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A Simple ZVT PWM Single-Phase Rectifier with Reduced Conduction Loss and Unity Power Factor

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ABSTRACT

This paper proposes a simple unity power factor zero-voltage-transition (ZVT) pulse-width-modulated (PWM) single-phase rectifier, which features reduced switching and conduction losses. The switching loss reduction is achieved by a simple auxiliary commutation circuit, and the conduction loss reduction is achieved by employing a single-stage converter, rather than a typical double-stage converter comprising of a front-end rectifier and a boost rectifier. Furthermore, thanks to good features such as a simple PWM control at constant frequency, low switch stress, low Var rating of commutation circuits, and simple power circuit structure, it is suitable for high power applications. The principles of operation are explained in detail, and a major characteristics analysis and the experimental results of the new converter are also included in this paper.

Keywords: Rectifier, Single-phase, Zero-Voltage-Transition (ZVT), Conduction loss, Unity power factor, PWM converter

1. Introduction

Nowadays, as the number of switching power supplies used in industries and homes increases, input current harmonic reductions and power factor improvements are receiving increasing pressure to satisfy harmonic standards such as IEC 61000-3-2 and IEEE-519 as well as to improve system efficiency. So far, several different power circuit schemes have been proposed, and some dedicated power factor corrected IC controllers are currently available.

One of the most popular power circuit schemes for power factor correction is the boost converter topology shown in Fig. 1(a). The topology is composed by a front-end rectifier followed by a boost DC/DC converter. However, this converter suffers from considerable conduction losses and switching losses because there are three semiconductors in the current path and their switch operation is hard-switched. For switching loss reduction of the converter, some different techniques have been proposed. The techniques in [1]-[2] achieve soft switching operation by using commutation circuits with auxiliary switches. Owing to the soft switching operation, they significantly improve the circuit efficiency and also reduce

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circuit EMI noise and acoustic noise. However, the problem of converter conduction loss is still present due to the circuit topology.

In order to reduce considerable conduction losses inherent in the above-mentioned converters, Ref [3] presents a different type of converter, that is, low conduction loss AC/DC converter which is shown in Fig.1 (b). It features much lower conduction losses because the current always flows through two semiconductors only, instead of three semiconductors in the front end followed by a boost converter Even so, the converter has considerable commutation losses in the main switches and diodes due to hard switching. So some efforts in reducing commutation losses have been made as proposed in [4]-[6]. One of the converters achieves soft switching by using an auxiliary commutation circuit [4]. But the auxiliary commutation circuit should include an additional active switch and transformer, and its control circuit. Another low power level converter which also achieves soft switching is uses a quasi-resonant circuit without an additional active switch [5]. However, this type of converter needs to be controlled by frequency modulation, not by pulse width modulation. The major drawbacks of this quasi-resonant type circuit are high current and voltage stress on the main switches and diodes and high reactive power (VAR) consumption in the resonant inductors and capacitors. Ref [6] presents a soft switching unity power factor PWM rectifier, which considerably improves circuit efficiency by soft switching the main switches through a commutation circuit without any auxiliary switches, and also achieves significant reduction of conduction losses thanks to a single-stage converter topology instead of a front-end rectifier followed by a boost converter. However, it has some disadvantages because it needs a number of power circuit devices.

Therefore, this paper proposes a simple ZVT PWM unity power factor PWM rectifier. Its power circuit consists of a combined low conduction loss AC/DC converter and a simple ZVT circuit. ZVT soft switching is achieved by using the simple ZVT circuit, and reduced conduction losses are achieved by employing a single-stage converter, instead of a typical double-stage converter composed of a front end diode rectifier and a cascaded boost rectifier. Furthermore, thanks to such beneficial features as a simple PWM control at constant frequency, low switch stress, low VAR rating of commutation circuits, and simple power circuit structure, it is suitable for high power applications.

