Transformer Parasitic Inductor and Lossless Capacitor-Assisted Soft-Switching DC-DC Converter with Synchronous Phase-Shifted PWM Rectifier with Capacitor Input Filter

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Abstract. : This paper presents a new prototype of soft-switching DC-DC power converter with a high frequency transformer link which has two active power controlled switches in full bridge rectifier with capacitor input type smoothing filter. In this DC-DC converter, ZVS of the inverter in transformer primary side and ZCS of active rectifier area in secondary side can be completely achieved by taking advantage of parasitic inductor component of high-frequency transformer and lossless snubbing capacitors. Its operation principle and salient features are described. The steady-state operating characteristics of the proposed DC-DC power converter are illustrated and discussed on the basis of the simulation results in addition to the experimental ones obtained by 2kw-40kHz power converter breadboard set up.

Keywords: DC/DC Power Converters, Zero Voltage Soft Switching(ZVS), Secondary Side Synchronous Phase-Shifted Control, Active ZCS Rectifier, Capacitor Input Type Low Pass Filter,

1 INTRODUCTION

In recent years,advanced developments of high-frequency soft-switching inverter type or chopper type DC-DC power converter circuits technologies have recently attracted special interest in promissing application fields of new energy interfaced power conversion conditioning and processing systems. A variety of circuit topologies of quasi-resonant ZVS PWM DC-DC power converters using MOS gate power transistors; MOSFETs and IGBTs as well as static Inductor power transistors; SIT,B-SIT have some remarkable advantages such as lowered switching power losses of power semiconductor devices, constant frequency operation, simple pulse modulation control scheme and high performance in steady state and transient state as well as reduced EMI and RFI noises. However, in general, most of quasi-resonant zero voltage soft-switching PWM DC-DC power converters with a high frequency transformer link which are previously developed includes some practical drawbacks such as relatively narrow ZVS range due to the duty cycle regulation mode, load dependent soft-switching operation and so on. Under these technical backgrounds, this paper proposes a novel soft-switching DC-DC power converter using synchronous active zero current soft switched PWM rectifier in transformer secondary side which can achieve complete soft-switching in spite of power regulation scheme by taking advantage of transformer parasitic inductive components and lossless capacitive snubbers. The operation principle and unique features of the proposed converter are illustrated and discussed on the basis of simulation results and experimental ones. Illustrative data represents the steady-state performances required for circuit design.

2 CONVERTER DESCRIPTION AND OPERATION ANALYSIS

A Circuit Topology

Figure 1 shows a newly-proposed power converter circuit topology with a high frequency transformer link. The transformer primary side converter circuit includes the full-bridge type high frequency inverter (S_1-S_4) with the lossless snubber capacitors (C_1-C_4; including internal capacitance of the power semiconductor switches). On the

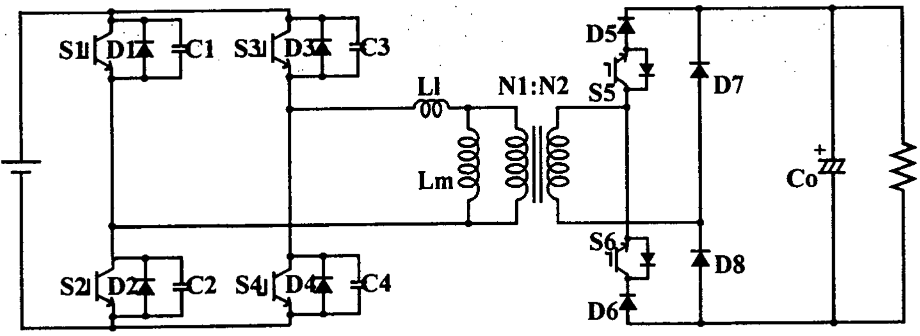


Fig 1. Proposed Soft-Switching Converter Circuit Topology with Capacitor Input Type DC Smoothing Filter

