An Unusual Full Bridge Converter to Realize ZVS in Large Load Scope

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Abstract - A current-stable switching power supply (300A) for magnet is designed on the basis of ZVS Converter and frequency-fixed PWM technology. An effective method is used to widen the load scope greatly to realize ZVS. Besides this, the saturated inductor is used to form the snubber circuit to help to solve this problem and reduce the duty cycle loss together. In this way, the noise emission and power loss were greatly reduced; the reliability of the power supply was improved obviously. This paper will introduce this effective method and analyze the working process of the converter in detail. The final experimental results are satisfactory and this switching power supply is in good use now.

Keywords – Zero voltage switching, Full bridge converter, ZVS.

I. INTRODUCTION

This converter is mainly used as a large power ZVS converter which can realize ZVS in very wide load scope, theoretically, it can realize ZVS in full load range. The combination of this kind of power converter with PFC or EMI technology, it can improve the power factor and efficiency greatly [1], [2]. In order to reduce the switching loss of the converter so as to improve the efficiency and protect the power switches, ZVS or ZCS technology is often used for high power converters, sometimes, resonant converters are chosen to solve this question [3-7]. With regard to the control method for this kind of power supply, ZVS-PWM method [8] is often used. People often use the leakage inductance of the high frequency transformer to provide energy for ZVS or ZCS realization; this will make the ZVS or ZCS scope limited [9-13]. It is very difficult to realize ZVS for the lagging leg, especially when the load is light. In order to solve this question, this paper introduces a new method to widen the ZVS scope greatly. The final experimental results suggest that this is a good method for large power converters.

This paper is organized as following: The introduction of this converter topology and the snubber circuit with saturated inductor are described in Section II. The detailed analysis of the method to realize ZVS in full load range will be presented in Section III. The experimental results are given in Section IV and finally, Section V presents the conclusion remarks.

The paper first received 08 Dec 2007 and in revised form 31 Mar 2008
Digital ref: AI70201182

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II. THE MAIN CIRCUIT OF THE CONVERTER

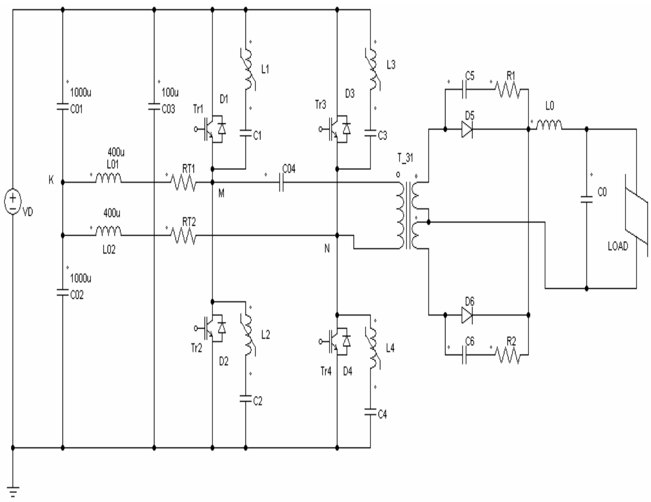

Fig. 1: The main circuit of the converter

A. The choice of the Converter frequency

A very high frequency can not be chosen for the high power switching converters with fixed frequency PWM control because of the component limit and the switching loss. Certainly, attention must be paid to make the power supply good in volume, weight, ripple, instant response speed and the cost to build it. In the end, the switching frequency of 25kHz was chosen for the main converter and the result proved it is proper. Certainly, with the improvement of the electrical cell element properties and the development of electrical technology, the frequency of the switching power supply will be higher in the future.

B. The brief statement of the main Converter Circuit

This paper only discusses the main DC-AC Converter in the power supply. Capacitors C_{01}, C_{02} , and C_{03} are the filter capacitors in the three-phase full bridge rectifier and filer circuit (~380V, 50Hz). One important reason for these three capacitors connected in this way is to connect another two RL branch in order to realize ZVS in full load range, meanwhile, C_{03} Provides a route for high frequency harmonics. In the snubber circuit, $C_1=C_2=C_3=C_4$; $L_1=L_2=L_3=L_4$.Certainly, $L_{01}=L_{02}$; $RT_1=RT_2$

II. THE DETAILED ANALYSIS OF THE METHOD TO REALIZE ZVS IN FULL LOAD RANGE.

In order to explain the working process of the converter clearly, the four control signals "V_{S1}, V_{S4}" and "V_{S2}, V_{S3}" for the four IGBTs are given in Fig. 2.