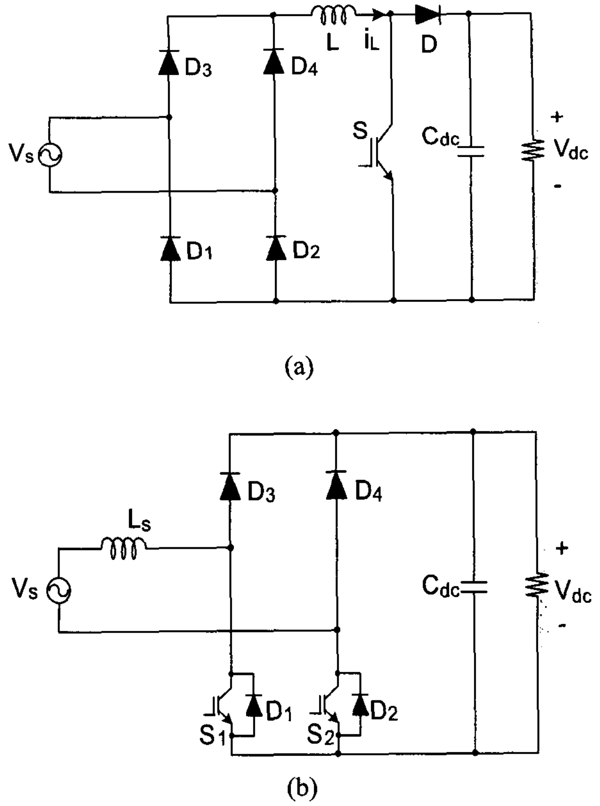


Fig. 1 Circuit diagrams of the conventional power factor correction topologies (a) front-end rectifier followed by a boost converter, (b) low conduction loss AC/DC rectifier

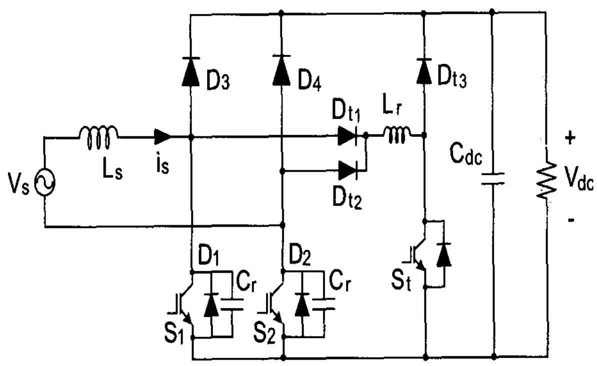


Fig. 2 Circuit diagram of the proposed ZVT PWM Unity Power Factor Single-Phase Rectifier

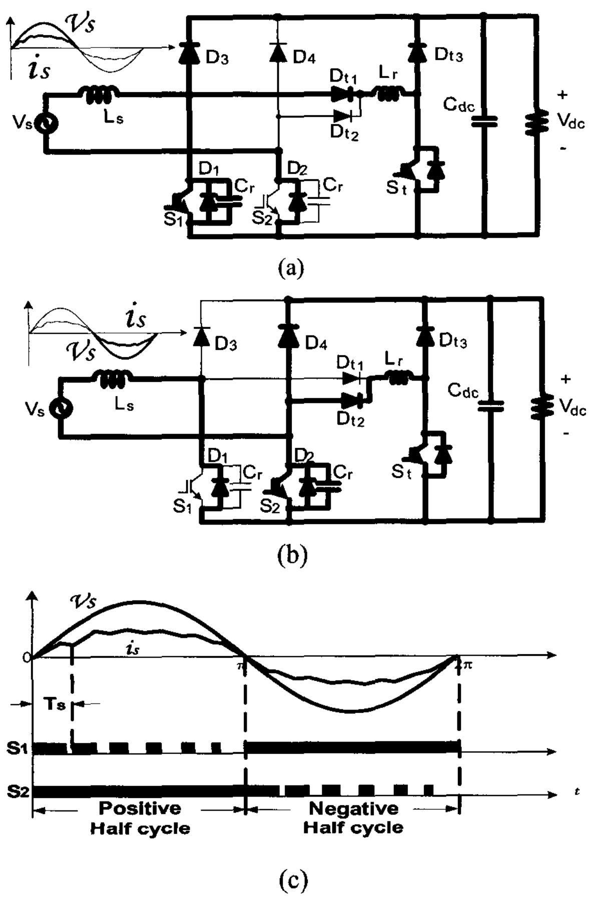


Fig. 3 Typical waveforms of the proposed ZVT PWM unity power factor Single-Phase rectifier (a) operating circuit(thick line) during positive half cycle of AC source voltage V_S, (b) during negative half cycle (thick line) and (c) related waveforms

2. Principles of Operation of Proposed Converter

The power stage circuit diagram of the proposed converter is shown in Fig. 2. The circuit can be divided into two parts. The first part is a pulse-width-modulated continuous current mode single-phase AC/DC converter which is composed of L_S, S_1, S_2, D_1-D_4, and C_{dc}. It operates as two boost DC-DC converters, each one in a half cycle of the input AC voltage. The second part is a ZVT commutation circuit to provide the first part with soft switching operation. It is composed of a small IGBT S_t, resonant inductor L_r, diodes D_{t1}, D_{t2}, D_{t3}, which are rated for low power when compared to the output power.