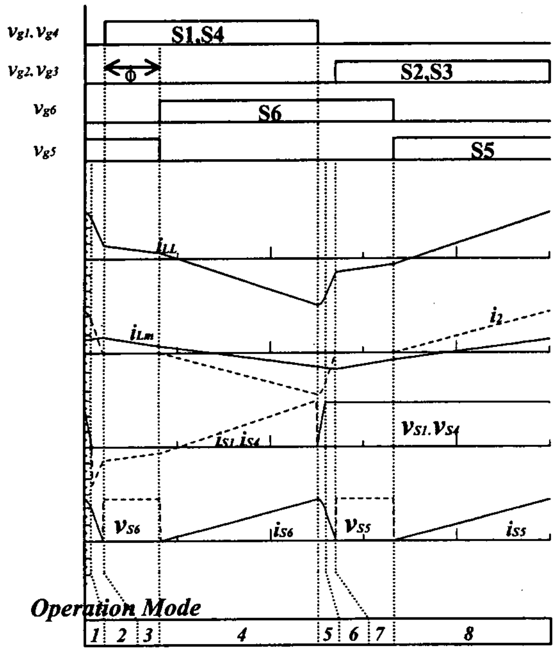


Fig 2. Operating Waveform of Proposed Converter

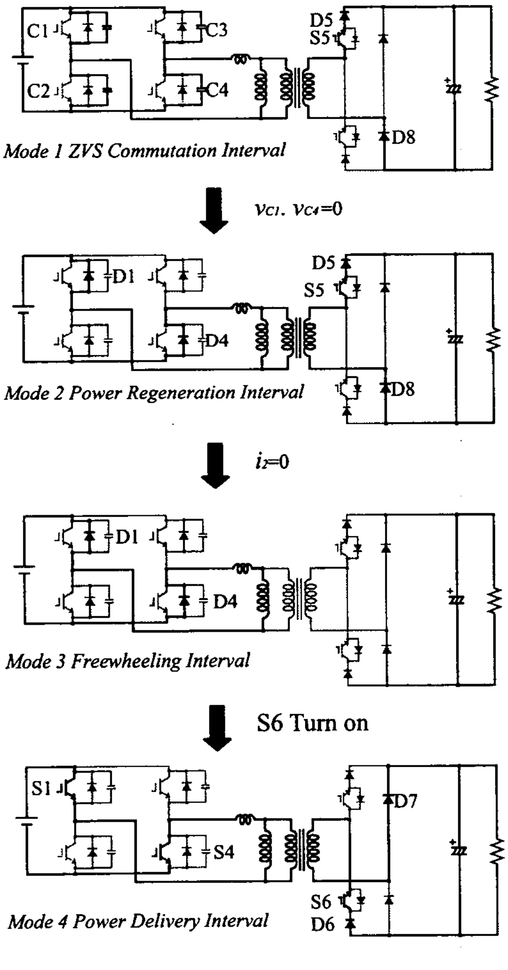


Fig 3. Equivalent Circuits during a Half Cycle Period

other hand, transformer secondary-side circuit consists of the diode rectifier with two active power semiconductor switches (S_5,S_6)in addition to capacitor input type DC smoothing filter (Co) in parallel with the load resistance(Ro). In this power converter, the parasitic magnetizing inductance of high-frequency transformer effectively operates as quasi-resonant commutation inductor snubber. The zero voltage soft switching inverter circuit which works under a constant frequency has about 50% constant duty ratio with a slight dead time and it provides no function to regulate the output voltage. The output voltage is continuously regulated under a condition of soft-switching PWM mode with an aid of active power semiconductor switches S_5,S_6 in the rectifier of transformer secondary-side under synchronous phase-shift PWM control strategy with respect to the inverter operated active power switches. The proposed DC-DC power converter can easily achieve ZVS operation of the transformer primary-side power switches as well as ZCS commutation of the transformer secondary-side active power switches with a low commutating current, because the load current do not almost influence upon soft-switching condition.

