QUASI-RESONANT ZVS-PWM DC-DC FORWARD CONVERTER WITH ACTIVE CLAMPED CAPACITOR FOR SOLAR PHOTOVOLTAIC ENERGY-DRIVEN BOAT SYSTEM

Kenya Sakamoto(Prof.), Masakazu Kanaoka,
Hidekazu Muraoka and Ryuhei Hojyo
Dept. of Ocean Electro-Mechanical Engineering, Kobe
University of Mercantile Marine,
5-1-1, Fukaeminami, Higashinada, Kobe, 658-0022, Japan
Phone +81-78-431-6274, Fax +81-78-431-6274

Mutsuo Nakaoka(Prof. Dr.)
Dept. of Electrical and Electronics Engineering,
Yamaguchi University,
2557 Tokiwadai, Ube, Yamaguchi 755-8611, Japan.
Phone +81-836-35-9946, Fax +81-836-35-9449

ABSTRACT

This paper presents a novel prototype of active voltage clamped quasi-resonant ZVS-PWM forward DC-DC converter designed for specific low voltage high current application. We establish the soft-switching forward converter with a high frequency isolated link which can efficient operate over wide load ranges under conditions of zero voltage soft-switching and active voltage clamped switching. In addition, we evaluate connection of the soft-switching forward converter with large capacitor which capacitance is over 100[F].

1. INTRODUCTION

In recent years, the soft-switching PWM DC-DC converters have attracted special interest for efficient energy conversion power conditioners. They can operate under the principle of zero voltage and/or zero current soft-switching using MOS-gate power semiconductor devices such as power MOSFETs, IGBTs, MCTs and IEGTs. It is more acceptable for high power applications that active voltage clamped soft-switching PWM DC-DC forward power converter operates at zero voltage soft-switching scheme in order to minimize the switching losses of power semiconductor devices and EMI/RFI noises. Therefore introducing soft-switching forward type converter to solar energy driven boat which including precision instruments in recent years is effective on decreasing switching-noises and losses to be higher efficiency than hard-switching forward type converter.

In this paper, we present a type of soft-switching dc-dc forward converter with asymmetrical PWM control of double arms.[1] Proposed quasi-resonant soft-switching PWM forward converter using power MOSFET is designed for a low voltage and high current power applications for solar photovoltaic generator driven boat system.[2]~[4] For 24 volts supply application evaluated circuit can be loaded up to 300 watts with 90.90 efficiency. Experiment results of over 1000 watts output circuit should be reported before long. In case of that high current streams at primary circuit, secondary battery voltage is dropped by its own resistance and discharging. Therefore converter output voltage is lower than calculated one, and converter output power is not given enough. For replenishing dropped battery voltage we evaluate charged large capacitor as auxiliary energy bank placing in parallel with battery. And cause of placing charged large capacitor bank in series with battery, motor is supplied constant voltage and is able to bring constant speed for a time on solar boat sprint race.

2. SYSTEM DESCRIPTION

Fig.1 shows a schematics of power processor, including system of power conditioning circuit for specific-application solar energy driven-boat system with DC motor in progress.[5]

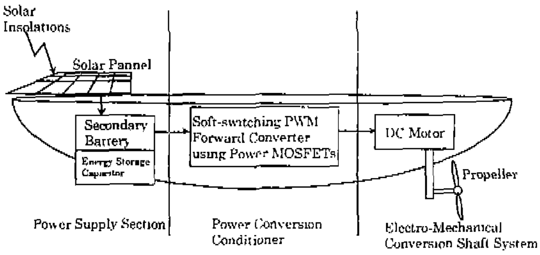


Fig.1 Overview for two types pannel, of solar photovoltaic power-driven boat system

This system is composed of solar panel, soft-switched PWM DC-DC forward converter with high frequency transformer link, and motor coupled direct drive mechanical propeller drive for this new energy boat system.

Table.1 indicates the design specifications of solar battery-driven DC motor coupling boat system.

