ZVS Operating Range Extension Method for High-Efficient High Frequency Linked ZVS-PWM DC-DC Power Converter

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Abstract: In this paper, a full bridge edge-resonant zero voltage mode based soft-switching PWM DC-DC power converter with a high frequency center tapped transformer link stage is presented from a practical point of view. The power MOSFETs operating as synchronous rectifier devices are implemented in the rectifier center tapped stage to reduce conduction power losses and also to extend the transformer primary side power MOSFETs ZVS commutation area from the rated to zero-load without a requirement of a magnetizing current. The steady-state operation of this phase-shift PWM controlled power converter is described in comparison with a conventional ZVS phase-shift PWM DC-DC converter using the diodes rectifier. Moreover, the experimental results of the switching power losses analysis are evaluated and discussed in this paper. The practical effectiveness of the ZVS phase-shift PWM DC-DC power converter treated here is actually proved by using 2.5kW-32kHz breadboard circuit. An actual efficiency of this converter is estimated in experiment and is achieved as 97% at maximum.

Keywords: Phase-Shift PWM DC-DC power Converter, High-Frequency Transformer Link, Zero-Voltage Soft-Switching, Center Tapped Synchronous Rectifier, Power MOSFETs, DSP-based Control Scheme

1. Introduction

In resent years, the problems on the electromagnetic noises generation and increased switching power losses caused by a high frequency hard-switching PWM operation of the active power semiconductor switching devices have become more and more significant. Under this technological background, a variety of soft-switching power conversion circuit technologies using MOS-gate controlled power devices have been attracted special interest for reducing switching power losses and minimizing electromagnetic noises.

In the conventional lossless snubber capacitor assisted edge-resonant type ZVS phase-shift PWM DC-DC power converter, however, the actual soft-switching operation, which can be achieved, practically is narrow. As a result, in full load designed DC-DC converters, the dissipated power losses in active power switching devices under light load can exceed power losses under full load. It causes an increase of the cooling elements. The lowered value of the magnetizing inductance used DC-DC converters have been evaluated. In this DC-DC converters the wide ZVS operating range can be obtained, though the idle magnetizing current make the actual efficiency decreases. [1]-[5]

In this paper, the novel full-bridge edge-resonant voltage mode based soft-switching PWM DC-DC power converter with a center tapped type high frequency transformer link is presented for extending ZVS operating range. The proposed DC-DC converter has power MOSFETs based on synchronous rectifier in its secondary side. The PWM operation of this converter is described in a comparison to conventional ZVS primary side controlled phase-shift PWM DC-DC converter. Due to using power MOSFETs as synchronous rectifier in the secondary side of the high frequency transformer, it is possible to achieve stable ZVS conditions from the rated load to no load without making use of magnetizing current. As a result, due to a high value of the magnetizing inductance design, the actual efficiency of this converter can be achieved as 97% at maximum. The practical effectiveness of the DC-DC power converter presented here is proved in experiment by using 32 kHz 2.5kW breadboard circuit.

2. Proposed Converter Circuit and Its Operation

Figure 1 demonstrates a newly proposed soft-switching DC-DC converter circuit topology with synchronous rectifier. The power MOSFET Q_{O1}, Q_{O2} are used as synchronous rectifier components in the secondary side. The output smoothing filter inductance L_0 is designed as 5 times smaller than rated. Due to using synchronous rectifier Q_{O1}, Q_{O2} as active power switches and reducing output inductance it is possible to support currents i_{Q11}~i_{Q14} to the value required for ZVS operation even under no load.

Figure 2 shows operating voltage and current waveforms of the proposed ZVS Phase-shift PWM DC-DC converter in the case of rated (full) load. Figure 3 illustrates operation principle of the newly presented PWM DC-DC converter circuit topology with synchronous rectifier under no-load condition. Figure 4 demonstrates mode transition and equivalent circuits of the proposed converter when it operates under extremely light load.

