Feasibility Study of Tapped Inductor Filter Assisted Soft-Switching PWM DC-DC Power Converter

S. Moisseev, S. Sato, S. Hamada, M. Nakaoka

Division of System Engineering, The Graduate School of Science and Engineering, Yamaguchi University
2-16-1 Tokiwadai, Ube City, Yamaguchi Prefecture 755-8611, Japan
Email: sergey@pe-news1.eee.yamaguchi-u.ac.jp

Abstract: This paper presents a novel high frequency transformer linked full-bridge type soft-switching phase-shift PWM control scheme DC-DC power converter, which can be used as power conditioner for small-scale fuel cell power generation system. Using full-bridge soft-switching DC-DC converter topology makes possible to use low voltage high performance MOSFETs to achieve high efficiency of the power conditioner. A tapped inductor filter is implemented in the proposed soft-switching converter topology to achieve soft-switching PWM constant high frequency operation for a wide load variation range, to minimize circulating and idling currents without using additional resonant circuit and auxiliary power switching devices. The practical effectiveness of the proposed soft-switching DC-DC converter is verified in laboratory level experiment with 1kW 100kHz breadboard setup using power MOSFETs. Actual efficiency of 94-96% is obtained for the wide load range.

Keywords: Full-bridge soft-switching DC-DC converter, Phase-shifted PWM, ZVS and ZCS bridge legs, Lowered circulating current, Tapped inductor filter, Small-scale fuel cell power generation system.

1. Introduction

In recent years the variety of high frequency transformer linked DC-DC power converter topologies have been proposed as power conditioner for fuel cell power generation systems. In this new energy utilization systems due to lowered switching power losses, voltage and current peak stresses and surges ZVS soft-switching Phase-Shifted PWM (PS-PWM) full-bridge converters have attracted much attention. [1] In the ZVS soft-switching PS-PWM full-bridge converters, however, a large circulating current flows through the transformer and its primary side circuit during a freewheeling interval caused by using PS-PWM control strategy. [2]-[3] During the freewheeling period, a circulating current flows through high frequency transformer and its primary side power semiconductor devices. Due to this current, conduction losses in the ZVS soft-switching PS-PWM DC-DC converter are higher compared to those of the hard-switching PWM converter. Moreover, the soft-switching operation is not obtainable for lagging bridge-leg switches due to insufficient current to charge/discharge lossless snubber capacitors of these switches under a light load. [4]-[6]

In this paper a new full-bridge PS-PWM DC-DC converter with ZVS and ZCS bridge legs using a tapped inductor filter is presented. The 1kW-100kHz prototype circuit using power MOSFETs is tested in experiment.

2. Proposed Soft-switching DC-DC Converter Circuit

2.1 Circuit configuration

Fig. 1 shows a schematic circuit topology of the proposed soft-switching high frequency transformer linked full-bridge type PS-PWM DC-DC converter with tapped inductor filter L_{d1}/L_{d2} in its output stage. Lossless snubber capacitors C_1 and C_2 in parallel with leading bridge-leg active power semiconductor switching devices (switches) Q_1 and Q_2 are used to obtain ZVS operation of these switches. The lagging bridge-leg switches Q_3 and Q_4 operate with ZCS at turn on due to effect of an inductance Ls. This inductance Ls can be presented by leakage inductance of the high frequency transformer T. On the other hand, the tapped inductor filter L_{d1}/L_{d2} is used to obtain ZCS for switches Q_3 and Q_4 at turn-off as well as to minimize circulating current during freewheeling interval.

The tapped inductor L_{d1}/L_{d2} in the proposed soft-switching converter operates as smoothing inductor and also as a passive clamp component, so that the rectified output voltage v_d is clamped in positive polarity during the freewheeling interval. Therefore, the rectifier bridge diodes D_5-D_8 are biased in reverse, and the output inductor current flows through the secondary freewheeling diode D_9 during the freewheeling interval. As a result, the circulating current through the transformer and its primary side circuit components becomes only magnetizing current of the transformer T.