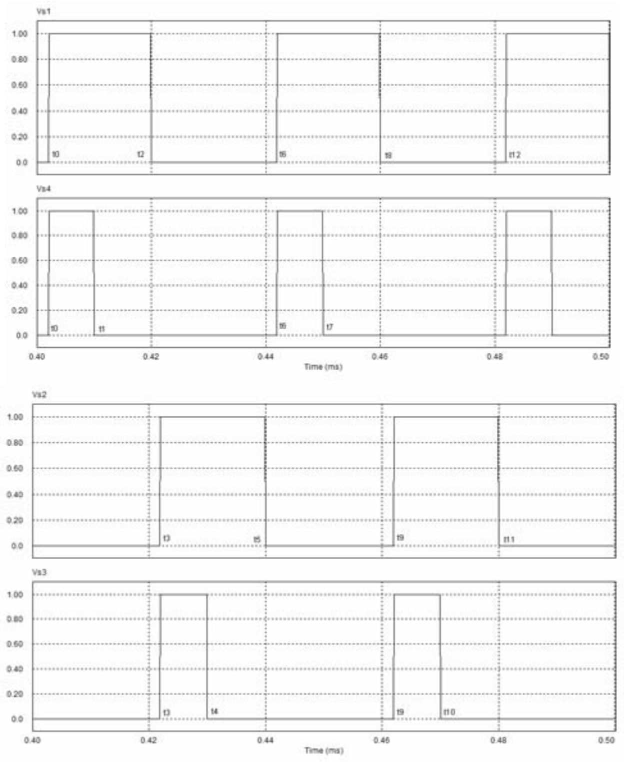

Fig. 2: The Control Signal Waves of the Converter

The time t_0, t_1, t_2 --- and t_{12} are given according to the time sequence of the four Control signals and the period begins at t_0. In this way, it will be more clearly to explain the working process of the ZVS-PWM Converter. The time between t_2 and t_3 or time delay "T_D" is equal to 2 micro-seconds.

A. Converter working process during period of t_0~t_1

1) During this period of time, it can be seen from Figure 2 that both the control signals V_{S1} and V_{S4} are valid positive voltage , so the situation in this period is the steady condition that $IGBT_1$ and $IGBT_4$ are "ON" and the main power U_d transmits energy to the load by way of $IGBT_1$ to main transformer to $IGBT_4$. During this steady period of time, the parallel LC snubber circuits of $IGBT_1$ and $IGBT_4$ are in zero voltage state because of the "ON" state of $IGBT_1$ and $IGBT_4$. This is because:

$$U_L + U_c = 0 \tag{1}$$

Because the voltage applied to these two snubber circuits are DC voltage and these two snubber circuits are in steady state, the current in the series LC circuit is always equal to zero (i =0), so:

$$U_L = L\frac{di}{dt} = 0(\mathrm{v}) \tag{2}$$

So: U_c=0 (V)

2) During this period of time, the parallel LC snubber circuits of $IGBT_2$ and $IGBT_3$ are also in steady state, their voltages are:

$U_c=U_d$, U_L=0.

This is because $IGBT_2$ and $IGBT_3$ are in "off "state, so:

$$U_L + U_C = U_d \tag{3}$$

The same as before, under the Dc steady state, the current in series LC circuit is always equal to zero (i =0), so:

$$U_L = L\frac{di}{dt} = 0\ (\mathrm{v}) \tag{4}$$

$U_c = U_d$

3) During this period of time, the situation of these two RL circuits is discussed as following:

(a) $L_{o1}RT_1$ Circuit: During this period of time (t_0~t_1), this circuit is in energy-storing state because $IGBT_1$ is "ON". The voltage division between C_{01} and C_{02} makes $U_k=U_d/2$, so, its differential equation is:

$$L_{01}\frac{di_{L1}}{dt} + RT_1 i_{L1} = \frac{U_d}{2} \tag{5}$$

The answer to it is:

$$i_{L1} = \frac{U_d}{2RT_1}\left(1 - e^{\frac{-RT_1 t}{L_{01}}}\right) \tag{6}$$

