts to increase supply to the load and as a result diode D5 conducts. The lossless snubber capacitor C_{r1} is charged reversely, and consequently the capacitor voltage reverses its polarity until the end of this mode.

The current of the main switch i_{Q1} during mode 1 and the turn-on transition of Q1, which corresponds with the discharged current of C_{r1}, are expressed as;

$$i_{Q1} = \sqrt{\frac{C_r}{L_{s1}}} \cdot V_{cr}^{0-} \sin \omega_o t + i_p \tag{3}$$

where i_p is the primary circuit current and V_{cr}^{0-} represents the initial voltage of Cr prior to the turn on of S1 and the resonant frequency $\omega_o = 1/\sqrt{C_r L_{s1}}$

Mode 2 (t_1-t_2): The high frequency transformer primary current I_p starts to rise at t_1, and the quasi resonance in the edge resonant snubber cell is terminated at t_1 when it matches with I_{Q1}. At the same time diode D3 commutates, the power is supplied now to the load through Q_1, C_s, HFT and diode D_5.

Mode 3 (t_2-t_3): As soon as the gating signal is applied (see Fig. 2) to Q3 the auxiliary switch S3 of the Q3 is turned on at t_2 and current flows through D1. A quasi-resonance due to L_{r1} and C_{r1} occurs which forces a negative current through the reverse conducting diode of the main switch (D1 of Q1) and I_{Q1} commutates while D_1 conducting. At this time, the gate drive signal of the main switch Q1 can be removed while the switch is under zero current conditions achieving Zero Voltage and Zero Current Switching (ZVZCS). Thus, turn-off commutation can be achieved for S_1.

As long as this diode conducts, the corresponding IGBT can be turned on with essentially zero voltage across it, thus performing a lossless switching.

At mode 3, the turn of the current of the main switch Q_1, is expressed by;

$$i_{Q1} = \sqrt{\frac{C_r}{L_{s1}}} \cdot V_{cr}^{0+} \sin \omega_o t - i_p \tag{4}$$

where V_{cr}^{0+} is the initial voltage of Cr prior to the turn -off of S1 and i_p is the primary circuit current.

Consequently, the current waveform of auxiliary switch Q_3 is defined by;

$$i_{Q3} = \sqrt{\frac{C_r}{L_{s1}}} \cdot V_{cr}^{0+} \sin \omega_o t + i_p \tag{5}$$

The overlap time T_o of the gating pulse period between the switch Q1 and auxiliary switch Q3, can be determined by;

$$T_o \approx \frac{\pi \sqrt{L_{s1} C_r}}{2} \tag{6}$$

The duty cycle as a control variable indicated by (1), (2) depends upon the value of T_o.

Mode 4 (t_3-t_4): Now the gating pulse is removed from Q_1 and the diode D_1 commutates. Current supplied to the load through the auxiliary switch Q_3 and diode D_6 in the secondary circuit starts conducting while current in D_5 decreases.