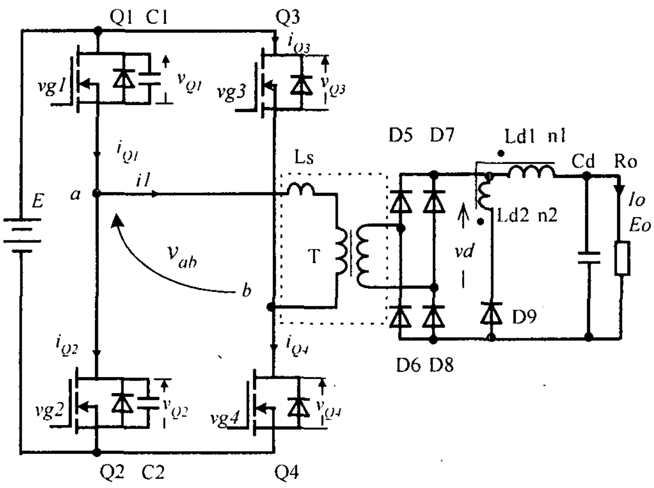


Fig.1 Proposed full-bridge soft-switching PS-PWM DC-DC converter

2.2 Circuit operation

Fig. 2 illustrates switching sequences and theoretical voltage and current waveforms of the converter in a steady state. The switches Q_1 and Q_2 are driven complementary with a short blanking interval t_d. This interval t_d is needed to achieve ZVS commutation at the switches Q_1 and Q_2 turn-on. The output voltage E_0 is regulated by varying an interval t_{on} (t_{on}=DT/2) as phase-shifted PWM control strategy with a constant switching frequency f=1/T.

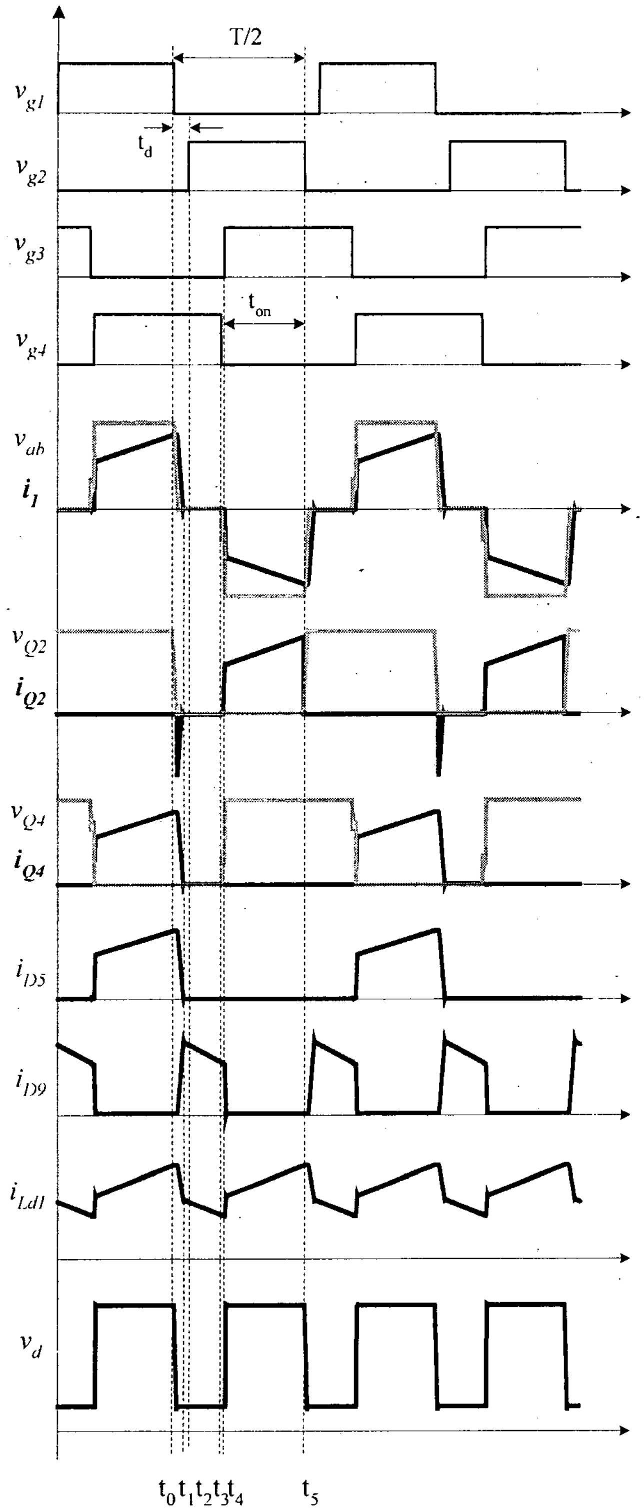


Fig. 2 Calculated waveforms of the proposed soft-switching PS-PWM DC-DC converter

The principle of the proposed converter circuit operation in a steady-state condition can be described as follows.