The reason to add this circuit is to use the energy stored in inductor L_{01} to help to realize ZVS in full load scope. If the Converter only relies on the energy stored in the leak inductor of the main transformer, it will not be able to realize ZVS for the lagging leg when the load current is low. This is because the energy stored in leak inductor of the transformer will reduce when the load current decreases. However, the energy required to realize ZVS does not reduce a little and it is still two times as much as the energy stored in the capacitors in the LC snubber circuit. So:

$$\frac{1}{2} L_L i_p^2 < C U_d^2 \tag{7}$$

The converter will not realize ZVS when the load current is low, however, the converter can use the total energy stored in inductor L_{01} and the leak inductor L_L to realize ZVS after we add the $L_{01}RT_1$ circuit, obviously, the ZVS range of the converter will increase a lot. In this circuit, the RT_1 is a heat sensitive resistor with negative temperature coefficient (NTC) .The reason to add RT_1 to this circuit is to protect inductor L_{01}. When use series circuit $L_{01}RT_1$, the initial current in this circuit will not be too high. As the time lengthens, the resistor will dissipate electrical power and its temperature will increase and its resistance will reduce. Therefore, it will not continue consuming energy after it finished its task.

(b) The analysis of ZVS realization range.

In order to make the lagging leg of the converter realize ZVS, the energy stored in inductor $L_{01}$and the leak inductor L_L must be able to satisfy the energy requirement to charge one snubber LC circuit and discharge the other snubber circuit. That is to say the total energy stored in L_{01} and L_L has to be more than two times of the energy stored in capacitor C in Snubber LC circuit (The inherent capacitance of IGBT and the capacitance between the turns of the transformer are neglected because they are much less than the capacitance of Capacitor C in snubber circuit). That is:

$$\frac{1}{2}L_L I_P^2 + \frac{1}{2}L_{01}I_{L1}^2 \geq CU_d^2 \tag{8}$$

where

L_L	:	Leakage inductance, it is equal to 4μH
L_{01}	:	The added inductance, it is 400μH
I_p	:	The current of the primary winding of the transformer when one IGBT in the lagging

leg is turned off

C : Capacitance in the snubber circuit, it is equal to 13000 pF

U_d : The output voltage of the rectifier and filter, it is equal to 514.86(V)

It is well known that the current changing rate in L_{01} RT_1 circuit reaches maximum when the resistance of RT_1 is equal to zero, therefore, the current value is highest after a definite period of time. Certainly, it can provide the most energy to realize ZVS, this is the situation that can realize the biggest ZVS scope. When the resistance of RT_1 is equal to zero, its differential equation is:

$$L_{01}\frac{di_{L1}}{dt}=\frac{U_d}{2} \tag{9}$$

The answer to it is: $I_{L1}(t)=\dfrac{U_d}{2L_{01}}t$ (10)

Substituting the corresponding values in the formula (8),

$$\frac{1}{2}\times 4\times 10^{-6}\times I_1^2+\frac{1}{2}\times 400\times 10^{-6}\times \frac{\frac{T^2}{4}\times(514.86)^2}{4\times(400\times 10^{-6})^2}$$

$$\geq 0.003446 \tag{11}$$

Because the frequency of the converter is equal to 25kHz, $T=1/f=4\times10^{-5}$(s). Substituting this value in formula (11),

$$\frac{1}{2}\times 4\times 10^{-6} I_1^2 \geq -0.029689 \tag{12}$$

This formula suggests that the power supply can realize ZVS in full load range and the heat sensitive resistor RT_1 need not be equal to zero initially.

(c) The initial Value decision of RT_1

From the discussion above, we know that the standard to decide the initial value of RT_1 is to enable the realization of ZVS in full load range. When the load current is equal to zero (I_o=0), certainly, the current I_1 is zero too. Therefore, formula (8) becomes into:

$$\frac{1}{2}L_{01}I_{L1}^2\geq CU_d^2 \tag{13}$$

Substituting the corresponding values in formula (13)

$$\frac{1}{2}\times 400\times 10^{-6} I_{L1}^2 \geq 0.003446$$

So, $I_{L1}\geq 4.15$ (A) (14)

This $L_{01}RT_1$ circuit will be always in the magnetic charged when $IGBT_1$ is "ON" in a half period (T/2). Therefore, the magnetic charging time for this circuit is: $\dfrac{T}{2}=2\times10^{-5}$(s).