B Circuit Operation

The steady-state operation principle of the proposed soft-switching DC-DC power converter is described for the a cycle modes corresponding to Mode 1 to Mode 8 using its relevant voltage and current operating waveforms illustrated in Figure 2 and its equivalent circuit of this power converter are respectively shown in Figure 3. The circuit operation in steady state is illustrated for each circuit mode as follows;

(a) $t_0 < t < t_1$; (Mode 1)

When $S2$ and $S3$ are turned off at time t_0, commutating currents $i_l/2$ flow through the lossless snubber capacitors, respectively. Thus, C_2 and C_3 are charged up to the DC supply voltage E, On the other hand, C_1 and C_4 are discharged. As soon as the voltage across C_2 and the voltage across C_3 reach DC supply voltage E. currents flowing through C_1 and C_4 are respectively commutated to D_1 and D_4.

b) $t_1 < t < t_2$; (Mode 2)

In this mode, voltage across magnetizing inductor is nearly equal to an output voltage, the current flowing magnetizing inductor increases. So inverter output current decreases to zero. Since S_1 and $S4$ are driven the gate voltage pulse signals while D_1 and D_4 are conducting, S_1 and S_4 are turned on under both conditions of ZVS in transformer primary side. In Mode 2 and Mode 3, the power converter system energy is not delivered from the supply source E to load Ro because S_6 is in off state.

(c) $t_2 < t < t_3$; (Mode 3)

At time t_2, transformer secondary-side current i_2 reaches zero, and the circulating current does not flow through the transformer primary circuit because S_6 is still off. In this case, only transformer magnetizing current flows through transformer primary circuit. S_5 turns off under ZVS and ZCS condition during this interval. Adjusting this interval continuously serves to regulate the output voltage.

(d) $t_4 < t < t_5$; (Mode 4)

After S_6 turns on, the converter system energy flow starts to be delivered from the supply source E to the load side.

When S_1 and S_4 are both turned off at time t_5, the operating mode to moves the Mode 5 and the half cycle operation of this power converter completes. On the other hand, the circuit operations for Mode 5-8 are the same as those for Mode 1-4. As mentioned above, all the switching power semiconductor devices in soft-switching DC-DC power converter with a high frequency transformer link and active power rectifier treated here can achieve complete hybrid soft-switching operations on the basis of ZVS for transformer primary side active power switches and ZCS for secondary active power switches.

3 SOFT SWITCHING CHARACTERISTICS

(A) Transformer primary side active power switches

The primary side active power switches are achieved soft switching by Zero Voltage Switching(ZVS). The ZVS is able to be achieved by taking advantage of current flowing magnetizing inductance. Fig 4 shows the relation between phase shifted angle and magnetizing inductance peak current value. In conventional power converter, the magnetizing peak value decreases under the low output. In contrast, the proposed converter, it is kept to a certain constant value. This proposed converter can completely achieve ZVS even under the low output ranges.

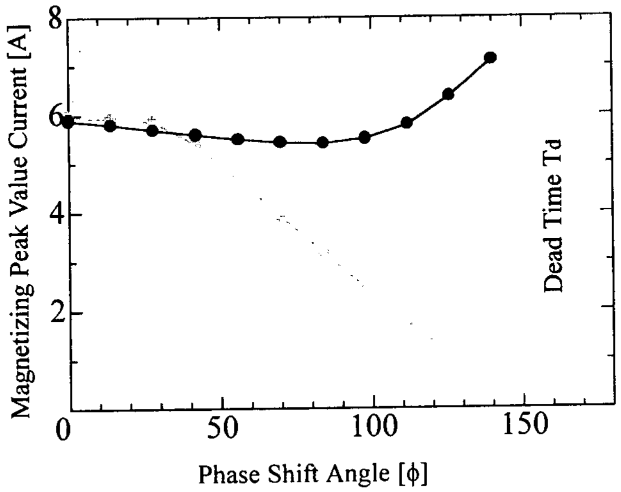


Fig 4. Comparison of Magnetizing Peak Value Current between proposed and conventional converters.
(--- Conventional —●— --- Proposed)

(B)Transformer secondary side active power switches

At operation mode 4, transformer secondary side active power switches can achieve ZCS for all output voltage regulating ranges by taking advantage of transformer parasitic leakage inductance and magnetizing inductance.