- Mode 1(t_0, t_1): Before time t_0 it is consumed that switches Q_1, Q_4 and rectifier diode D_5 are conducting.

Mode 2(t_0, t_1): At the instant t_0, Q_1 is turned off under a principle of ZVS with the aid of the lossless snubber capacitors C_1 and C_2.

The freewheeling diode D_9 starts to conduct when v_d reaches a value $\alpha_L E_0$, where α_L is the turns ratio of the tapped inductor defined as $\alpha_L = n_2/(n_1+n_2)$; n_1, n_2 are the number of turns of L_{d1} and L_{d2}, respectively.

- Mode 3(t_1, t_3): Due to presence of the leakage and magnetizing inductances in transformer primary side diode D_2 starts to conduct. At the instant t_2, pulse signal v_{g2} is applied to a gate of the switch Q_2.

After the current i_{d5} reaches zero the whole output current flows through D_7, L_{d2} and L_{d1}. The output current reflected to the transformer primary side becomes zero. Only a small magnetizing current of the transformer T circulates through Q_4 and D_2. This interval ends when the switch Q_4 is turned off with ZCS at instant t_3.

- Mode 4 (t_4, t_5): At time t_4, depending on the phase shift angle ϕ, Q_3 is turned on with ZCS due to effect of leakage inductance L_S.

The switch Q_2 is also turned on with ZVS and ZCS. The output current reflected to primary side of the transformer flows through Q_2 and Q_3. On the other hand, current through L_{d2} and D_9 decreases and diode D_9 turns off.

The energy is being delivered through the switches Q_3, Q_2, and transformer T, and rectifier diodes D_6, D_7. The half cycle of operation ends at instant t_5.

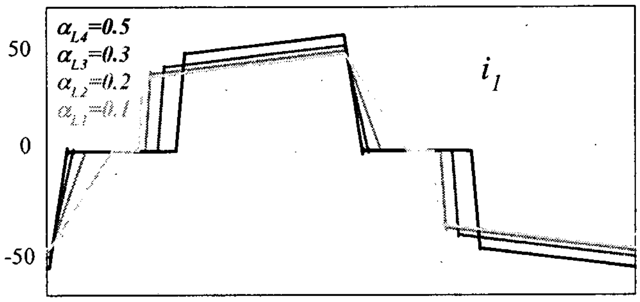
The operation during next half-cycle is symmetrical with mentioned above half-cycle. As described above the switches Q_1 and Q_2 are turned on and turned off with ZVS, while the switches Q_3 and Q_4 operate with ZCS at turn-on and turn-off. The circulating current during freewheeling interval t_0-t_3 is substantially lowered with no additional auxiliary resonant circuits.

3. Experimental Results

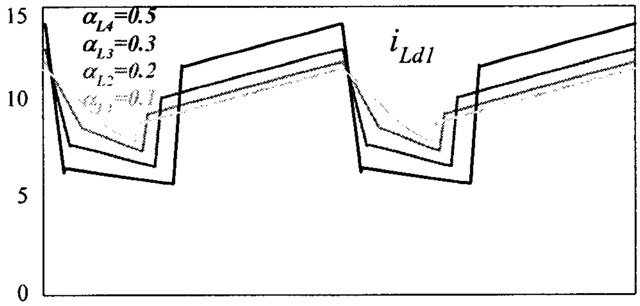
To verify the operating principle and evaluate steady state characteristics, the laboratory level experiment is carried out with a 1kW 100kHz breadboard circuit. To achieve high efficiency and high performance of the DC-DC converter power MOSFETs are selected as power active switching devices. The power circuit components parameters are indicated at the Table 1. The design of the tapped inductor L_{d1}/L_{d2} turns ratio is made on basis of the simulation results under closed loop control scheme. The simulated waveforms of the transformer primary side current i_1, inductor L_{d1} current i_{Ld1}, and rectified voltage v_d are shown at Fig.3. To achieve the reduction of the circulating current and at the same time to prevent the increase of the output current ripple the tapped inductor turns ratio is set as 0.3 for 100kHz DC-DC converter operating frequency.