The overall operation can first be divided into two half cycles depending on the polarity of the AC input voltage. The positive half cycle and negative half cycle are shown in Fig. 3. For unity power factor operation, the current waveform is the same as the voltage. Thus, during the positive half cycle only a combination of S_1, D_2 and D_3 works as main switches. While during the negative half cycle only S_2, D_1, and D_4 work. For each half cycle, each combination of the main switches operates as a basic boost converter. The current path from the input AC power supply to the DC output includes only two semiconductors, that is, two semiconductor voltage drops, which achieve significant reduced conduction losses. The ZVS switching for both the main IGBT devices and the rectifier diodes are achieved through a simple ZVT commutation circuit, which results in improved circuit efficiency. Furthermore, since the ZVS switching occurs during a short time when compared to the switching period, it does not have significant influence on the overall output characteristics of a basic AC/DC converter such as PWM control and linear input and output conversion characteristics.

When looking into the operation of the proposed converter in more detail, its operation can be divided into 7 operational modes for one switching period, T_S as shown in Fig. 4 and 5. Since the operation of the positive half cycle is the same as that of the native half cycle, only the operation of the positive half cycle is explained as follows under assumptions that

1) initial voltages of C_1 and C_2 and initial current of resonant inductor i_{Lr} are V_{dc}, 0, and 0, respectively,
2) the capacitances C_1 and C_2 are the same,
3) and the AC source voltage is almost constant during one switching period.

•**Mode 1** (Fig. 4(a)): Linear mode

At the beginning of this mode, a gate signal is applied to the drive circuit of IGBT S_t. Thus IGBT S_t and diodes D_2, D_3 are conducting, while the current through D_3 begins to decrease linearly to zero level while the current through Lr, D_{t1}, and S_t increases from zero at the same rate. So the operation enables S_t to achieve ZCS turn-on switching. And diode D_3 avoids any severe reverse recovery problems by designating the rate of change of resonant inductor current i_{Lr1}. As diode current i_{D3} reaches zero, diode D_3 is turned-off and the next mode starts.