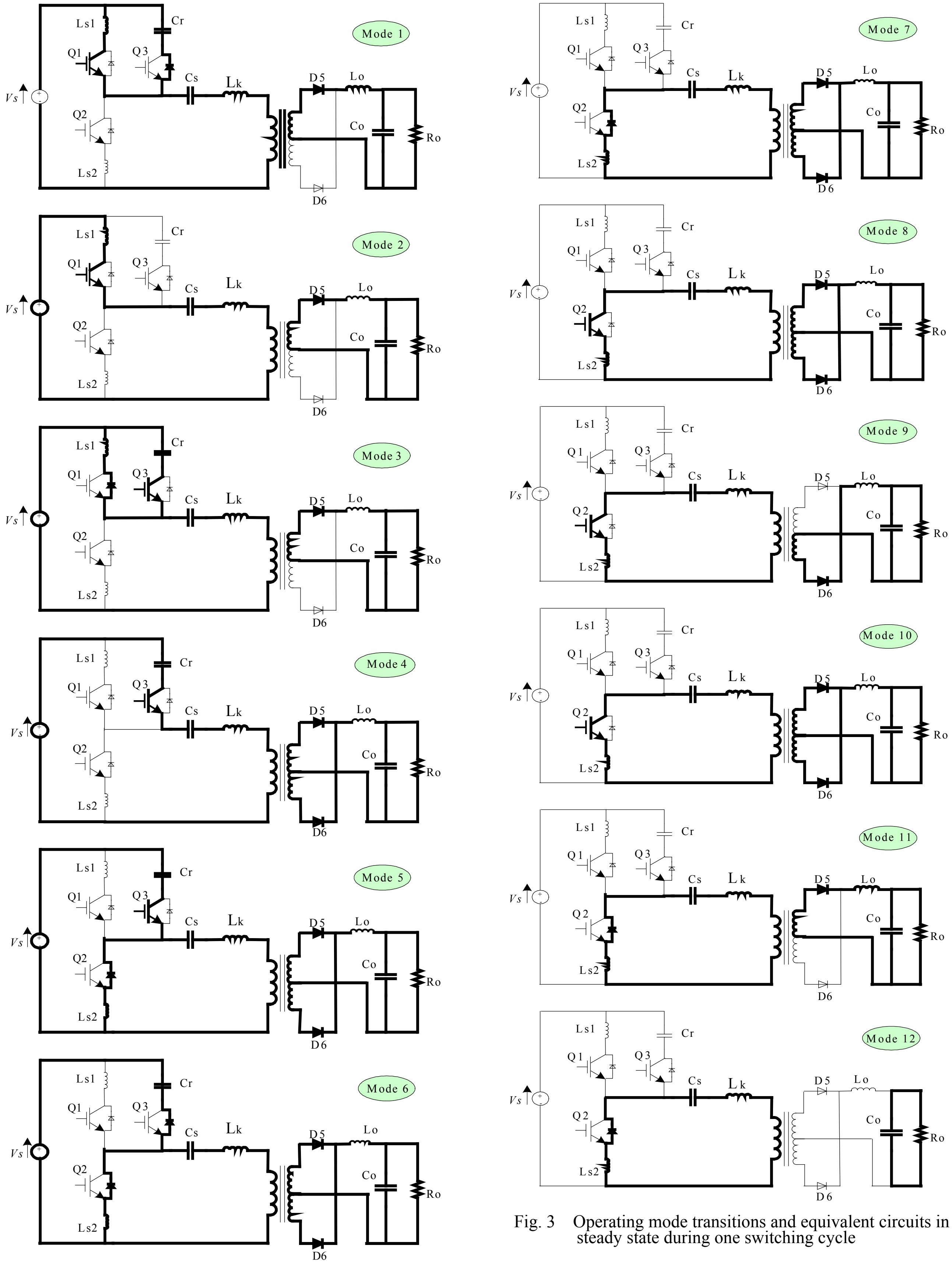


Fig. 3 Operating mode transitions and equivalent circuits in steady state during one switching cycle