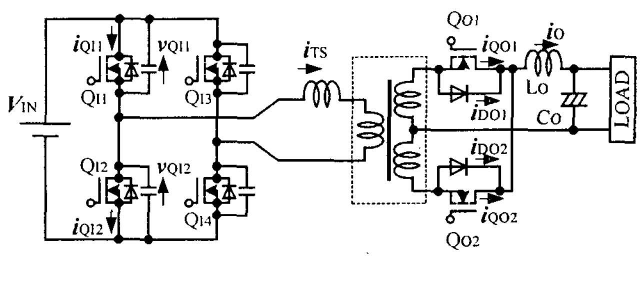

Fig.1. Newly proposed DC-DC converter circuit topology

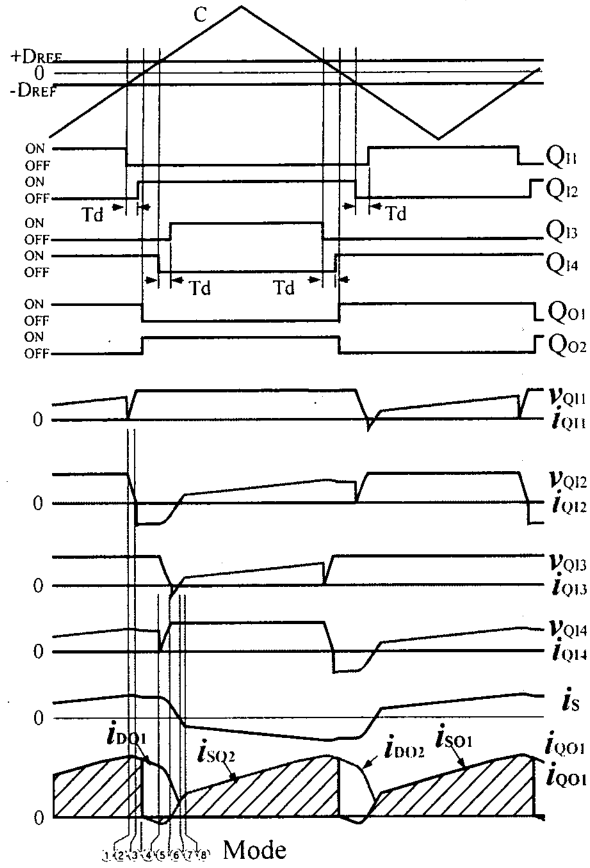

Fig.2 Operating voltage and current waveforms of the proposed DC-DC converter under rated load

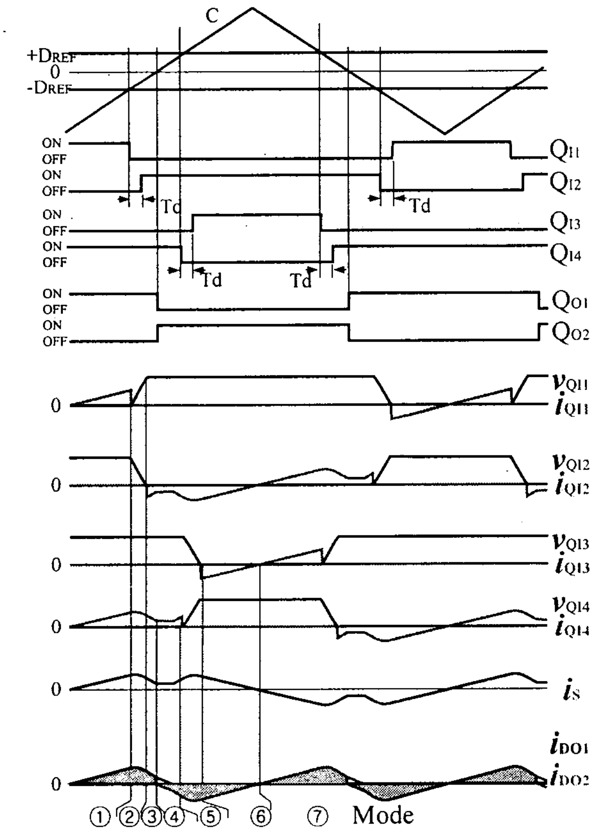

Fig.3 Voltage and current waveforms in case of zero load

The operation of the proposed DC-DC converter under full load (see Figure 2) is the same to the conventional DC-DC converter and its explanations are shortened. The operation under light or zero loads goes as follows (see Figure 3 and Figure 4).