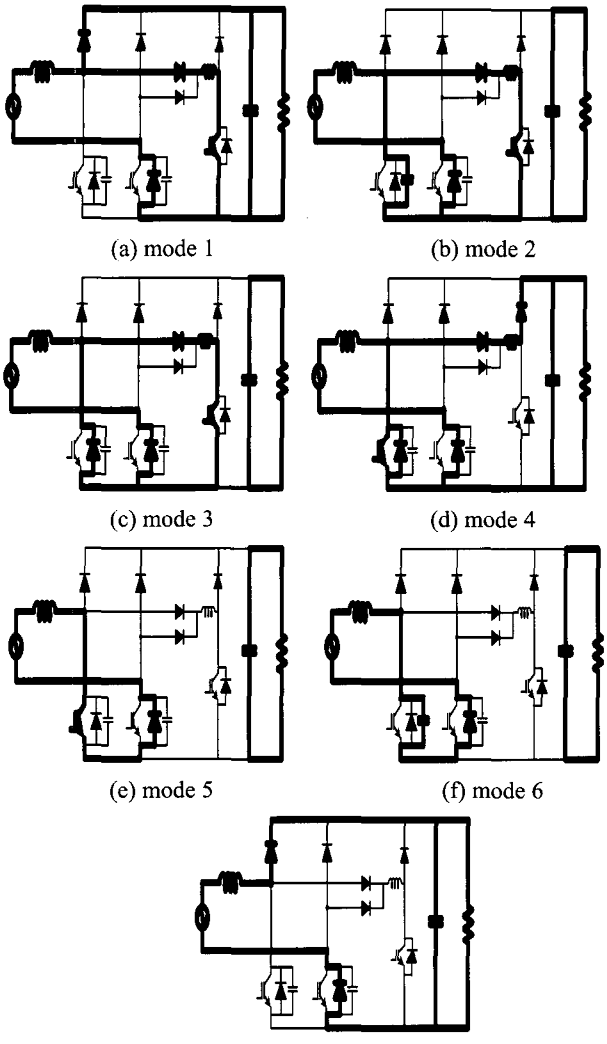

(a) mode 1 (b) mode 2 (c) mode 3 (d) mode 4 (e) mode 5 (f) mode 6 (g) mode 7

Fig. 4 Operation modes during one switching period TS of proposed ZVT PWM rectifier (a) mode 1, (b) mode 2, (c) mode 3, (d) mode 4, (e) mode 5, (f) mode 6, (g) mode 7

•**Mode 2** (Fig. 4(b)) : Resonant mode

During Mode 2, resonant operation occurs by a resonant circuit composed of L_r and C_1. Capacitor C_1 begins to discharge in a resonant way from V_{dc} to zero. The operation ensures the smooth recovery process of diode D_3 by providing the diode with ZVS turn-off. When capacitor voltage v_{C1} is discharged equal to zero, diode D_1 turns on, and then the next mode starts.

•**Mode 3** (Fig. 4(c)) : ZVS turn-on mode

During this mode, part of current i_{Lr} freewheels through diode D_1 and capacitor voltage v_{C1} is equal to zero voltage. Thus IGBT switch S_1 has a chance to turn on under the condition of ZVS switching. By turning on switch S_1 and turning off S_t the next mode starts.

•**Mode 4** (Fig. 4(d)): Resetting mode

By turning off auxiliary switch S_t, the current through S_t diverts to D_{t3}. Current i_{Lr} through Lr decreases linearly with a slope of V_{dc}/L_r. When the current is reset to a zero level, the next mode will start.

•**Mode 5** (Fig. 4(e)): Energizing mode

This mode is similar to the energizing mode of the basic boost converter PWM counterpart. The source current through source inductor L_S continues to increase linearly with a slope of Vs/Ls until the IGBT S_1 is turned off.

•**Mode 6** (Fig. 4(f)): Resonant mode

At first, main switch S_1 is turned off, then source current i_S begins to charge capacitor C_1 from zero to V_{dc}. At the end of this mode, when C_1 is charged fully to output voltage V_{dc}, diode D_3 turns on and the next mode starts.

•**Mode 7** (Fig. 4(g)): De-energizing mode

This mode is similar to the de-energizing mode of the basic boost converter PWM counterpart. The current through L_S decreases linearly and the stored energy in Ls will be transferred to the output stage. At the end of this mode, IGBT S_t turns on and the next cycles starts.

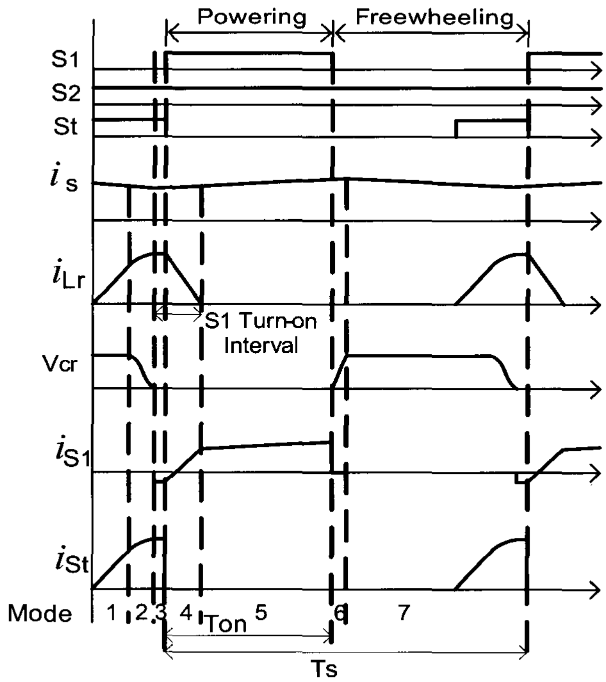


Fig. 5 Typical waveforms during one switching period of the proposed ZVT PWM rectifier