Table.1 Design specifications of solar battery-driven boat system

Solar Pannel	500W , Single Crystal Type
Secondary Battery	12V, 6.5Ah × 4(2p × 2s) Series resistance = 40 mΩ
Converter Output Power	1kW(MOSFET:2SK1382)
DC Motor	480W continuous

3. CONVERTER CIRCUIT IMPLEMENTATION AND ITS OPERSTION

Quasi-resonant forward ZVS-PWM converter[3] is indicated in Fig.2. Capacitance Ca is applied to supply reset voltage to the transformer. Ca acts as voltage clamper instead of resonant capacitor for soft-switching.[6]

Delay times of reciprocal switching of SWa and SWb is important and sensitive to ZVS operation.

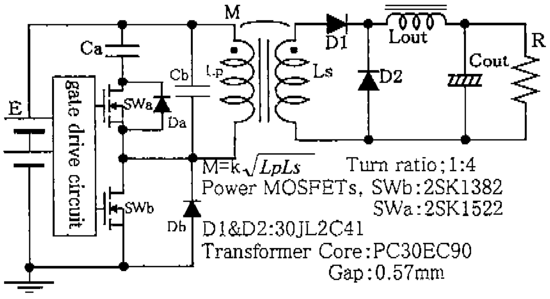


Fig.2 Soft-switching PWM forward converter using low voltage high current power MOSFETs

Table.2 indicates the design specifications of this trially-produced forward converter.

Table.3 indicates electrical characteristic of main-switch SWb:2SK1382

Table.2 Design specifications

Items	Symbols	Design Values
Supply Voltage	E	24 V
Quasi-Resonant Capacitor	Cb	0.1 μ F
Active Clamped Capacitor	Ca	3.47 μ F
Primary Winding Inductance	Lp	20 μ H
Secondary Winding Inductance	Ls	320 μ H
Smoothing Reactor Inductance	Lout	30 μ H
Smoothing Capacitor Capacitance	Cout	470 μ F

Table.3 Electrical characteristic of 2SK1382

2SK1382

		Symbols	Value	Unit
Drain-source voltage		VDSS	100	V
Gate-source voltage		VGSS	±20	V
Drain current	DC	ID	60	A
	Pulse	IDP	240	A
Input capacitance		Ciss	8000	pF
On resistance		RDS(on)	15~20	mΩ

Fig.3 shows the analyzed operational modes of ZVS-PWM DC-DC forward converter with active clamped capacitor.

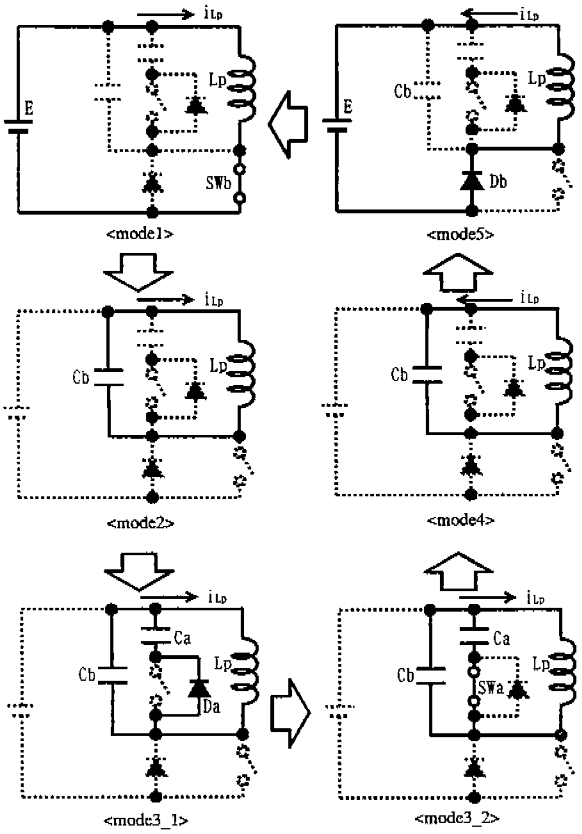


Fig.3 The operational modes of PWM forward converter operating at zero voltage soft-switching

This forward type PWM DC-DC converter has some operational modes analyzed by transient phenomena with only inductance and capacitor elements. ZVS soft-switching is performed with those modes transition as follows.

