The Developing of a Novel Zero-Voltage Zero-Current Switching Full Bridge Converter Using a Simple Transformer Auxiliary Winding

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Abstract

In this paper, a novel zero-voltage zero-current switching (ZVZCS) full-bridge DC/DC converter is presented to improve the previous circuit. The operation principle of previous topology has been analyzed at first. Since the ZVS effect of the previous converter's leading-leg IGBT cannot be realized very well in the light-load situation, the previous ZVZCS full-bridge converter was optimized. For the purpose of testing and validating the operating principle of improved ZVZCS full-bridge converter and all the analysis, the simulation of this novel ZVZCS full-bridge converter has been carried out with the software. With the purpose of charging up the electric vehicle's power storage battery which was used in 2008 Olympic Games, a prototype (10KW 130V/80A) adopting modified ZVZCS converter is designed and validated by experiment. Finally, the experimental results are provided to verify the principle of this novel ZVZCS converter.

Index Terms : Full bridge (FB) converter, phase shift (PS), pulse width modulated (PWM), zero voltage switching (ZVS), zero current switching (ZCS)

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I. Introduction

Full-bridge converter topology is one of the most common circuits in the power technology. In pursuit of the efficient and diminutive power equipment all the while, soft-switching technology has been widely applied as an important instrument at the present time. Researchers have done lots of research work in the field of soft-switching full-bridge converter circuit, and have developed many topologies especially in the high-power power supply, full-bridge converter circuit is the first choice of topology circuits. Since ZVS (zero-voltage switching) full-bridge converter has some obvious advantages, it's quite fitting for applying in the situations of high-frequency and MOSFET adopted switching.

However, when it comes to the situation of high-voltage which is 500 V above and high-power which is 25KW above IGBT (Insulated gate bipolar transistor) will be considered as a power device instead of MOSFET [1]-[5]. but IGBT's higher switching loss which comes from the tail current during the turn-off period, researchers used to adopt ZVZCS (zero-voltage zero-current switching) to reduce the turn-on or turn-off switching loss[7].In this paper, previous phase-shifting controlled ZVZCS full-bridge converter with a simple auxiliary resonance circuit is presented and researched. Besides, this paper deals with its problem that leading-leg cannot realize zero voltage turning on while light-load situation. Through the improvement of the converter, the paper realized soft switching of all loads situation.

2. Principle Of Previous Topology

The previous circuit of ZVZCS full-bridge converter which adopted phase-shifting control has been presented in Figure.1. S_1 and S_3 compose the leading-leg. S_2 and S_4 compose the lagging-leg. The auxiliary resonance circuit consists of Cc, Dc, and Dh. C_1 and C_3 are the capacitances which are added in parallel with the leading-leg. L1k is the leakage inductance of the transformer which acts as a resonance inductance. To illustrate steady-state operation, is assumed that all components and devices are ideal and the output filter inductor is a constant current source. The converter has nine operating modes within each operating half cycle. The operation waveforms have been shown in Figurer. 2[1],[6].

Mode1 (t_0~t_1): Phase of L1k-Cc's resonance and capacitance Cc's charge. S_1 and S_4 are conducing and the input power is delivered to the output. The clamping capacitor Cc begins the resonance with leakage inductance of the transformer. At the end of this mode, the clamping capacitor voltage V_{cc} reaches twice(Vs/k-V0) after a half resonance period, where 1/k is the transformer's turn ratio. There should be a resonance in reverse direction; however, it would not happen because of the diode. Thus this mode is over.

Mode2 (t_1~t_2): Phase of energy transmission. It's an ordinary PWM phase, and energy is transmitted to the load through the transformer. DC is turned off and the rectifier voltage is returned to the nominal value Vs/k.Dh is never turned on during this mode, unless the duty cycle is smaller than 0.5.