$$t_{d1} \geq \frac{2CE}{i_{m(to)}}$$

When operation mode moves to this interval, the current starts flowing to the transformer secondary side switch S_6 from zero current. The gradient of this current is given by the following equation.

$$\frac{di_2}{dt} = \frac{1}{L_l}(v_{ab} - n \cdot v_2)$$

where L_l : leakage inductance of high frequency transformer. v_{ab}: inverter output voltage. v_2 : voltage across transformer secondary side. Regarding this equation, more large leakage inductance makes proposed converter achieved certain zero current soft switching of the at secondary side switches.

4 DESIGN CONSIDERATIONS

(A) Dead time of primary side active power switches

The transformer primary-side active power switches need an optimum dead time enough to charge or discharge the lossless snubber capacitor under no load or light load operation range. A required dead time t_{d1} can be approximately estimated as follows;

where, $i_{m(to)}$: magnetizing current i_m at time to in beginning of mode 1, C: lossless snubber capacitance ($C=C_1$-C_4). If $i_{m(to)}$ is able to be increased, it becomes to be easy to accomplish ZVS commutation of the primary-side active power switches but their conduction losses tend to be also increased. The transformer parasitic magnetizing inductor L_m should be selected appropriately for this power converter.

(B) Secondary side ZCS

After the commutation from C1 and C4 to D1 and D4, the operation mode moves to mode 2. The current flowing secondary side active power switches decrease to zero. Secondary side active power switch turn off : should be achieved after the current reaches to zero, that is, mode 3. The optimum time of secondary side switches are given by this equation.

$$t_{d2} = t_{d1} + \frac{Ll \cdot i_{2(to)}}{E + {}^{v_o}\!/_{n}}$$

where $i_{2(to)}$: current flowing secondary switches at to. n : turn ratio (N2/N1). Secondary side turn off should be achieved after this time.

Since the phase-shifted angle ϕ, that is, interval from the time t_1 (or t_5) to the time t_3 (or t_7) serves to regulates the output power of the newly-proposed power converter, the secondary-side switches are to be operated under phase-shift PWM-based duty cycle control strategy for the primary-side switches. At $\phi=0$, the rated output power is delivered for this power converter. At $\phi=180-\phi_d$, using ϕ_d

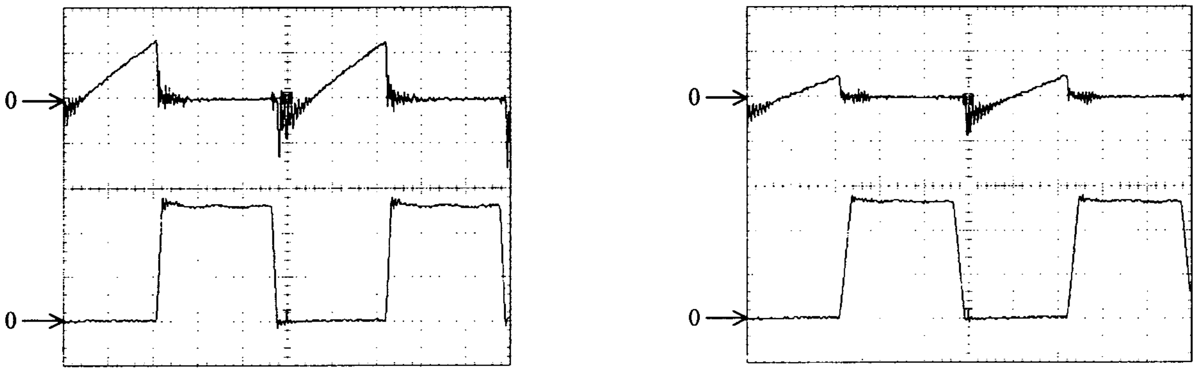
corresponding to the dead time t_d, the output power is set to zero.