< mode 1 >

This mode is Duty period streaming high current through the main switch SWb. Switch current is the sum of load current and magnetizing current.

< mode 2 >

At the end of mode 1 period, switch SWb turns off to fall into mode 2. Magnetizing current at primary transformer inductance Lp streams into quasi-resonant capacitor Cb to charge. Therefor ZVS soft-switching is performed when switch SWb turns off.

< mode 3_1&3_2 >

If quasi-resonant capacitor Cb's voltage exceeds active clamped capacitor Ca's voltage, diode Da is on, and operational mode is led to mode 3_1. After diode Da conducting, switch SWa turns on that operational mode translates to mode 3_2. Therefor ZVS-ZCS soft-switching is performed when switch SWa turns on. In mode 3_2, parallel capacitor Ca & Cb is discharged after their capacitor charging by magnetizing current.

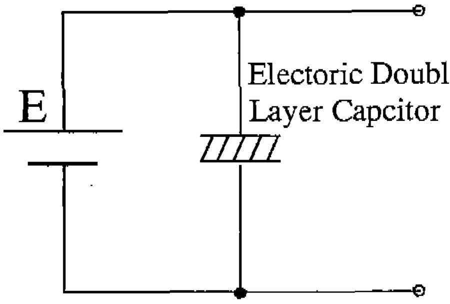
< mode 4 >

Switch SWa turns off to quasi-resonant capacitor Cb starts to discharge the junction capacitance voltage of SWb.

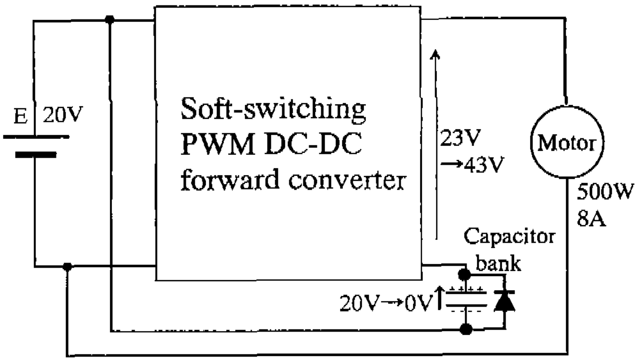
< mode 5 >

Voltage of quasi-resonant capacitor Cb being over power supply's voltage, diode Db is switched on. Switch SWb should be turned on before the current direction of primary transformer inductance Lp turning to opposite direction. Therefor ZVS-ZCS soft-switching is performed when switch SWb turns on.

Fig.4 shows two types of cooperative method of soft-switching DC-DC forward converter with large capacitor (Electric double layer capacitor) bank. Fig.4 (a) shows the charged large capacitor bank established in parallel with battery for replenishing battery voltage drop at streaming high current period. Fig.4 (b) shows placing the charged large capacitor bank at bias route from power supply to the load in series with battery, accordingly the load is supplied constant voltage and is able to keep at an even speed for a time under dropped power supply voltage condition in the interest of solar boat sprint race.



(a) Placing in parallel with battery



(b) Placing at bias route from power supply to the load in series with battery

Fig.4 Place of Large Capacitor Bank to Generate Power Efficiently

Capacitor voltage, converter output voltage, power supply voltage, and motor power value in Fig.4(b) are examples. Detailed their examples' contents for making up dropping voltage of inserted capacitor bank discharging by converter output voltage is indicated in Table.4. Capacitance of bank is decided for 120[F], because it is able to discharge for 2 minutes with 20[A] and 1[kW]. Originally, power supply voltage is 24 [V], but we suppose dropping voltage into 20[V].

Table.4 Correlation of capacitor voltage and converter output voltage (E=20V)

	The start of capacitor discharging		The finisn of capacitor discharging	
motor power	300W, 5A	500W, 8A	300W, 5A	500W, 8A
Capacitor voltage	20V	20V	0V	0V
Converter output	20V	23V	40V	43V
Converter's duty	25%	29%	50%	54%

Consideration for large capacitor charging method which is conformed by charging fixed current[7] and inserting method of charged capacitor bank is necessary.