3. Control of the Proposed ZVT PWM Single-Phase Rectifier

Fig. 6 shows the overall configuration of the proposed rectifier which consists of two parts, that is, an AC input-side circuit and PWM AC/DC converter. First, the AC input-side circuit is made up of a no-fuse breaker (NFB), fuse, magnetic contactor 1 (MC1), magnetic contactor 2 (MC2), charging resistor RP and discharging resistor Rdch for a DC link capacitor, and auxiliary contacts RMC1 and RMC2 of contactors MC1 and MC2, respectively. The main function of the AC input-side circuit is to start and stop the overall system, and smoothly charge and discharge the DC link capacitor during initial starting and stopping intervals. Second, the PWM AC/DC converter, which consists of AC reactor Ls, full bridge IGBTs and DC link capacitor C_{dc}, controls input power factor to almost unity value, and regulates the DC link voltage to a nominal value of 400 [V]. For smooth start/stop operation, the proposed rectifier is controlled according to the timing chart shown in Fig. 7.

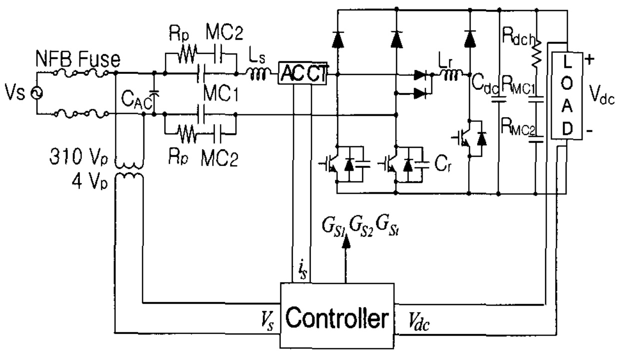


Fig. 6 Overall configuration of the proposed ZVT PWM rectifier

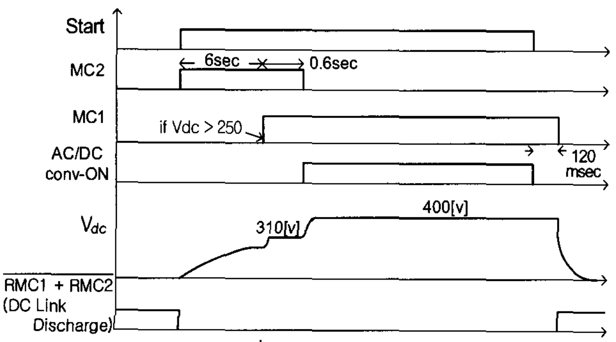


Fig. 7 Overall operating timing chart of the proposed ZVT PWM rectifier

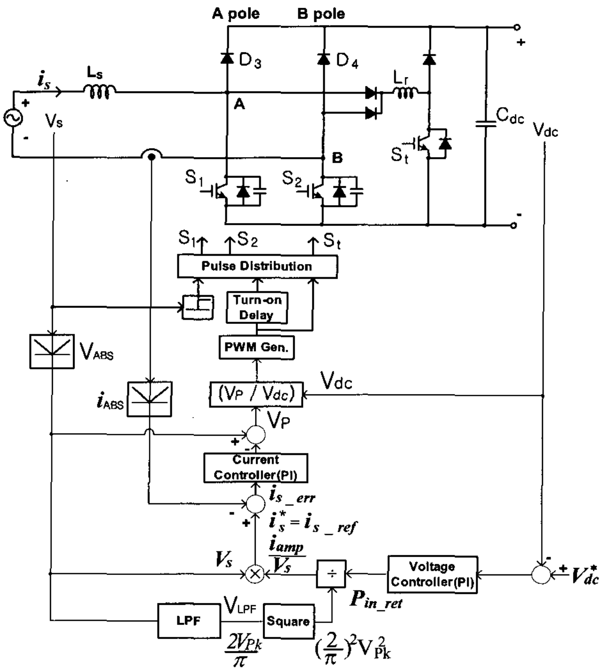


Fig. 8 Detailed feedback and feedforward control block diagram of ZVT PWM rectifier