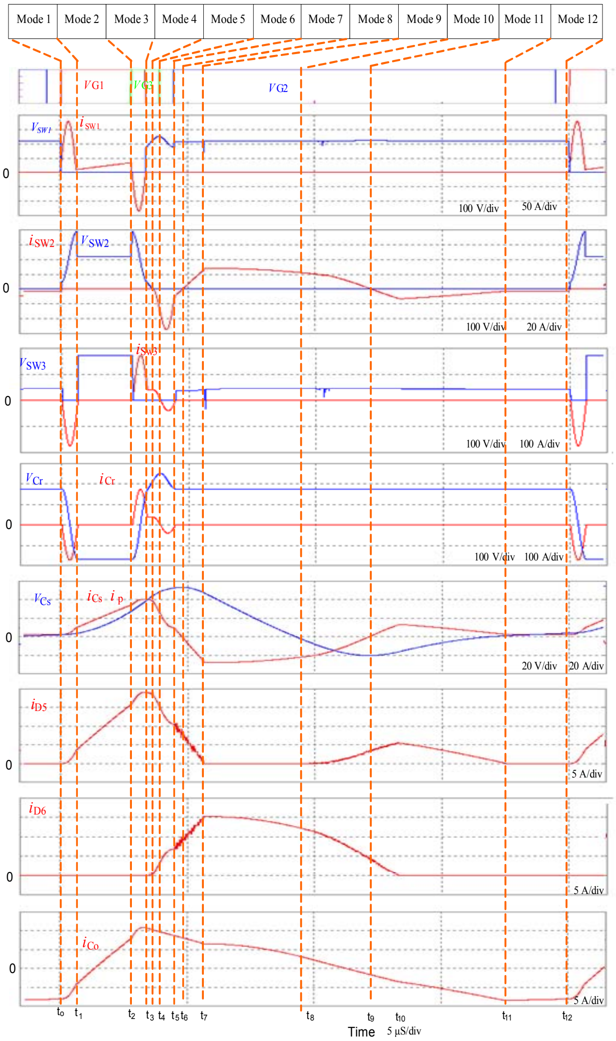


Fig. 4 Voltage and current operating waveforms during one switching cycle for a duty cycle D= 0.36

Mode 5 (t_4-t_5): Before switch Q_3 turns off, the diode D_2 of the main switch Q_2 starts to conduct to compensate for the difference between I_{Q3} and I_p (I_{Cs}), the stored energy in the primary circuit increases charge of capacitor C_s.

Mode 6 (t_5-t_6): The gating pulse signal is removed from auxiliary switch Q_3 and its reverse conducting diode D_3 conducts so that SW3 turns off at zero voltage zero current switching ZVZCS commutation.

Mode 7 (t_6-t_7): At t_6, reverse conducting diode D_3 commutates. Although the gating pulse is applied to Q_2 the diode D_2 continues conducting and the stored energy in the high frequency transformer leakage inductor and compensating capacitor is supplied to the load. The capacitor current I_{Cs} reaches zero value at t_7, while V_{Cs} reaches it maximum value.

Mode 8 (t_7-t_8): The switch SW_2 of Q_2 turns on at ZVZCS commutation. At t_7, the capacitor Cs starts discharging.

Mode 9 (t_8-t_9): SW2 of Q_2 is still conducting and D5 in the secondary circuit commutates at t_8.

Mode 10 (t_9-t_{10}): The capacitor voltage will be zero and starts to increase in the minus direction so that diode D5 will conduct.

Mode 11 (t_{10}-t_{11}): SW2 is turned off with ZVZCS at t_{10} and D2 starts conducting. As a result, the current through the primary circuit changes its direction charging the capacitor Cs.

Mode 12 (t_{11}-t_{12}): D5 commutates with no power transfer from the primary to secondary circuit and energy stored in the output filter capacitor C_o will supply the load. D2 still conducts and current circulating exists in the primary circuit. Thereafter, the aforementioned operating processes are periodically repeated in sequence during each switching cycle.

5. Simulation Analysis and Discussions

The prospective experimental setup assembly is implemented by using trench gate reverse conducting IGBTs with low saturation voltage to validate the steady state performance evaluations of the proposed zero current soft switching high frequency link DC-DC converter circuit. The design specifications and circuit parameters used in the simulation are indicated in Table 1. The circuit parameters of this high frequency ZCS-PWM DC-DC converter are determined by considering the operating condition of zero current soft switching commutation and the required output power ranges.

Although the proposed high frequency switching DC-DC converter operating under a principle of asymmetrical PWM control or duty cycle control can achieve a complete soft switching commutation operation in low and medium output power settings, it becomes a partially hard switching commutation operation in certain high power settings and its actual efficiency for this reason might be substantially reduced. The soft switching range is from D=0 to 43% for all switches. However, this high frequency DC-DC converter can still operate under a considerably wide soft switching operations, because the main switch Q1 and auxiliary switch Q3 are turned on and off at soft switching conditions in the whole power range. In the case of duty cycles D more than 0.43, switch Q2 turns on at ZCS, but turns off during hard switching. In the case of low and medium output power settings, a requirement of the duty cycle PWM control scheme, a soft switching operation is employed.