4. PERFORMANCE EVALUATIONS AND DISCUSSION

4-1. SIMULATION RESULTS

Fig.5 shows the illustrative switching-time chart of SWa & SWb that explaining delay times which are both switches SWa and SWb closing period.

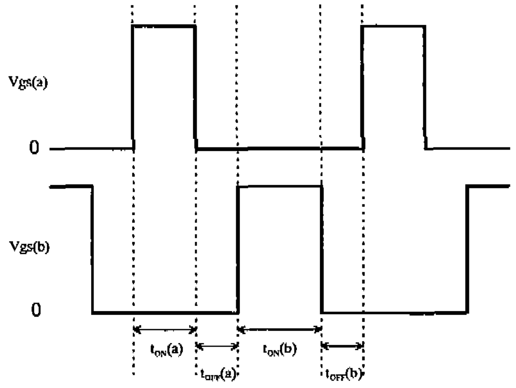


Fig.5 Switching time chart of SWa & SWb (gate-source voltage of SWa & SWb)

Fig.6 displays the calculated drain-source voltage across SWb and drain current waveforms obtained in simulation analysis (PSpice) that demonstrating to perform ZVS soft-switching when switching of following SWb.

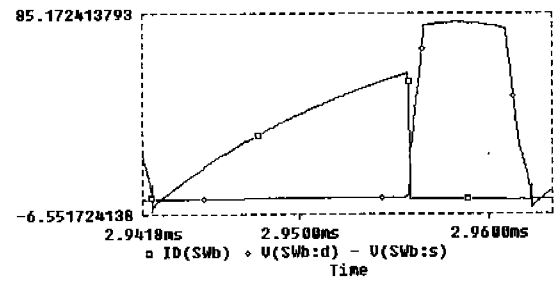
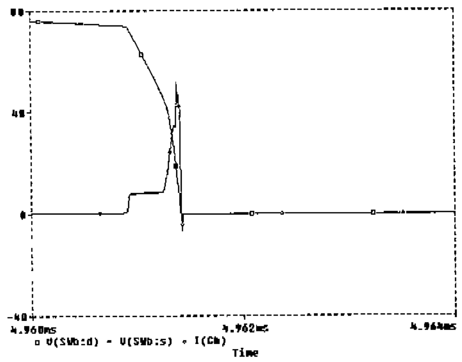
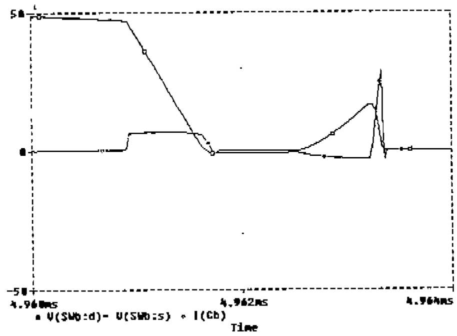


Fig.6 Calculated drain-source voltage across SWb and drain current (Duty 65%)

To establish soft-switching for wide range, setting transition delay times of reciprocal switching of SWa and SWb is important and sensitive to ZVS operation. Fig.7 shows drain-source voltage across SWb and Cb current waveforms analyzed in simulation about delay times. In case of short toff(a) or excess toff(a). In case of short toff(a), SWb closes with remaining voltage of Cb that discharging short current turn into switching-loss. In case of excess toff(a), SWb closes remaining Cb's voltage which charging again that discharging short current turns into switching-loss.



(a) In case of shortage toff(a) (toff(a)=1 μ s)



(b) In case of excess toff(a) (toff(a)=3 μ s)

Fig.7 Simulation results analyzing about delay times

The best suited toff(a) analyzing in transient phenomena is indicated.