Substituting this value in the formula (6),

$$\frac{514.86}{2RT_1}\left(1-e^{\frac{-RT_1}{400\times10^{-6}}\times 2\times 10^{-5}}\right)\geq 4.15$$

Its answer is: $RT_1\leq 25.55$ (Ω) (15)

Therefore, if RT_1 is chosen with the resistance less than 20 Ohms ($RT_1\leq 20\Omega$), it can make the converter realize ZVS in full load range.

(d) $L_{02}RT_2$ Series Circuit:

In the period of (t_0~t_1), the $IGBT_4$ is "ON", so, this circuit is in magnetic energy storing state, too. The situation of this $L_{01}RT_2$ circuit is similar to $L_{01}RT_1$ circuit. Its differential equation and the answer to the equation are the same as those of $L_{01}RT_1$ Circuit; there is no need to list them again here. Certainly, the function of this circuit is to help to realize ZVS in full load range. Because the time that IGBT4 is "ON" is "D·T/2" in this Converter, the time for $L_{02}RT_2$ circuit to store magnetic energy is "D·T/2".We choose RT_2= RT_1 and L_{02}= L_{01}. In this way, either the left leg or the right leg can act as the lagging leg and it will make no difference for the converter to realize ZVS in full load range. Certainly, this will make it more convenient for engineer to design a suitable Control Circuit for the power converter.

4) The calculation $i_p(t)$ in "t_0~t_1"

Both $IGBT_1$ and $IGBT_4$ are all "ON" from time t_0 to t_1 (t_0～t_1), so its differential equation is:

$$U_{c04}+(L_L+L_0^{'})C_{04}\frac{d^2U_{c04}}{dt^2}=U_d \tag{16}$$

The initial values for equation (16) are:

$i_p(0+)=0$, $U_{c04}(0+)=0$

This is because the energy of C_{04} and L_L had released totally and the energy of L_o would not transfer to the primary winding of the transformer before the beginning of period of *TD/2*. This will be analyzed later. To make Laplace conversion for equation (16),

$$U_{c04}(s)+(L_L+L_0')C_{04}[s^2U_{c04}(s)-SU_{c04}(0+)]=\frac{U_d}{s}$$

$$\therefore U_{c04}(s)=\frac{U_d}{[(L_L+L_o^{'})C_{04}s^2+1]\times s} \tag{17}$$

where

$L_L=4\mu H$

$C_{04}=10\mu F$

$L_0'=81L_o=567\mu H$

Substituting these values in formula (17)

$$U_{c04}(s)=\frac{1.1486\times 10^{11}}{(5.71s^2+10^9)\times s} \tag{18}$$

Make Laplace reverse-conversion for formula (18).

$$U_{c04}(t)=514.86-514.86\cos 13229\,t \tag{19}$$

Therefore, the current of primary winding in "t_0~t_1" is :

$$i_p(t)=C_{04}\frac{du_{C_{04}}(t)}{dt}=10\times10^{-6}\times514.86\times13229\sin 13229t$$

$$=68.1\sin 13229\,t \tag{20}$$

In the period of "t_0~t_1", we can get the oscillation frequency of the primary current $i_p(t)$ from formula (20) :

$$f_1=\frac{13229}{6.28}=2106.53\ (\text{Hz}).$$

The frequency of the converter is: f=25kHz, therefore: f_1=0.08426 f.

This means "T_1=11.87T". Therefore, the current of the primary winding *ip(t)* is nearly rising linearly in this period of time.