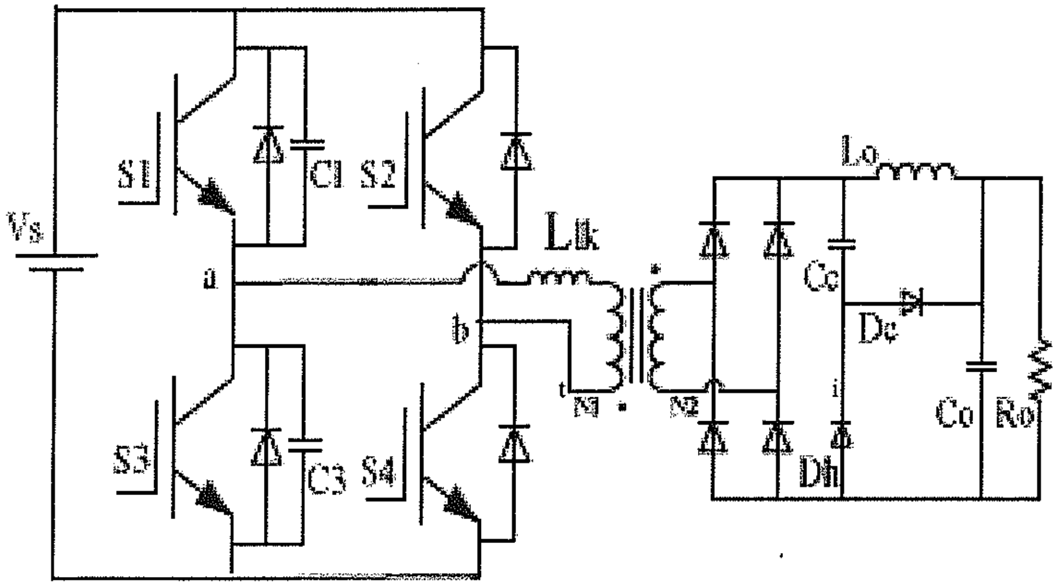

Figure 1: The circuit of previous ZVZCS full-bridge converter.

Mode3 (t_2~t_3): Phase of primary voltage decreases linearly. At the beginning of his phase, S_1 turns off and then the current through the primary charges C_1 and discharges C_3. The primary voltage is linearly decreased and the secondary rectifier voltage is also decreased with the same rate.

Mode4 (t_3~t_4): Phase of primary current starts to decrease. At the time of t_3, the rectifier voltage Vrec decreases to the clamping capacitor V_{cc}, the diode Dh is turned on and Cc provides energy to the load. The stored energy still charges C_1 and discharges C_3. The current of primary side starts to decrease.

Mode5 (t_4~t_5): Phase of primary current decreases rapidly. At the time of t_4, C_3 is completely discharged and then diode DS_3 which is in reverse parallel with S_3 is conducting. S_3 could realize zero-voltage conducting and S_4 provides the current. The current of primary side decreases quickly. The clamping capacitor Cc provides the current of the load, I_c continues to risen. Till the time of t_5, the current of primary side decreases to zero and this phase is over.

Mode6(t5~t6): Phase of energy transmits form Cc to the load. The primary current is completely reset, S_4 keeps on conducting, and no current flows through the primary side. Then, Cc supplies the whole load current and, thus , the secondary rectifier voltage is decreased quickly. Till the ending of this phase, Cc discharges completely and Vrec falls to zero.

Mode7,8 (t_6~t_7~t_8): Phase of secondary current freewheels. In both two phases, the rectifier diodes freewheel all the time. When Cc discharges completely, the rectifier diodes start to conduct and load current freewheels through the rectifier. At the end of the freewheeling period, S_2 is turned off with ZCS, since there is no current in the device.

Mode9(t_8~t_9): Phase of primary current increases linearly. S_2 is turned on. The primary current can't change abruptly