- Mode 1: Power supply mode

The power is transferred from the DC sources Vin through the switches Q_{11}, Q_{14} to the load. The currents flow through the leakage inductance Ls and magnetizing inductance Lp, so the energy is stored in them.

- Mode 2: ZVS turn-off commutation of the switch Q_{11}

The switch Q_{11} is turned off under ZVS. The energy stored in the leakage inductance Ls by means of current $i_{TS}(t_1)$ charge lossless snubber capacitor of the switch Q_{11}. The voltage v_{Q11} across this switch raises with the slope defined by the current $i_{TS}(t_1)$. At the same moment the voltage v_{Q12} across the switch Q_{12} falls down from V_{IN} toward zero.

- Mode 3: Freewheeling interval

After the voltage v_{Q12} across switch Q_{12} reaches zero the body diode of this switch starts to conduct. The gate pulse to the switch Q_{12} is supplied during this interval. Moreover, during this interval the current io through Lo decreases, crosses zero and changes direction.

- Mode 4: Q_{01} turn-off/Q_{02} turn-on commutations

The switch Q_{01} turns off; and the whole output current flows through the switch Q_{02} in the direction from load to the transformer. Due to this current *io* from load through the switch Q_{02}, the current of the switch Q_{14} is boosted.

- Mode 5: ZVS turn-off commutation of the switch Q_{14}

The switch Q_{14} is turned off with ZVS by means of the boosted current i_{TS}. The voltage v_{Q14} across the switch Q_{14} raises to Vin. At the same moment, the voltage v_{Q13} across the switch Q_{13} falls to zero. The voltage v_{Q13} must reach zero before the gate pulse is applied to this switch to obtain ZVS commutation.

- Mode 6: ZVS and ZCS turn-on commutation of the switches Q_{12} and Q_{13}

The voltages across the switches Q_{12} and Q_{13} are zero and their body diodes are conducting. The switches Q_{12} and Q_{13} turn on with ZCS and ZVS.

- Mode 7: Power supply mode

The power is transferred from the DC source *Vin* through the switches Q_{12}, Q_{13} to the load. The currents flow through the leakage inductance *Ls* and magnetizing inductance *Lp*, so the energy is stored in them. The next half cycle operation of the DC-DC converter is the same, and its explanation is shortened.

The ZVS operation range of Q_{13} and Q_{14} is extended to zero load due to the transformer secondary side current i_{Q02} (i_{Q01}) supporting primary side current i_S as can be seen from Mode 4 and Mode 5 (see Figure 4).