B. Period of "t_1~t_2 "

At the time t_1, Control signal Vs_4 reduces to zero, so, $IGBT_4$ will turn off at time t_1. Because the energy stored in the transformer still exists and the voltage of the secondary winding is not equal to zero, the filter inductor *Lo* in the output circuit and the energy stored in it can not release freely through the secondary winding of the transformer and the rectifier diodes. Therefore, the energy stored in inductor L_0, leak inductor L_1 and additional inductor L_{02} will be used to charge L_4C_4 snubber circuit and discharge L_3C_3 snubber circuit. Generally speaking, the energy stored in output filter inductor L_0 is much more than the energy stored in L_1 and L_{02}. Therefore, the energy needed to realize ZVS for the leading leg is enough. Certainly, the turning off of $IGBT_4$ is finished under the Zero-Voltage state. T_3 is assumed to be the time for capacitor C_3 to discharge completely. The current *ip(t)* is nearly two times of current through $L_3 C_3$ snubber circuit in this period of time. In the period of T_3, the capacitor C_3 will be discharged totally, so, the voltage Uc_3 will be equal to zero at $t_1 + T_3$, Certainly the voltage U_{L3} is equal to zero at this time . This is because: "U_{c3}=0" means that i_{c3} reaches its peak value, U_{L3}=L $\frac{dic_3}{dt}$ causes "U_{L3}=0"; Certainly, if the inductor L_3 has already saturated, its voltage will have no choice but to be zero, therefore, $U_{c3}+U_{L3}=0$. This will make the counter – parallel diode D_3 turn on, so, $IGBT_3$ is able to realize ZVS at this time. Because the control signal V_{s3} is low in this period of time, the stored energy has not released totally and $IGBT_1$ is still "ON", these will make the diode D_3 continue to be "ON". Therefore, this constitutes a free – wheeling period of time. During this period of time, the energy stored in L_L, L_{02} and *Lo* will continue to release and the voltage of the secondary winding will continue to reduce. In fact, the free-wheeling period begins at "t_1+T_3". For the wave shape of control signal and primary current during this period of time, please see Fig. 2, Fig. 3 and Fig. 4.

C. Period of "t_2 ~ t_3"

The control signal Vs_1 will become zero at t_2 and $IGBT_1$ will turn off . The remaining energy in L_L and L_{o1} will begin to charge the L_1C_1 snubber circuit and discharge the L_2C_2 snubber circuit. At this time, the voltage of the secondary winding has already reduced to zero; so, inductor *Lo* will form the free–wheeling circuit through the output rectifier diodes and it will not take part in the ZVS realization of the main converter. If we only use leak inductor L_L to realize ZVS, it will be impossible to do so for the lagging leg when the load current is low. In order to solve this problem, we add a series circuit $L_{01}RT_1$ to guarantee the ZVS realization in full load range. When the resistance of RT_1 is lower than 20 Ω, it will be no problem to realize ZVS in full load range. Certainly, the capacitor C_2 in $L_2 C_2$ snubber circuit will have released its stored energy completely before t_3; we assume the time needed to do so is "T_2". After the time "t_2+T_2", the parallel diode D_2 will be "ON" and this enables $IGBT_2$ to realize ZVS. From time "t_2+T_2" to time t_3, the parallel diodes D_2 and D_3 are "ON", This makes inductors L_{01} and L_L return their remaining energy to the input supply. The control signals for $IGBT_2$ and $IGBT_3$ become high at t_3 and the inductors have already released their energy totally at t_3, so, $IGBT_2$ and $IGBT_3$ begin to turn on at t_3. The input power begins to transfer energy to the output again. The waveforms of control signal and primary current are shown in Fig. 2, Fig. 3 and Fig. 4.

D. The converter working process during other periods

The method for following stages analysis is the similar to the above, so, there is no need to analyze them in detail again. In order to be convenient, the inductor *L* in *LC* snubber circuit is assumed to be a linear one in the above working process analysis. If the inductor *L* is turned into a saturated one, we only need to divide into several more stages to analyze the working process of the converter and the analysis method is the same as before. When the output current is very small, the simulation results for the current of the primary winding *ip(t)*, the voltage "*Vce1(t)*" and "*Vce4(t)*" during the whole period are as following: (The unit for "*ip(t)*" is "Ampere"; The unit for "*Vce1(t)*" and "*Vce4(t)*" is "Volt".)