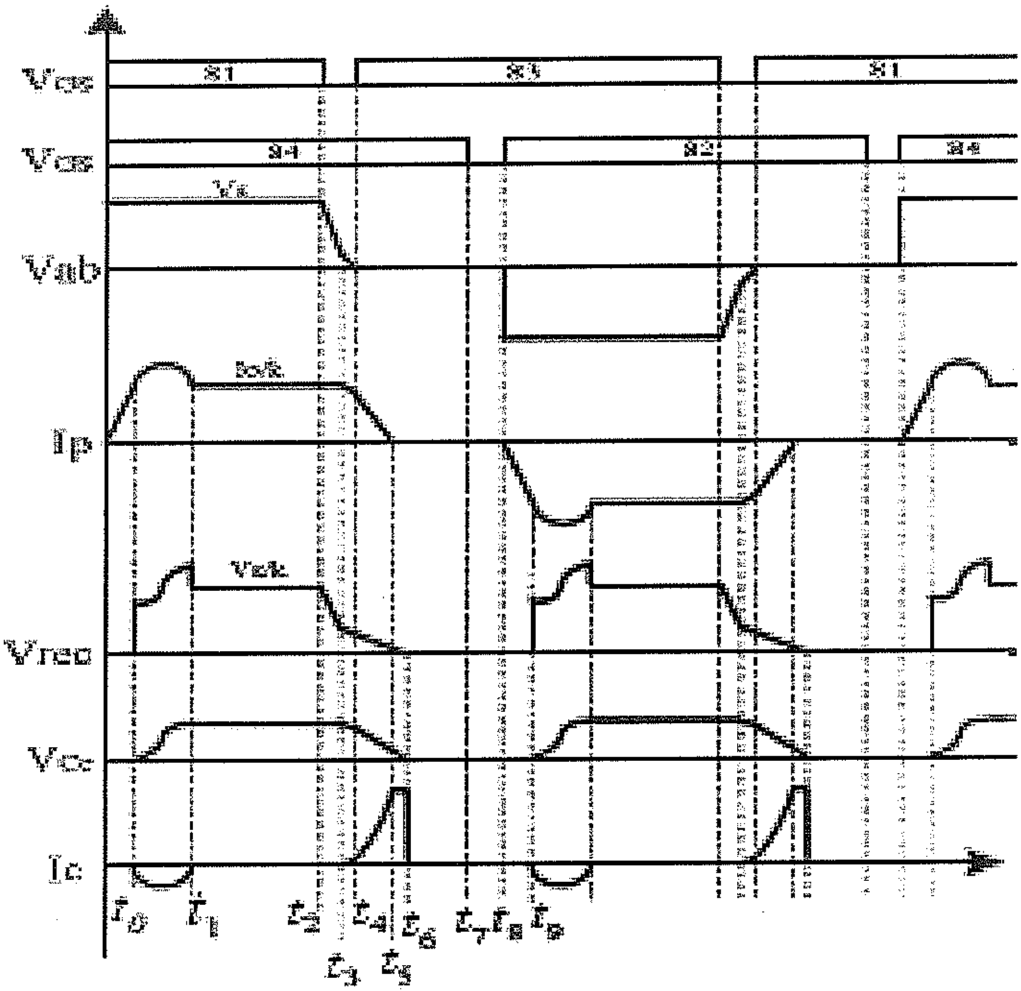

Figure 2 : Waveforms of previous ZVZCS full-bridge converter.

because of the leakage inductance. This turn-on process is also ZCS. After the conduction of S_2, primary current increases linearly. Thus, an operating half cycle is ended.

3. The Improvementof A Previous Zero-voltage Zero-current Switching Full-bridge Converter.

A. The Problem of the Zero-Voltage Zero-Current Switching Full-Bridge converter.

According to the analysis of the previous ZVZCS's characteristics, it is clear that it's difficult to consider both leading-leg's ZVS condition and lagging-leg's ZCS condition at the same time. Generally, researchers have to abandon ZVS of the leading-leg while light-load situation in order to insure that lagging-leg's IGBT could realize ZCS while full-load situation all the same. However, when the leading-leg's IGBT lose the condition of ZVS, the energy that stored in capacitance C_1 and C_3 is released at the moment of IGBT's turning on. This increases not only IGBT's stress of current and loss, but also causes the fact that capacitance C_1 and C_3 are more likely to be broken. If C_1 or C_3 was broken down, S_1or S_3 will be shorted out. Naturally, the reliability of the system is reduced.

With the purpose of charging the electric vehicle's power storage battery which was used in 2008, Olympic Games, we developed a prototype of 10kW modified ZVZCS converter, and its output is 130V/80A consequently, the converter will not be operating in the situation of full load all the time. Charging the storage battery can be divided to two steps: constant current charge and constant voltage charge. When it is step of constant voltage charge, the converter charged the battery in low current output. The converter worked well while full-load situation. Four IGBT's of the full bridge realized soft switching, and the efficiency gone up to 92%.

The ZVS of leading-leg's IGBT cannot be realized while the converter works in the light-load situation. Accordingly an auxiliary circuit was added in front of the leading-leg in order to realize ZVS of leading-leg's IGBT while light load situation. As shown in Figure.3, the auxiliary circuit inside the frame which was drawn in dashed worked independently. Besides increasing the ZVS range of the leading-leg's IGBT, it didn't affect other parts of the converter. As a result, the converter could realize ZVZCS at all range of the load, and the reliability of this system has been risen up.