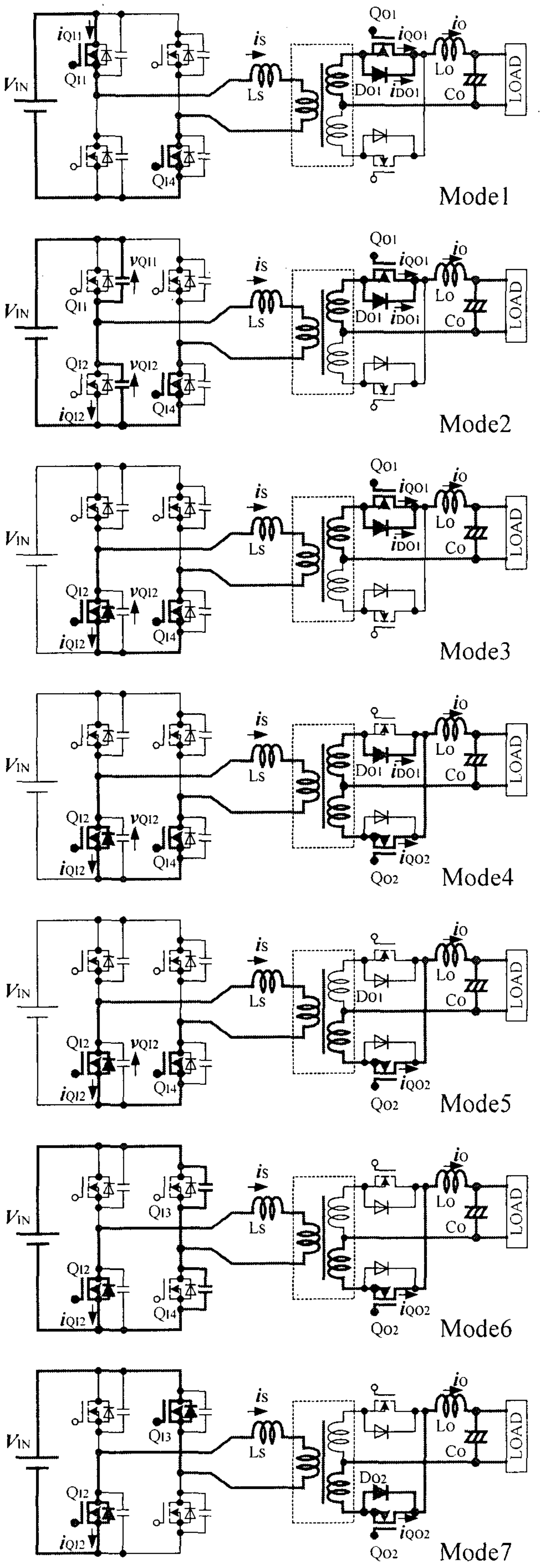

Fig.4. Mode transition and equivalent circuits

3. Experimental Results

To verify practical effectiveness of the proposed ZVS phase-shift PWM DC-DC converter circuit topology with synchronous rectifier the experiment is carried out. The 32 kHz 2.5kW breadboard setup is tested. The design specifications of the experimental breadboard circuit and circuit parameters are indicated at Table 1.

Figure 5 presents the experimental converter setup circuit structure.

Figure 6 demonstrates measured voltage and current operating waveforms under a condition of load current 50A at full load. All the active power switches operate with soft-switching conditions and no circulating currents flow through primary side in case of rated load.

Measured voltage and current waveforms under a condition of no-load are shown in Figure 7. The soft-switching conditions are obtained for switching devices without using the magnetizing current.

Table 1 Design specifications of experimental setup and circuit parameters

Input DC Voltage V_{IN}	350VDC
Output DC Voltage V_O	51V
Operating Frequency f_S	32kHz
Primary side MOSFETs Q_{11}~Q_{14}	2SK1522×3 in parallel
Secondary side MOSFETs Q_{O1}, Q_{O2}	2SK3154×6 in parallel
Lossless snubber capacitors C_{11}~C_{14}	4.7nF×2 in parallel
Leakage inductance L_S	20μH
Output filter inductance L_O	6μH
Output filter capacitor C_O	1000μF×6in parallel
High Frequency Transformer Core	PQ50/50 Ferrite PC44