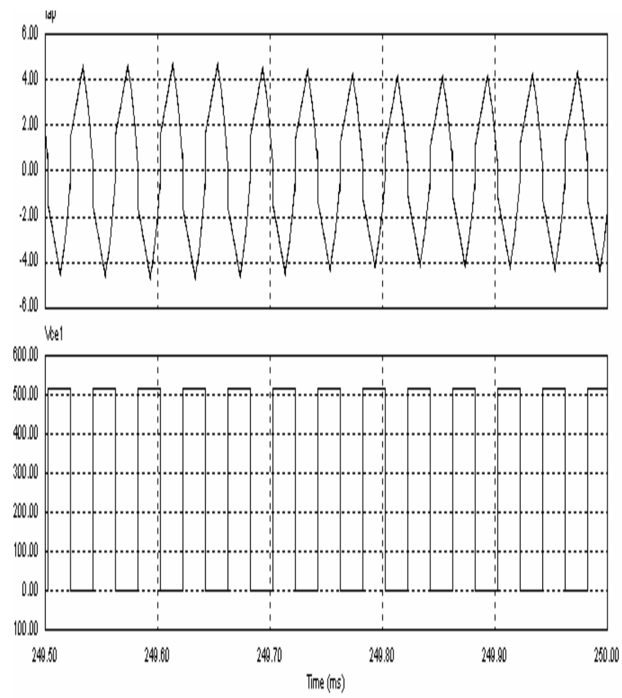

Fig. 3: $I_p(t)$ and V_{ce} of IGBT waveforms

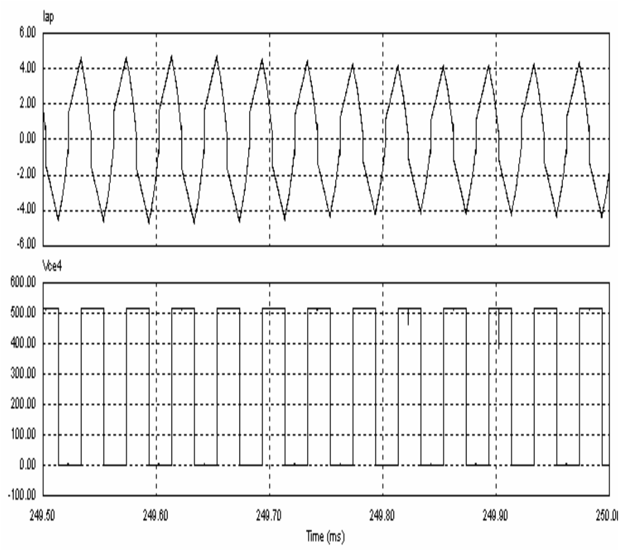

Fig. 4: I_p *(t)* and V_{ce} of $IGBT_4$ waveforms

III. The Final Experimental Results

The experimental result is satisfactory. This power supply can realize ZVS in nearly full load range (0~300A). Its current stability is: s =0.000347. Here, several working wave shapes and the current stability test curves for this power supply are listed as following.

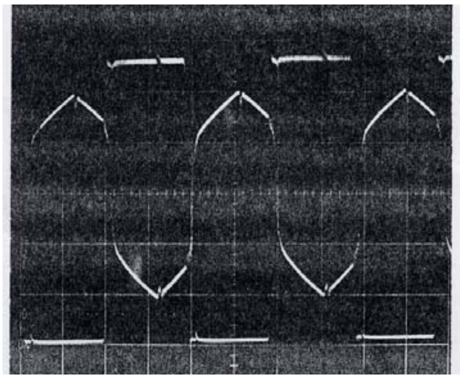

Fig. 5: I_p *(t)* and $V_{ce}$of $IGBT_1$

(V_{ce}: 100V/div; I_P *(t)*: 10A/div; *t*: 10μs/div)

In Fig. 5, the square wave is V_{ce} of $IGBT_1$; the approximate sine wave is $I_p(t)$.

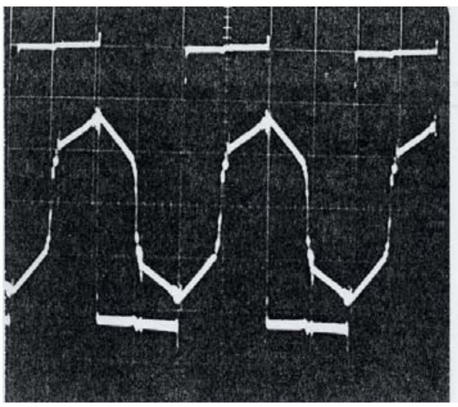

Fig. 6: I_p *(t)* and $V_{ce}$of $IGBT_3$

(V_{ce}: 100V/div; I_P *(t)*: 10A/div; *t*: 10μs/div)

In Fig. 6, the square wave is V_{ce} of $IGBT_3$; the approximate sine wave is $I_p(t)$.