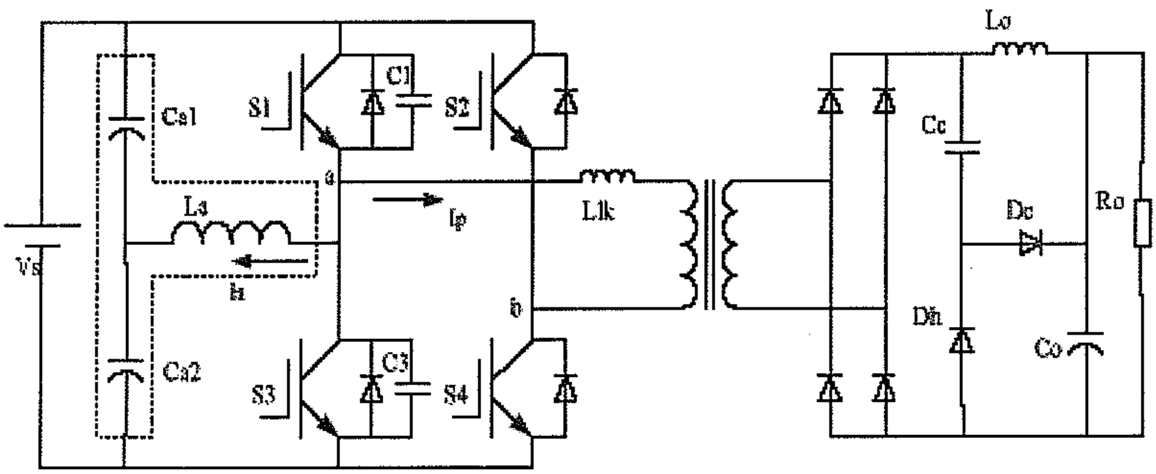

Figure 3 : Improved ZVZCS full-bridge converter

B. Analysis of the Leading-Leg ZVS Principle

The zero-voltage turning off of leading-leg's IGBT Taking S1 as an example, when S_1 is turning on, the voltage of C_1 is zero. When S_1 is turning off, the voltage of C_1 cannot increase abruptly because of the existence of C_1. As a result, the zero-voltage turning off of S_1 has been realized. According to this, the bigger of C_1 and C_3's value, the better effect of zero-voltage turning off of leading-leg's IGBT.

The zero-voltage turning on of leading-leg's IGBT: For the sake of S_1/ S_3's zero-voltage turning on, it's necessary to turn on the diode which is in reverse parallel with S_1/ S_3. Taking S_1 as an example, after the turning off of S_3, S1 will turn on since dead time. In other words, it's necessary to decrease the voltage of C1 to zero during the dead time. S_3 is turned off and then the current charges C3 and discharges C1. It's necessary to insure that the discharging of C_1 has been finished and the diode which is in reverse parallel with S_1 has turned on before the turning on of S_1. Consequently, S_1's zero-voltage turning on has been realized.

C. Auxiliary Circuit Operating Principle

When the current of load is small, Ip is small too Therefore, Ip has fallen to zero before C_1 is discharged completely. With the adding of auxiliary circuit, a current Ia has been supplied to enhance the effect of Ip. The direction of Ia is the same as that of the current Ip which flows in transformer's leakage inductance.

Namely, Ia flows into node a when Ip flows into node a. Contrarily, Ia flows out of node a when Ip does so. Ia enhances the effect of Ip as a result. Both Ip and Ia charge or discharge C_1 an d C_3, so that the realizing range of ZVS has been magnified in leading-leg's IGBT S_1 and S_2