Table1 Circuit parameters

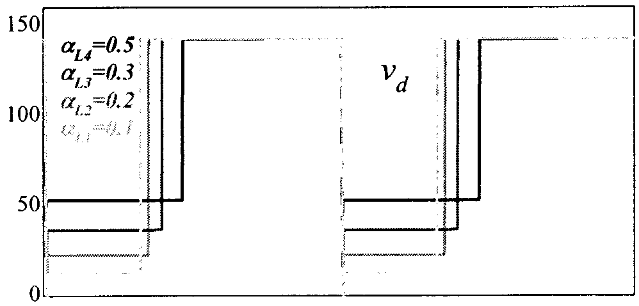
MOSFETs	Q_1-Q_4	2SK3228,V_{DS}=80V, R_{DS}=0.006 Om, I_{DS}=75A
Diodes	D_5-D_8	30JL2C41 V_{RRM}=600V,I_O=30A
Lossless snubber capacitors	C_1, C_2	33nF
Transformer turns ratio	α_T	1:4
Magnetizing inductance	L_m	70uH
Leakage inductance	L_S	300nH
Tapped inductor	L_{d1}, L_{d2}	L_{d1}=50uH,L_{d2}=13uH
Tapped inductor turns ratio	α_L	0.3
Output capacitor	C_d	250uF



(a) Waveforms of the transformer primary side current i_1

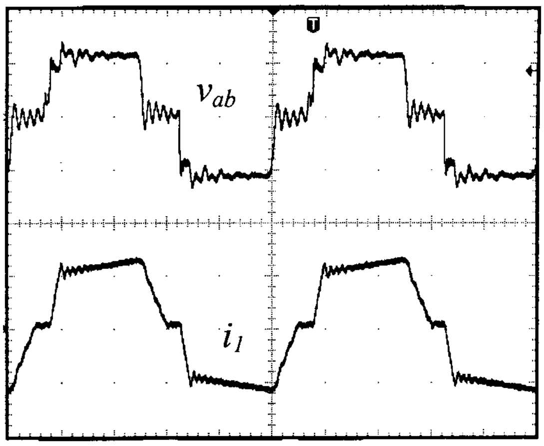


(b) Waveforms of the filter inductor L_{d1} current i_{Ld1}



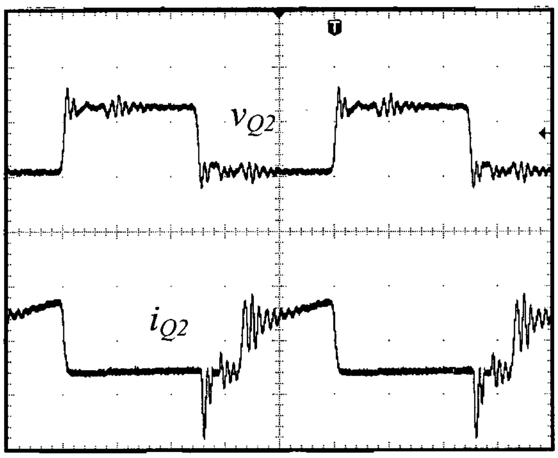
(c) Waveforms of the recified voltage vd

Fig. 3 Calculated Results under closed loop control



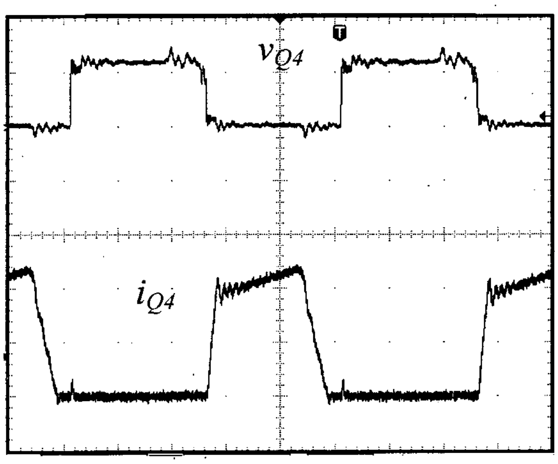
(a) High frequency transformer T voltage and current waveforms

v:[30V/div], i:[50A/div], time:[2μs/div]



(b) Voltage and current waveforms of switch Q_2

v:[30V/div], i:[50A/div], time:[2μs/div]



(c) Voltage and current waveforms of switch Q_4

v:[30V/div], i:[20A/div], time:[2μs/div]