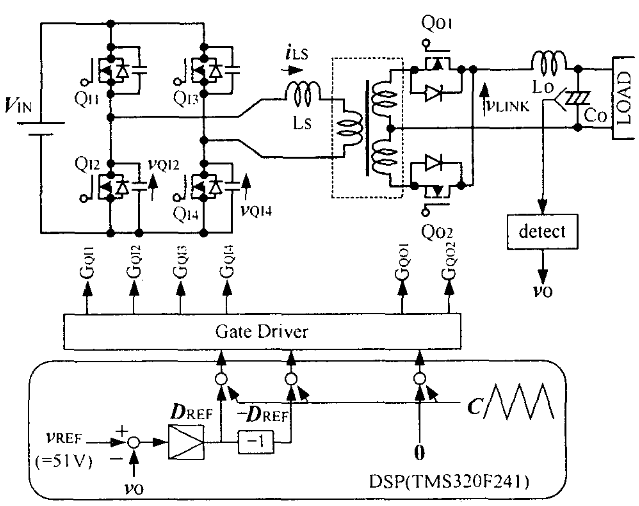

Fig.5. Experimental converter setup

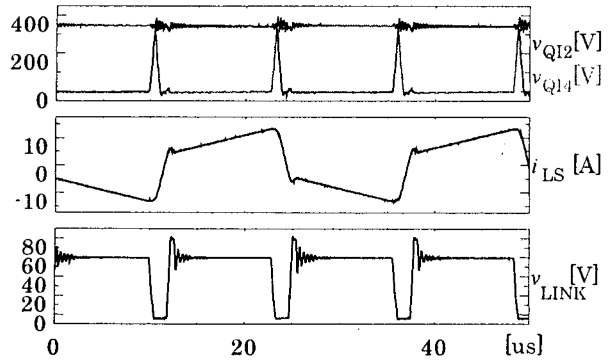

Fig.6. Measured voltage and current waveforms under condition of load current 50A

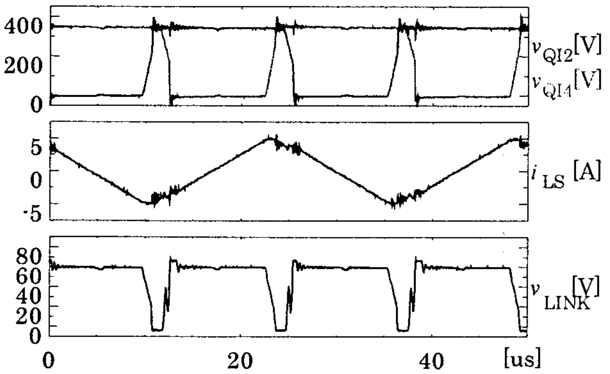

Fig.7. Measured voltage and current waveforms under condition of no-load

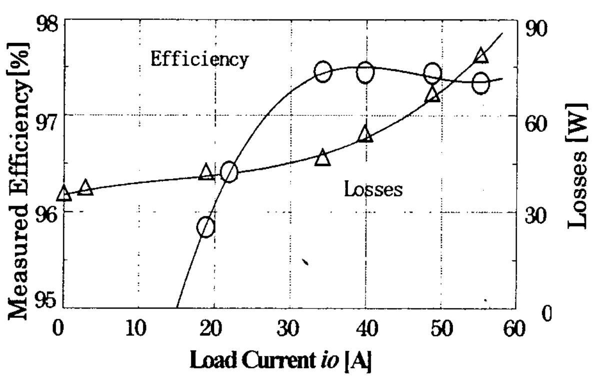

Fig.8. Efficiency and power loss vs. load current characteristics

Figure 8 represents measured actual efficiency and power losses under different load current characteristics As result of a high value of the magnetizing inductance design, the power converter actual efficiency of this converter can be obtained above 97%.

4. Conclusions

The quasi-resonant voltage mode based soft-switching phase-sift PWM DC-DC power converter with a high frequency transformer link was presented in this paper. The synchronous rectifier was implemented in the secondary side center-tapped transformer of the proposed converter. The PWM operation of this converter was described in comparison with conventional one. Due to using power MOSFET as synchronous rectifier in the secondary side of the high frequency isolated transformer, it is possible to extend stable zero voltage soft-switching (ZVS) commutation of the active power switches from no load to the rated load with no requirement of a magnetizing current. As result of a high value of the magnetizing inductance design, the power converter actual efficiency of this converter is achieved as 97% in experiment. Moreover, results of the switching losses analysis were discussed from an experimental point of views in this paper. The feasible effectiveness of the power converter treated here was proved by using 32 kHz 2.5kW breadboard circuit.

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