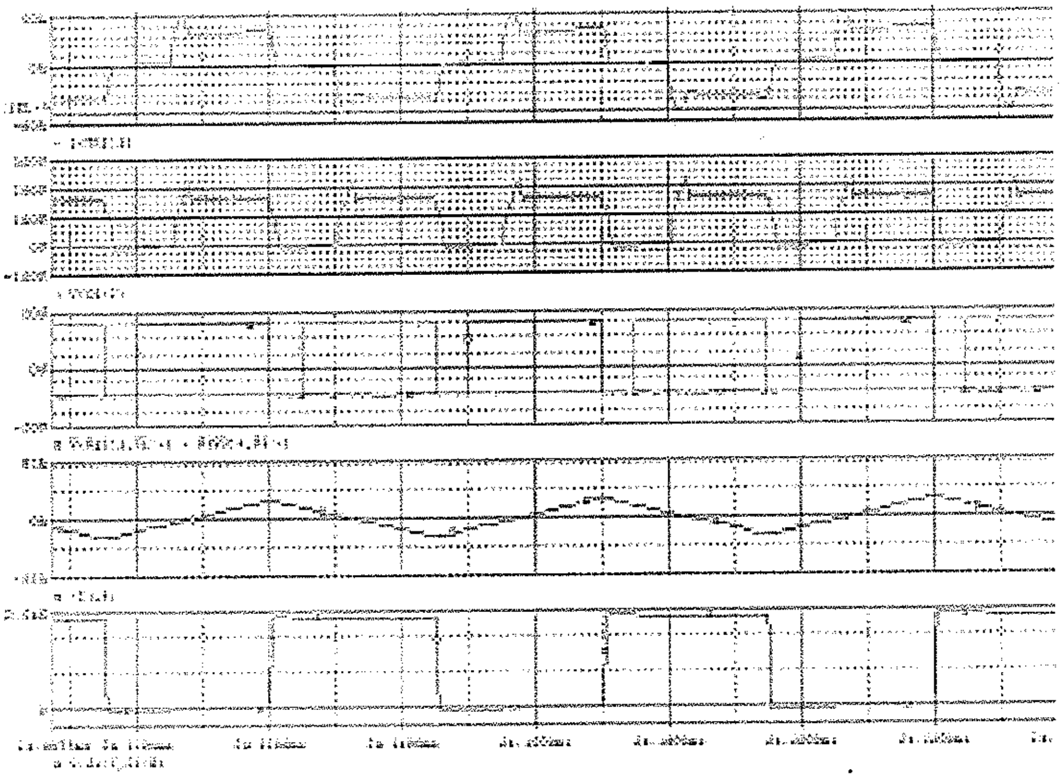

Figure 4 : Simulation waveforms of novel ZVZCS full- bridge converter

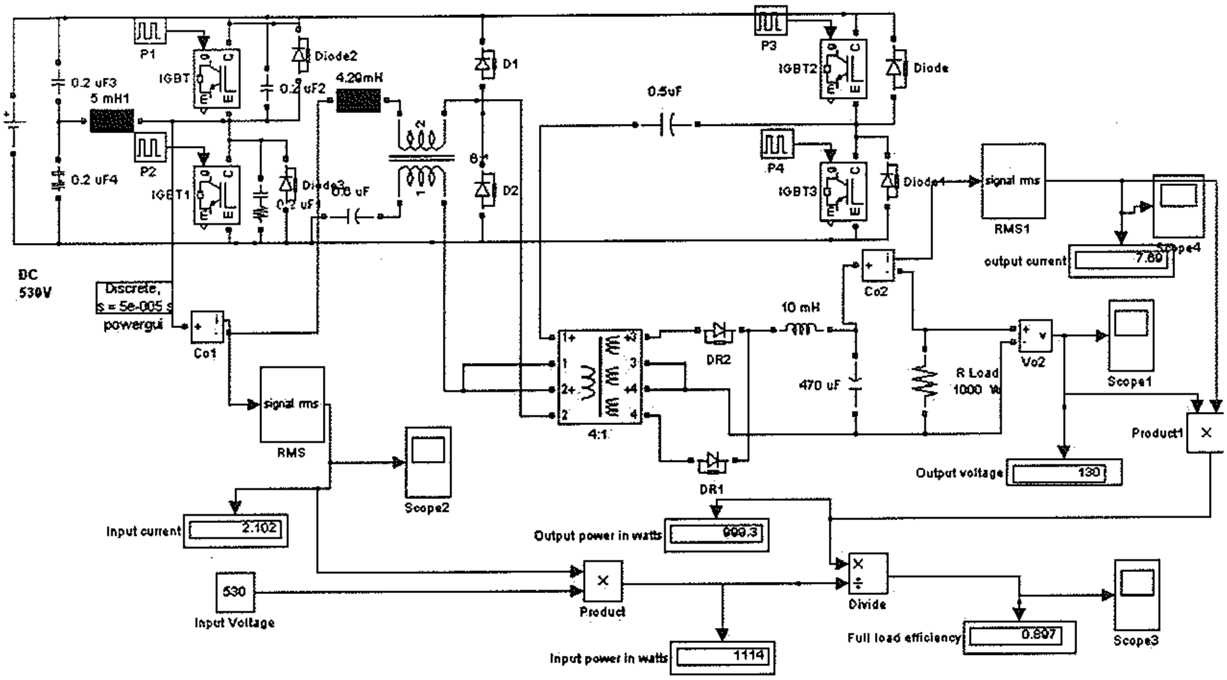

Figure 5 Matlab/Simulink model of proposed zero-voltage zero-current switching full-bridge converter