Fig. 8 describes the detailed feedback and feedforward control block diagram of the single-phase AC/DC converter in detail. The control block diagram is largely composed of a line current control loop, DC link voltage control loop, and two AC line voltage-related feedforward controls. The line current control loop, as an inner loop, is composed of a PI current controller, a modulation waveform calculator, a PWM generator, an AC/DC converter, and an AC reactor. Its function is to control input line current i_S in phases with source supply voltage waveform v_S for the unity line power factor operation. To accomplish this, line current command $i_S{}^*$ is obtained by multiplying sensed supply voltage v_S by magnitude information i_{amp} of line current obtained from the DC link voltage control loop of the outer loop, and can be expressed as

$$i_s^* = |v_s| \left(\frac{P_{in\_ret}^*}{4V_{pk}^2 / \pi^2} \right) \tag{1}$$

where V_{Pk} is the peak value of supply voltage v_S and
where V_{Pk} is the peak value of supply voltage v_S and
$P^*_{in\_ref}$ is the input power command of the rectifier obtained from the PI controller of outer DC link voltage

control loop. On the other hand, the DC link voltage control loop is composed of a LPF, a PI voltage controller, a divider, a line current control loop, and a DC link capacitor to regulate the DC link voltage at a constant value.

Two AC line voltage-related feedforward controls are shown in the control block diagram of Fig. 8. One of them is composed of an absolute block, LPF, squarer, and divider to detect peak value V_{Pk} of supply voltage v_S. Peak value V_{Pk} is utilized to determine line current command i_S^* as shown in (3). Its function is to dampen variations in DC link voltage V_{dc} due to sudden changes in magnitude of line voltage v_S and thus makes it independent of sudden changes in the line voltage. For instance, without such feedforward control, a sudden increase in line voltage would result in an increase of line current, and in turn increases DC link voltage, and vice versa. The other feedforward control is to add line voltage to PWM reference signal V_P just before calculating the modulation waveform m_l given by

$$m_l = \frac{V_p}{V_{dc}} \tag{2}$$

Hence, at the initial stage of PWM operation while starting the AC/DC converter, pole-to-pole voltage v_{AB} which is, in a transient state, is equal to line voltage v_S, thus considerably eliminating large in-rush current which would normally occur without the feed forward control. Furthermore, thanks to this, the line current control is, in steady state, free from variations in the input line voltage that would function as a disturbance, thus facilitating the design of the current controller.

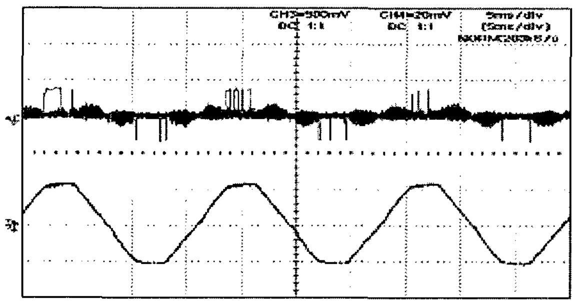


Fig. 9 Input line current i_S (upper) [10A/div] and voltage v_S (lower) waveforms at no load condition [250V/div], V_{dc} = 400[V]

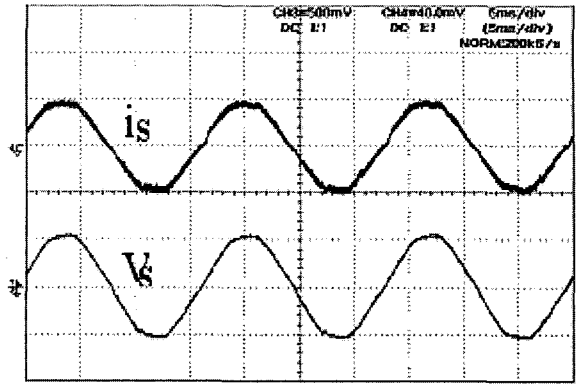


Fig. 10 Input line current i_S (upper) [100A/div] and voltage v_S (lower) waveforms at 12 kW of full load [250V/div], V_{dc} = 400[V]