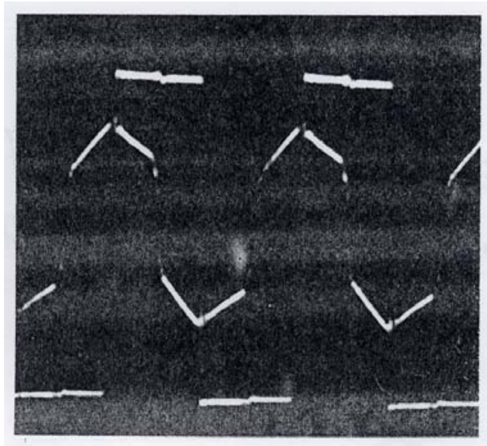

Fig. 7 I_p *(t)* and V_{ce} of $IGBT_4$

(V_{ce}: 100V/div; I_p *(t)*: 10A/div; *t*: 10μs/div)

In Fig. 7, the square wave is V_{ce} of $IGBT_4$; the approximate sine wave is $I_p(t)$. The amplitude of the square wave approximately has 5.15 grids. The amplitude of the current wave approximately has 1.8 grids. The periods of current and voltage approximately have 4 grids. From these experimental working shapes, it can be seen that this power supply has realized ZVS in a wide load scope. Although it has been already proved that this power converter can accomplish ZVS-PWM in full load scope with this method theoretically, its working station when the electrical current $I_p(t)$ is zero was not tested because this wide load scope has already reached the requirement satisfactorily. With regard to the stability of the output electrical current, please see Fig. 8; the Hall sensor was used to measure the output current and connect with the main control circuit. Because the output voltage of the Hall sensor is proportional to the output current of the power supply, its voltage can represent the output current. This curve was tested when the output electrical current is equal to 300 Amperes and the output voltage is equal to 30 Volts.

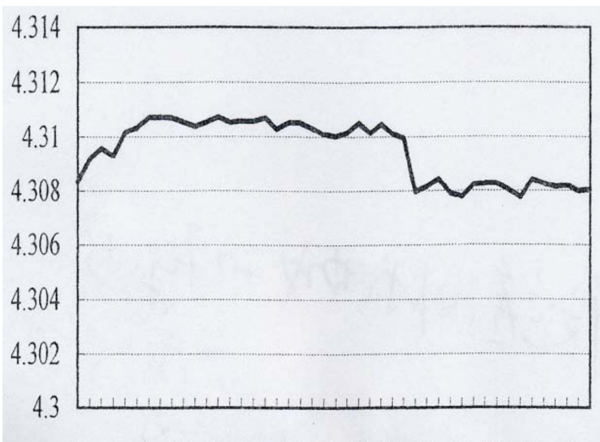

Fig. 8: The curve of the output electrical current
(X-axis unit: 11minutes/div; Y-axis: Volts)

From this curve, it can be seen that *Imax* is *A8* (4.31074V) and I_{min} is *A39* (4.30775V); and there is:

(A8 – A39)/2 =0.001495; (A8 + A39)/2 =4.309245

S=0.001495/4.309245=0.000347

Therefore, the current stability is: S =0.000347. This value satisfies the design requirement (S≤0.001) very well. From all of these experimental results, it can be seen this method is successful to widen ZVS-PWM scope.

IV. Conclusions

The application of the saturated inductor to form snubber circuit and the additional two *RL* branches to enlarge the ZVS scope for the large power full bridge converter has been presented. The specifications of this switching power supply have been improved greatly and the converter can realize ZVS-PWM in a much more wider scope with this topology. IGBT locked-up problem can be solved and ZVS can be realized effectively with this snubber circuit. The recently developed frequency-fixed PWM control method is used for this power supply. In this way, it will make the ZVS converter work more steadily than before. The final experimental result proves that using this method is a good choice for large power full bridge ZVS converter.

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