The value of Ia is negative before S_3 turns off. Since S_3 turns off, Ia and Ip flow into node a together, then discharge C_1 and charge C_3. A moment later, C_1 is discharged up completely while the value of Ia is still negative. The diode Ds1 which is in reverse parallel with S_1 conducts to satisfy the requirement of S_1's zero- voltage conduction. As far as the conducting pulse of S_1has arrived, the absolute value of Ia begins to decrease. During the time that S_1 is conducting, the value of I_a turns to positive from negative. When S1 turned off, I_a and Ip flows out of node a together charging up C_1 and discharging up C_3. C_3 discharges completely after a while, and the value of Ia is still positive. The diode Ds3 which is in reverse parallel with S_3 conducts to satisfy the requirement of S_3's zero-voltage conduction. Till the conducting of S_3, the value of Ia begins to decrease. Since the value of I_a decreases to zero, I_a begins to increase in negative direction.

As it can be seen from Figure. 4: From the top to the end it is waveform of Ip, V_{rec}, trigger pulse of S_1 and S_3, I_a, V_{ce} of S_1 in turn

4. Simulation And Experiment

A complete simulation model of novel zero voltage zero current switching full bridge converter is developed as shown in Figure 5 The performance of the improved machines is investigated. The parameters of the proposed converter in this study are summarized in Appendix A. Figure 6 shows output voltage and current waveform, Figure 7 shows output efficiency and input current waveform. Table 1 presents simulation results of proposed FB ZVZC Switching converter scheme.

Table 1 : Simulation Result Of Proposed Full-bridge Converter

S.No	Factor	Proposed Full-bridge converter
1	Input Voltage	530 V
2	Input Current	2.10A
3	Input Power in watt	1114
4	Output Voltage	130 V
5	Output Current	7.69 A
6	Output Power in watt	999.3
7	Full load Efficiency	89.7%