In addition, the zero current soft switching operating range of the proposed DC-DC converter can be actually extended by the use of new control scheme based on high frequency pulse density modulation (PDM) control strategy under low power settings or by the use of a dual mode implementation of the PWM control. The output voltage regulation characteristics versus the duty cycle is shown in Fig. 5

Table 1 Design specifications and circuit constants

Item	Symbol	Value
DC Source Voltage	V_s	220 V
Switching Frequency	f_{sw}	50 kHz
ZCS-assisted Inductor	L_{s1}, L_{s2}	0.2 μH
Snubber Capacitor	C_r	0.2 μF
Series tuned capacitor	C_s	2 μF
Output filter inductance	Lo	50 μH
Output filter capacitance	Co	5 μF
HF transformer turns Ratio	N_1:N_2:N_3	1:2:2
HFT magnetizing inductance	L_m	5mH
HFT primary leakage inductance	L_1	1 μH
HFT secondary leakage inductance	L_2	1 μH

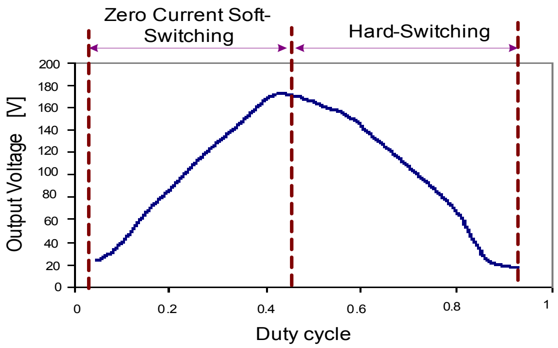


Fig. 5 Output power regulation vs. duty cycle

6. Conclusions

In this paper, a new topology for an active auxiliary quasi-resonant snubber-assisted voltage source type ZCS-PWM DC-DC power converter using IGBTs was proposed. It is composed of an active auxiliary switched snubber capacitor and two lossless snubber inductors. The high frequency operation principle, switching mode transitions and the operating characteristics of this converter were illustrated and evaluated on the basis of simulation analysis. The practical effectiveness of the newly-proposed voltage source type multi resonant ZCS-PWM DC-DC converter with high frequency transformer link has been proved on the basis of simulation results. A wide soft switching commutation operation range was obtained as compared with previously developed voltage source type ZVS-PWM DC-DC converters with high frequency transformer links.

It was found that the high frequency power regulation strategy of this proposed converter could be efficiently supplied from full power to relatively small power settings. By applying a dual mode pulse modulation control strategy with an asymmetrical PWM, the output power of this soft switching pulse modulated multi resonant DC-DC converter could be regulated under a condition of expanded stable soft switching operation ranges as compared with previously developed ZVS-PWM high frequency DC-DC converters. This dual mode ZCS PWM DC-DC converter could actually achieve higher efficiency, higher performance and wider soft switching operating ranges for fuel cell power conditioners.

In the future, the new prototype topology of this ZCS-PWM DC-DC converter with high frequency link should be evaluated for use in PEM fuel cell stack power conditioners. This ZCS-PWM DC-DC power converter using 100 kHz IGBTs or 150 kHz IGBTs should be introduced and discussed further with the aid of a high frequency planar transformer.

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Khairy Fathy Abd El-Sayed received his B.S. degree in Electrical Power and Machines in 1997 from Assiut University, Assiut, Egypt. He is now working towards his Masters degree at Graduate School of Electrical Engineering, Kyungnam University, Masan, Korea. His research interests include soft switching DC-DC power converter topologies, high frequency inverter applications, renewal energy related power conditioners and control schemes. He received the 2001 Best Student Paper Award at the 57 소 annual conference of the International Appliances Technical Conference IATC2006 held at Crowne Plaza, Chicago, USA, March 27-29. He is a student member of KIEE, KIPE and IEEE.

Soon-Kurl Kwon received his B.E. degree in Electrical Engineering from Young-Nam University, Daegu, Korea, and received his M.S. degree in Electrical Engineering from Busan National University, Busan, Korea, He received his Ph.D. (Dr-Eng) degree in Electrical Engineering from Young-Nam University, Daegu, Korea. He joined the Electrical Engineering Department of Kyungnam University, Masan, Korea in 1983 as a Professor. He was a Visiting Professor in VPEC at Virginia Polytechnic Institute and State University, USA from 1997 to 1998. His research interests include soft switching DC-DC power converter topologies, high frequency inverter applications, renewal energy related power conditioners and control schemes. He is a member of KIEE , KIPE,and IEEE.