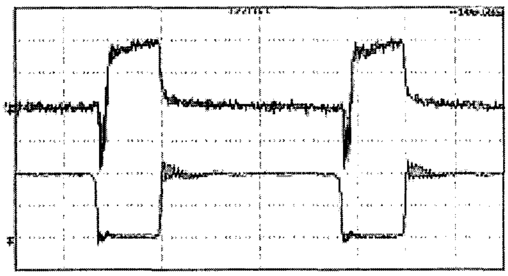
4. Experimental Results

The proposed ZVT PWM single phase PWM rectifier was implemented with rating power 12[kW] and controlled output voltage 400[V]. The range of input voltage is AC 180[V] to 260[V] and the output voltage is controlled through PWM operation with a switching frequency equal to 20[kHz]. The proposed converter in this experiment utilizes IXYS IGBT MID300-12A4 of current rating 300[A] for main switching devices S_1, S_2, D_1, D_2, D_3, D_4, IXYS DESI2×31 for auxiliary diodes D_{t1}, D_{t2}, IXYS MID150-12A4 for S_t, D_{t3} of commutation circuit, electrolytic capacitor of 450[V], 6800[μF] of output filter capacitor, steel core of 500[μH], 90[A] for input filter LS, ferrite core inductor of 5[μH], 90[A] for resonant inductor Lr, and polypropylene capacitor of 50[nF], 600[V] for resonant capacitor Cr (C_1, C_2).

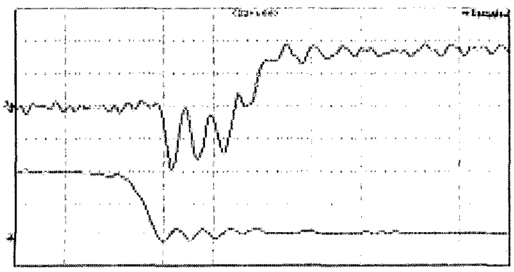
Fig. 9 shows measured input line current i_S (upper) and line voltage v_S (lower) waveforms at no load condition. As shown in Fig. 9, there is almost no fundamental component of the input line current, and only its ripple component exists. Fig. 10 shows measured input line current i_S (upper) and line voltage v_S (lower) waveforms at a load condition of 12.0 [kW]. As shown in Fig. 10, the fundamental component of the input line current is almost sinusoidal in phase with the line voltage, thus proving that the AC/DC converter is controlled very well.

Several waveforms of the proposed converter are shown, as in Fig. 11. Fig. 11(a) shows that the switch current and switch voltage of the proposed converter are clamped to the input current and output voltage, respectively, resulting in low current and voltage stress of the switching devices. Fig. 11(b) and (c) show that the proposed converter achieves soft switching at turn-on and turn-off. Fig 11(d) and (e) show that the handling power of the commutation circuit is very small compared to the rated power of the converter, thus enabling the proposed converter be applied to high power applications.

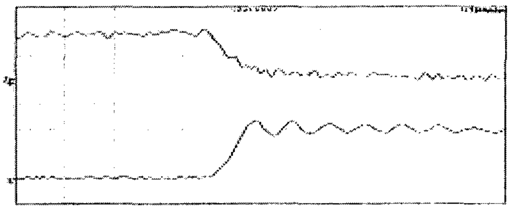
Fig. 12 shows DC link voltage waveform V_{dc} during the starting time interval which can be divided into several operating time periods, that is, the DC link charging period through the anti-parallel diodes of the AC/DC converter, switching-on instant of MC1, DC link charging period by PWM operation of the AC/DC converter, and finally the steady-state period at a DC link voltage of 400[V]. Fig. 13 shows the DC link voltage waveform when applying and then disconnecting rating power 3[kW] of the output load, which proves that the overall control loop of the AC/DC converter operates very well. Fig. 14 shows the measured efficiency of the proposed single-phase rectifier for various loads. As shown in Fig. 14, the efficiency of the proposed single-phase rectifier is improved by almost 1.5-2%. Fig. 15 shows the measured power factor of the proposed single-phase rectifier for various loads. The power factor is controlled at almost unity depending on the load variation.



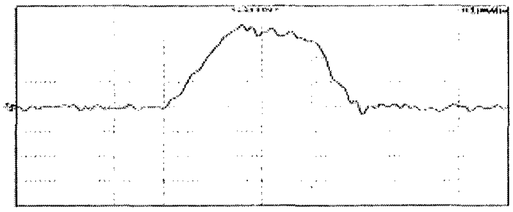
(a)



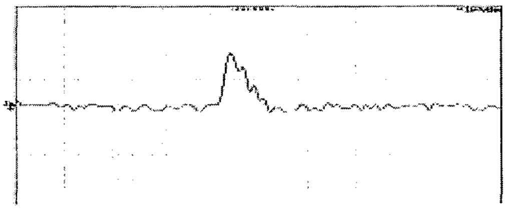
(b)