Fig. 4 Experimental results under full load
E=36V, Eo=100V, Io=10A, f=100kHz

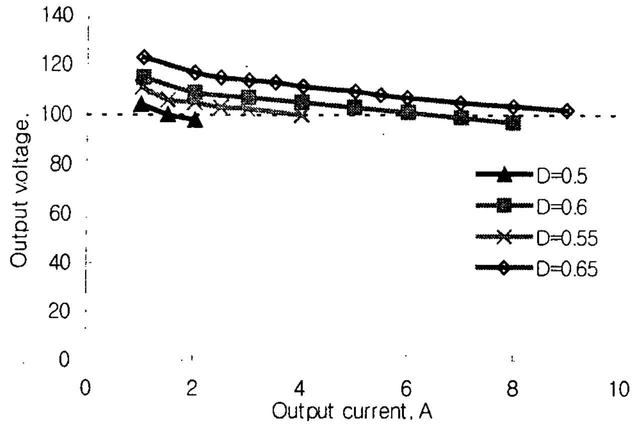


Fig.5 Output voltage Eo characteristic as function of output current Io and duty cycle D

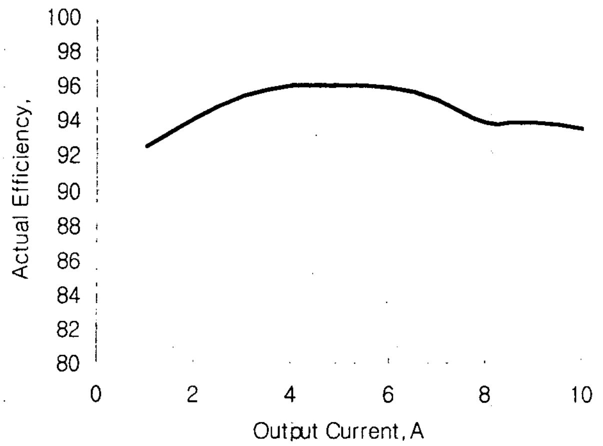


Fig. 6 Actual efficiency η vs. load current I_0

Fig. 4 illustrates experimentally the measured voltage and current waveforms of the high frequency transformer T and power switches Q_2 and Q_4 under full load.

Observing Fig. 4(a), it is obvious that the circulating current does not flow through high frequency transformer T and its primary side circuit components during freewheeling period caused by PS-PWM control scheme. Moreover, the switches Q_1 and Q_2 are turned on and turned off with ZVS, while Q_3 and Q_4 operate with ZCS at turn-on and turn-off. The circulating current is substantially lowered with no additional auxiliary circuits.

The switch Q_2 operates with ZVS and ZCS at turn-on and with ZVS at turn-off; switch Q_4 operate with ZCS at turn-on and turn-off as demonstrated at Fig. 4 (b), (c). The output voltage Eo of the tested DC-DC power converter as a function of the output current Io under different duty cycle value D is shown at Fig. 5.

Fig. 6 demonstrates actual efficiency as a function of the output current Io with a constant duty D=0.6. The actual efficiency as 94-96% was obtained over the wide load range.

4. Conclusions

The novel tapped inductor filter assisted high frequency transformer linked full-bridge type soft-switching phase-shift PWM control scheme DC-DC power converter with ZVS and ZCS bridge-legs has been presented in this paper. The generation of the conduction losses during freewheeling period caused by using phase-shift PWM control scheme has been suppressed due to make use of the tapped inductor filter. High efficiency stable soft-switching operation ability of the proposed DC-DC power converter has been verified on the bases of the experimental results using 1kW 100kHz breadboard circuit. The soft-switching operation range has been extended to 15%-100% load variation range.

The proposed soft-switching DC-DC power converter has enough ability to be used as high performance isolated type DC-DC power conditioner for 1kW class fuel cell systems or as step-up DC-DC power converter in 42V automobile power system.

References

[1] O.D.Patterson and D.M.Divan, "Pseudo-resonant full bridge DC/DC converter", IEEE PESC Conf. Rec., pp.424-430, June, 1987.

[2] Eun-Soo Kim, Kee-Yeon Joe, Moon-Ho Key, Yoon-Ho Kim, and Byung-Do Yoon, "An improved soft-switching PWM FB DC/DC converter for reducing conduction losses", IEEE Trans. PE, Vol.14, No.2, pp.258-263, 1999.

[3] J.G.Cho, J.W.Back, C.Y.Jeong, D.W.Yoo, and K.Y.Joe, "Novel Zero-Voltage and zero-current-switching Full Bridge PWM Converter Using Transformer Auxiliary Winding", IEEE Trans. PE, Vol.15, No.2, pp.250-257, 2000.

[4] S. Moisseev, S. Hamada, M. Ishitobi, E. Hiraki, M. Nakaoka, "High-Frequency Forward Transformer Linked PWM DC-DC Power Converter with Zero Voltage Switching and Zero Current Switching Bridge Legs", KIPE-Journal of Power Electronics, Vol.2 No.4, pp.278-287, 2002.