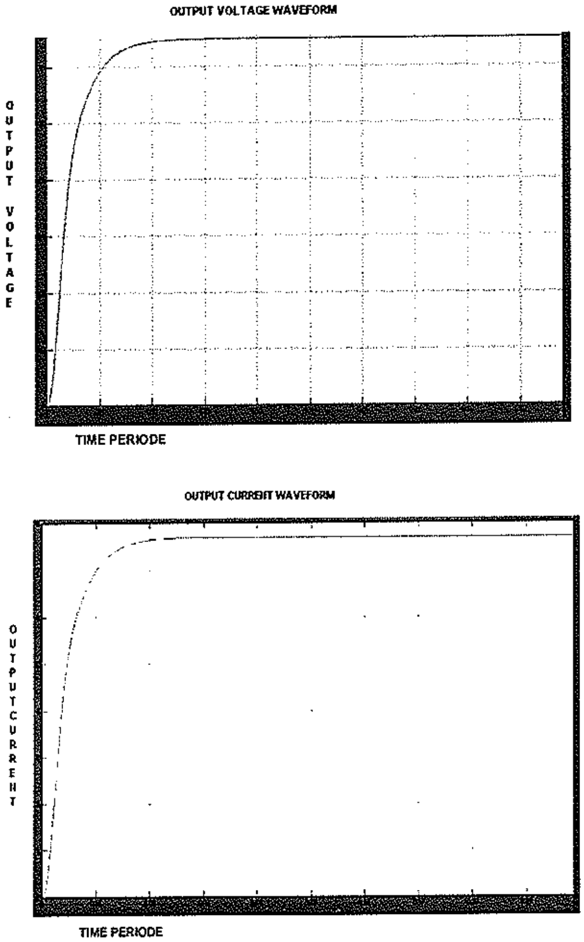

Figure 6 : Output Voltage and Current waveform

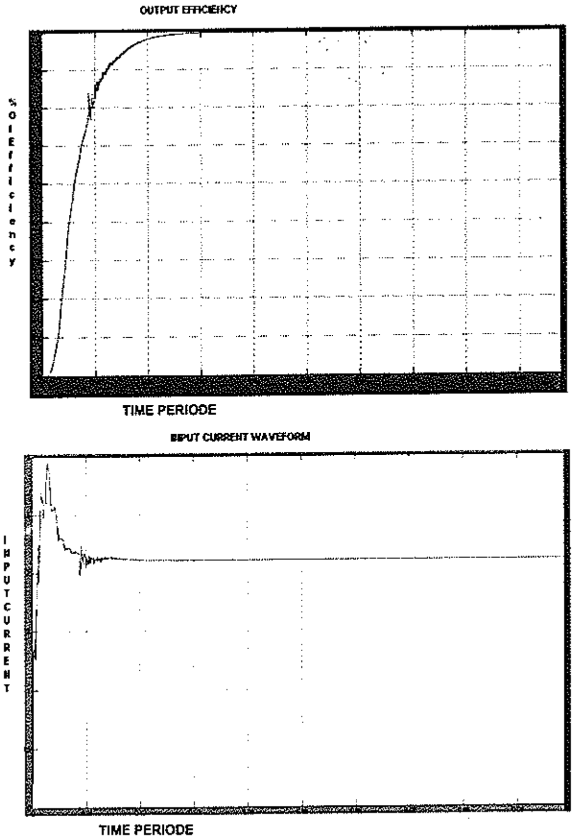

Figure 7 Output Efficiency and Input Current waveform

In addition, a prototype has been made which adopted 380V three phase alternating current, and the input direct voltage via rectifying and filtering is 530V. Figure 8 is the output waveforms of prototype while full-load situation in the experiment has been carried through with the soft ware P-SPICE.

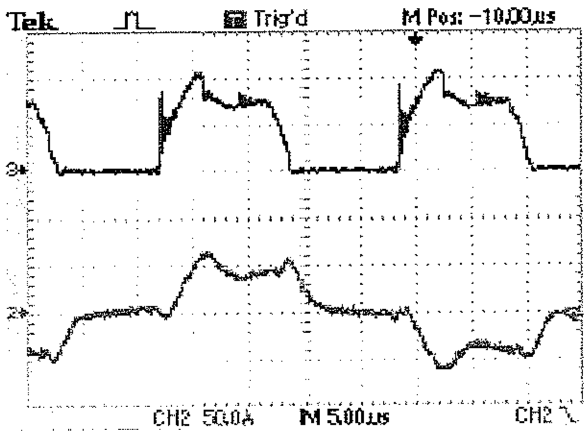

Figure 8 : Experimental waveforms of the prototype(full load)

The top of the figure 8 is the waveform of V_{rec} which is the rectified output of transformer's secondary side. The bottom waveform belongs to primary side's current Ip.

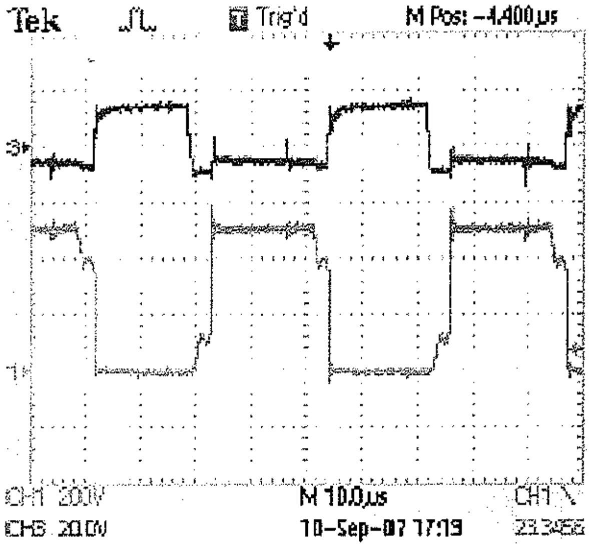

Fig 9: Experimental waveforms of the unimproved prototype(light load)

What we can see from Figure. 9 is the waveform of S_1's voltage V_{ce} and drive pulse $V_{ge.}$ When the converter is light-loaded I_0 10 A, without auxiliary circuit. The conducting of the IGBT is not zero-voltage conduction as that can be seen from Figure 9.

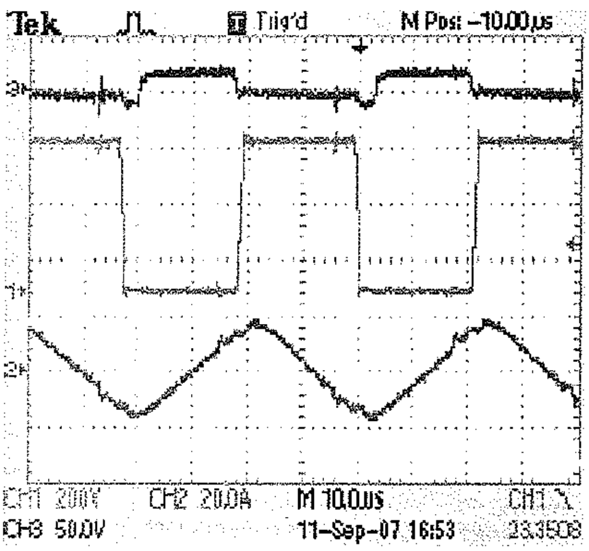

Figure 10: Experimental waveforms of the improved prototype(light load)

However, in the same situation of light load Io 10A with auxiliary circuit, from the top to the end in Figure.10, it is waveform of S1's drive pulse V_{ge} and voltage V_{ce}, as well as current Ia of additional inductance Lr in turn.