5 EXPERIMENTAL RESULTS AND DISCUSSIONS

A 2kW-40kHz prototype set up of the transformer parasitic inductive components and lossless capacitive snubber assisted soft-switching inverter type DC-DC converter using IGBT power modules is practically built to verify the principle of operation with the specifications given in Table 1. Figure 5 shows the measured voltage and current waveforms of the proposed power converter. It is proved that the proposed DC-DC power converter using IGBT power modules can commutate with soft-switching transition by observing these operating voltage and current waveforms. In addition to this, the proposed DC-DC power converter can eliminate the wasteful circulating current. Accordingly, the conduction power losses and current stresses of the switching semiconductor devices can be substantially reduced. The conduction power losses in transformer secondary active rectifier circuit are seemingly increased since the switching power devices S_5 and S_6 are added in series with the diodes as the passive power switches in the rectifier, but the switching power losses are actually rather diminished because transformer primary side switches ZVS and secondary side active power switches ZCS are accomplished over the all output ranges. As mentioned above, the proposed converter with a capacitor input type smoothing filter is more cost-effective circuit and achieves improvement of power conversion efficiency under phase-shifted PWM. And Figure 6 depicts the power conversion efficiency versus load current characteristics by load variation and ZVS ranges at primary

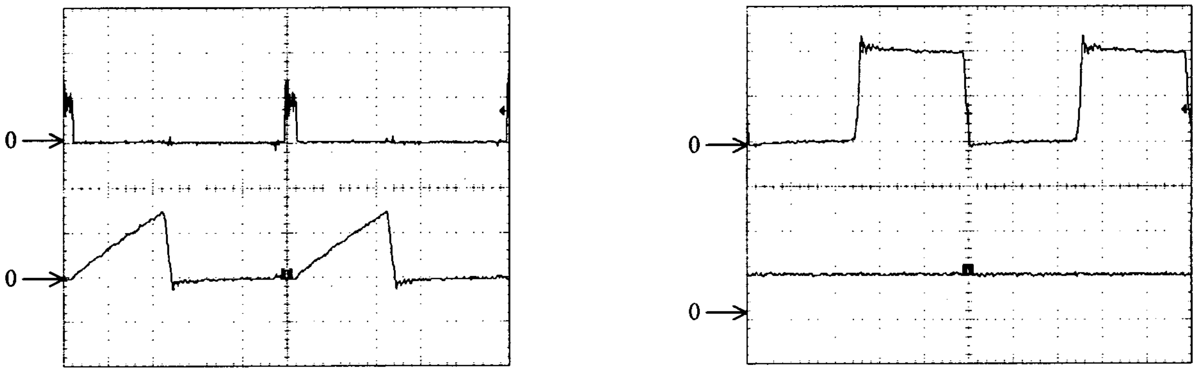
Table 1. Design Specifications and Circuit Parameters

Components	Symbol	Parameter
DC Voltage Supply	E	280[V]
Maximum Output Power	P_{out}	2[kw]
Load (Open Loop)	R_o	25[Ω]
Switching Frequency	f_{sw}	40[kHz]
High Frequency Transformer		
Turn Ratio	n(N2/N1)	8:8
Leakage Inductance	L_l	18[μH]
Magnetizing Inductance	L_m	160[μH]
Lossless Capacitor	C(C1-C4)	22[nF]
DC Smoothing Capacitor	C_o	5.6[mF]



(a) Primary Side Switch S4 current[20A/div] voltage[100V/div]

(c) Primary Side Switch S4 current[20A/div] voltage[100V/div]



(b) Secondary Side Switch S6 voltage [100V/div] current[20A/div]

(d) Secondary Side Switch S6 voltage [100V/div] current[20A/div]

Fig 5. Experimental Voltage and Current Waveform
(a).(b)-Rated Output (c).(d)-No Load Output
Time Scale-5[μs/div]

side switches. Regarding this, proposed power converter can achieve ZVS for all load variation ranges and the PWM-based duty cycle strategy in the transformer secondary side.