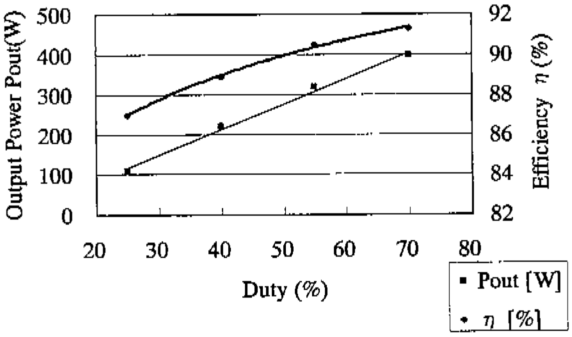
$$\sqrt{Lp\cdot Cb}\,\tan^{-1}\left(-\frac{Q_2}{I_3\sqrt{Lp\cdot Cb}}\right)<t_{off}(a)$$

$$<\sqrt{Lp\cdot Cb}\,\tan^{-1}\left(-\frac{Q_2}{I_3\sqrt{Lp\cdot Cb}}\right)-\frac{I_4\cdot Lp}{E} \qquad (1)$$

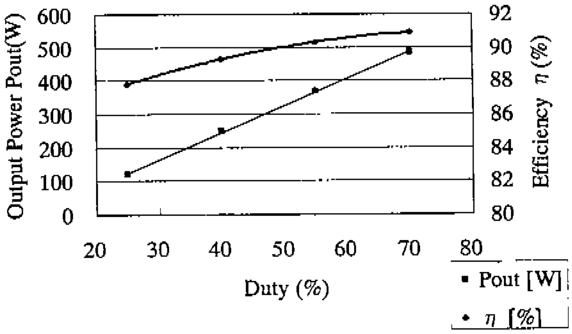
where,

Q_2 : Electric charge which is end of mode 2
I_3 : Current which is end of mode 3
I_4 : Current which is end of mode 4

Fig.8 shows the calculated output power and efficiency for duty factor. Fig.8(a) is a case of load resistance R=11[Ω] as to load power 300[W] and 5[A] in Table.4. And Fig.8(b) is a case of load resistance R=8[Ω] as to load power 500[W] and 8[A] in Table.4. Fig.9 shows lost power for duty factor in case of R=11[Ω] and R=8[Ω].



(a) In case of load resistance R=11[Ω]



(b) In case of load resistance R=8[Ω]

Fig.8 Calculated output power and efficiency for duty factor (E=24[V],n=4,fsw=50[kHz])

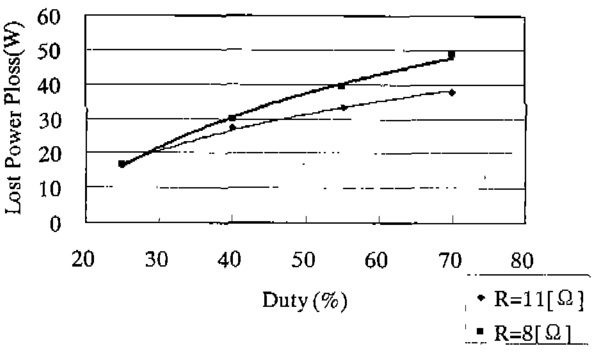


Fig.9 Lost power for duty factor (E=24[V],n=4,fsw=50[kHz],R=8 and 11[Ω])

It is high efficiency that proposed circuit's operation for wide range of duty factor. But there is a bit lower efficient portion at low duty than middle and high duty range. At low duty range, on account of low current, Cb charges again before discharging to zero voltage. Therefore closing SWb with remained Cb's voltage turns into switching-loss. Fig.10 shows established drain-source voltage across SWb on 15[%] duty by simulation.

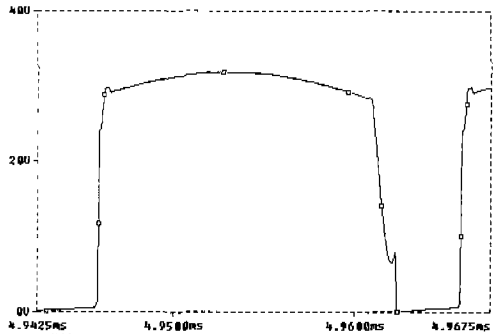


Fig.10 Established drain-source voltage across main-switch SWb (Duty 15%,E=24[V], n=4,fsw=50[kHz],R=11[Ω], toff(a)=1.5[μs])

It is sure that above-mentioned problem is settled by making primary transformer inductance Lp into smaller inductance. However small inductance brings large current and deterioration of efficiency accompany with increasing current. Consequently, should not lower primary transformer inductance value too much.