(c)



(d)



(e)

Fig. 11 (a) Current (top trace) and Voltage(bottom trace) waveforms of switch S_1 (25A/div, 200V/div, 10usec/div), (b) Zoomed current (top trace) and Voltage(bottom trace) waveforms of switch S_1 during ZVS turn-on time interval (25A/div, 200V/div, 1usec/div), (c) ZVS turn off time interval (25A/div, 200V/div, 1usec/div), (d) resonant inductor current i_{Lr} (25A/div, 1usec/div), (e) current i_{Dt3} through diode D_{t3} (25A/div, 1usec/div)

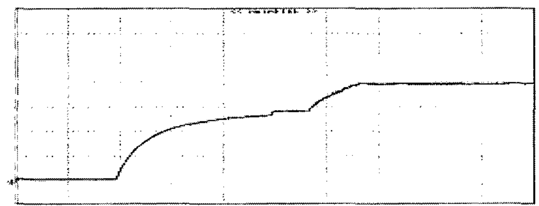


Fig. 12 DC link voltage waveform V_{dc} during starting time interval [100V/div, 2sec/div]

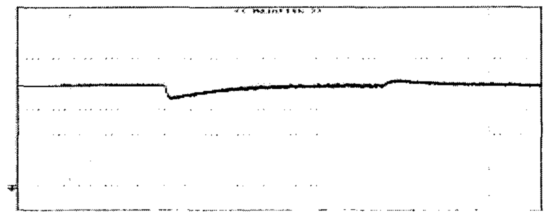


Fig. 13 DC link voltage waveform V_{dc} when applying and disconnecting 3kW load [100V/div, 2sec/div]

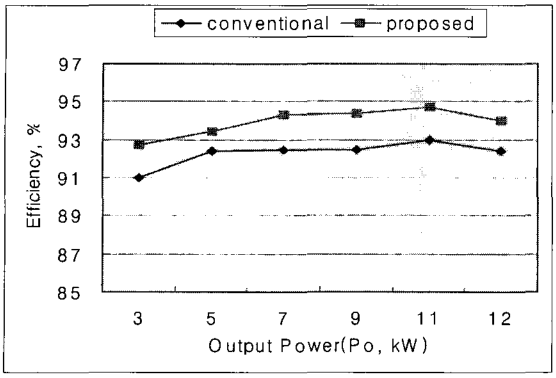


Fig. 14 Measured efficiency of proposed single-phase rectifier for variation of load

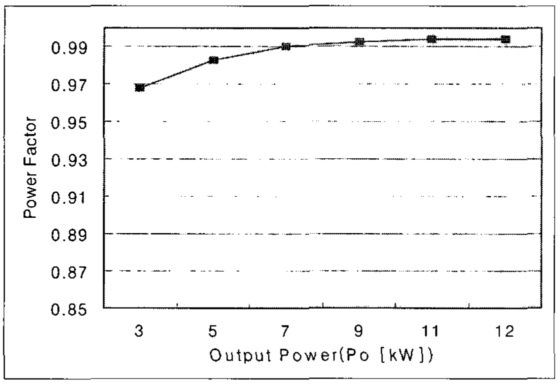


Fig. 15 Measured power factor of proposed single-phase rectifier for variation of load

5. Conclusions

A new simple ZVT PWM unity power factor single-phase rectifier is presented. The proposed rectifier improves circuit efficiency considerably through both switching and conduction loss reductions. The switching loss is reduced by soft commutation of main switches S_1-S_2 and D_1-D_4 using an auxiliary commutation circuit. Conduction loss reduction is achieved by a single-stage converter rather than by the conventional two-stage conversion that employs a front-end rectifier followed by a boost converter. Furthermore, owing to such good features as simple PWM control, low voltage and current stress of the semiconductor devices and low VAR rating of the commutation circuits, it is suitable for high power applications. In summary, the advantages of the proposed converter over those of conventional converters are as follows:

1) Zero voltage switching through a simple ZVT commutation circuit,
2) Significantly reduced conduction losses,
3) Simple PWM control at constant frequency,
4) Low device stress of main switches and low VAR rating of inductors and capacitors,

Acknowledgment

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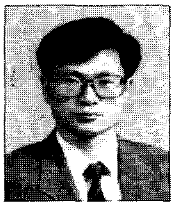

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