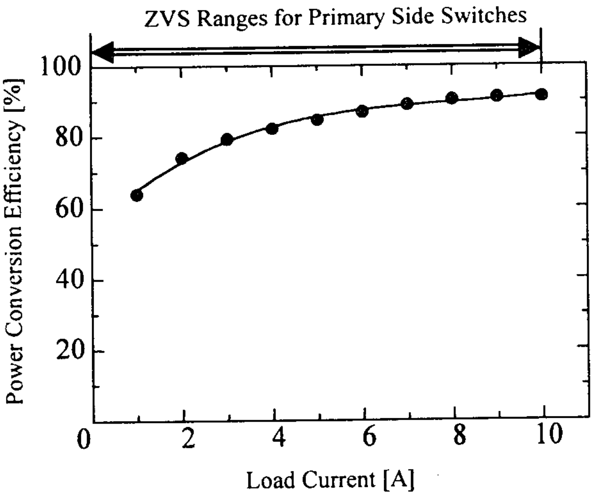


Fig.6 Power conversion efficiency characteristics in constant voltage control closed loop operation (under v_{out}=230[V])

6 EXTENDED CONVERTER TOPOLOGY

Fig.7 depicts an extended converter topology. This is transformer parasitic components assisted soft-switching DC-DC converter with voltage doubler rectifier (a) and current doubler rectifier (b). These converters also can achieve zero voltage switching in primary side active power switches and zero current switching in secondary side active power switches. In these converters, gate pulse signal of all the active power switches and output voltage control scheme is similar to proposed converter with full bridge type rectifier.

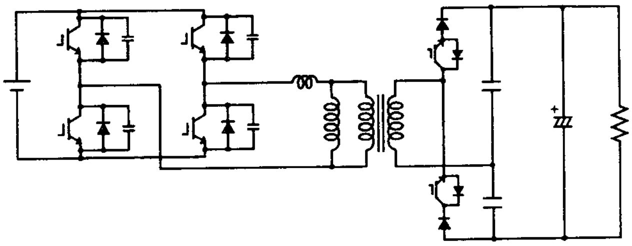


Fig.7(a) proposed DC-DC converter with voltage doubler rectifier

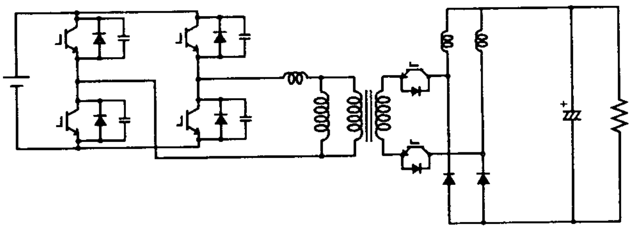


Fig.7(b) proposed DC-DC converter with current doubler rectifier

7 CONCLUSIONS

A novel soft-switching DC-DC power converter circuit topology using the zero voltage soft-switching(ZVS)in active power switches of the transformer primary side and secondary-side phase-shifted PWM rectifier with a capacitor input type smoothing filter which is based on synchronous zero current soft-switching(ZCS) active power switches in high-frequency transformer secondary side has been presented in this paper. Its operation principle and unique salient features have been described and discussed on the basis of simulation and experimental results obtained by 2kw-40kHz converter breadboard set up. It has been proved that the proposed soft-switching DC-DC converter using IGBT power modules can lower commutating current required for achieving soft-switching operation because the ZVS commutation is not influenced upon the load current condition and PWM-based duty cycle strategy. As a result, total switching losses were considerably reduced in comparison with previously-proposed soft-switching transformer primary-side phase-shifted PWM DC-DC power converter under a condition of lowered output power regulation range. Furthermore, it was noted that the proposed soft-switching DC-DC converter with active power switches in transformer secondary side could completely achieve soft-switching operation independently of the load current conditions and PWM regulation scheme.

In the future, the dynamic operating performances of this soft-switching PWM power converter should be evaluated for the power conditioning and processing systems for new energy utilization systems; small scale fuel cell based cogeneration and solar photovoltaic power generation. The switching frequency of this converter should be increased up to several hundred kHz using advanced MOSFETs for further realization of further downsizing and high-dynamic performance.

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