4-2. EXPERIMENTSL RESULTS

Fig.11 displays the measured output power and efficiency for duty factor. And Fig.12 shows the measured power loss for duty.

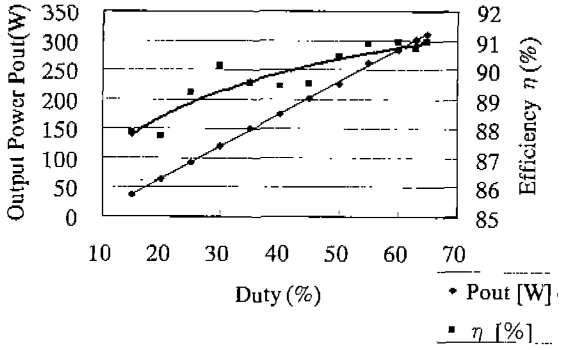


Fig.11 Measured output power and efficiency for duty (E=24[V],n=4,R=10.7[Ω],fsw=50[kHz])

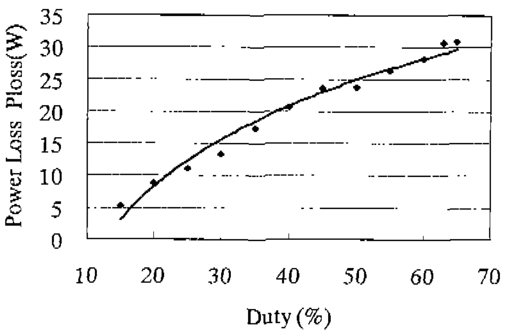


Fig.12 Measured power loss for duty (E=24[V],n=4,R=10.7[Ω],fsw=50[kHz])

The experimental circuit can be loaded with efficiency 90.9[%] at E=24.0[V], Vout=57.6[V], R=10.7[Ω] and Pout=310 [W] for the present.

In experiment the proposed circuit operates efficiently with wide range of duty. Its experimented results of efficiency and lost power is consistent with analyzed results. But lowering efficiency a little at low duty range is consistent with calculated results, too.

Fig.13 displays the measured drain-source voltage waveform across main-switch SWb with establishing long toff(a)(=2.3[μs]).

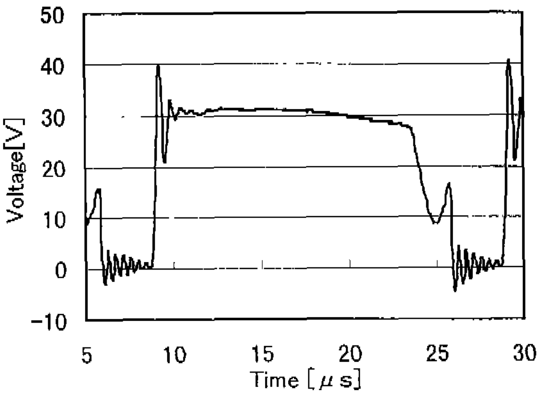


Fig.13 Measured drain-source voltage waveform across main-switch SWb (Duty 15%,E=24[V], n=4,R=10.7[Ω],fsw=50[kHz],toff(a)=2.3[μ s])

It is clear that quasi-resonant capacitor Cb discharges again before dropping till zero voltage. Main-switch SWb turns on with being left Cb voltage.

5. CONCLUSIONS

Zero voltage soft-switching PWM DC-DC forward converter for a specific applications which are low voltage and high current input is presented. It is confirmed that experimental results agree with simulation analytical results pretty good at low output power. We suppose that efficiently operation and fixed output power for a time is realized by cooperation of soft-switching PWM DC-DC converter and large capacitor bank placing in series with battery on bias route. According to their analyzed and examined results, we establish soft-switching for wide range except turning on SWb at low duty. However, switching-loss with SWb turning on at low duty can be diminished that delay time toff(a) is set up for shorter period which is 1.3[μ s] by way of example.

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