As what can be seen from Figure.10, the trailing edge of V_{ce} has declined to zero when the rising edge of drive pulse V_{ge} arrives. It is to say that soft switching of IGBT's leading-leg has been realized. In addition, we can see that soft switching also could be realized when the output current of converter is 1A through the waveform of V_{ce}.

TABLE 2

Compare of ZVZCS full-bridge converter with and without Improving in efficiency.

V_o=130V	I_o=80A Full load	I_o=40A Half load	I_o=10A Light load
Efficiency of unimproved machines	92%	91%	83%
Efficiency of improved machines	90%	89%	75%

As what can be seen from table 2, the efficiency of the improved circuit was a bit lower than that of the original unimproved circuit. That is the result of the current in the additional inductance L_a which always exists and generates heat that increases the loss. Naturally, the efficiency will be reduced. However, when it's the situation that the load is light at most time such as charging the battery, the improved circuit is much more reliable than the original unimproved circuit. Before the conducting of leading-leg IGBT, C_1 or C_3 has released all their energy, and the ZVS of the leading-leg has been realized. This will lead the fact that capacitance C_1 and C_3 are no longer easily broken, as well as $S_1$and S_3. The reliability of system has been increased.

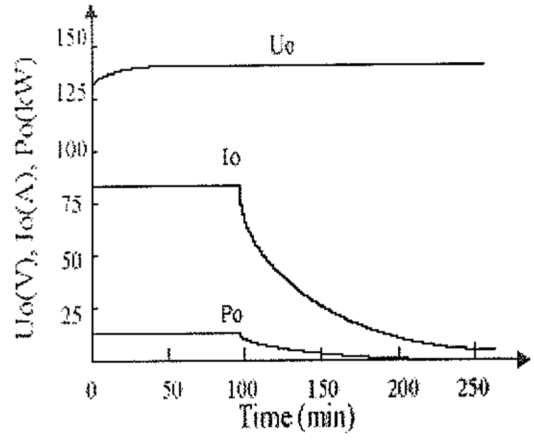

Figure 11: Practical charging curves.

Figure .11 is the practical charging curves which has shown the fact that its light load at most time in the charging process. Since reliability of the chargers is very important, considering and paying attention to both the efficiency and the reliability at the same time, the improved circuit has its own sense.

5. Conclusion

This paper has presented a novel ZVZCS full-bridge converter and the improvement basing on the analyze of its operating principle, circuit characteristics. At last, the feasibility of circuit topology has been proved. According to the simulation and experimental analyses, some conclusions can be drawn:

1. The novel ZVZCS full-bridge converter is quite fitting for DC/DC equipment which is large power and IGBT adopted

2. Realize soft switching of all loads situation, and reduce the switching loss effectively

3. No active switch added. Simple topology and control circuit

4. Because the current of additional inductance La always exists and generates heat that increases the loss, the efficiency will be reduced

5. After the improvement, the reliability of system has been increased.

In conclusion, although the efficiency of improved converter declined a little, the improved novel ZVZCS full-bridge converter is feasible and effective indeed, considering the high reliability of the system and the soft switching in all loads situation.

APPENDIX A DESIGN PARAMETER

S.No	PARAMETERS	VALUE
1	Input Voltage Vin	530 V, DC
2	Blocking Capacitor CB1	0.6μF
3	Transformer Leakage Inductance L1K	4.29mH
4	Supperest severe voltage ringing D1,D2 (Vf)	0.8V
5	Constant voltage source CB2 (Blocking capacitor)	0.5μF
6	Constant current source Lf	10mH
7	Co-Output capacitance	470 μF
8	DR1,DR2 (Rectifier)-Vf	0.8V
9	R-Load	1000W
10	Auxiliary Inductance	5mH
11	Used for achieve full FBC1, C3-Capacitance	0.2 μF
12	Anti parallel 4 diodes connected across IGBT (Vf)	0.8V

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