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

Kuiyuan Wu and William G. Dunford

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.

II. 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 filter 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, \( L_{01}=L_{02}; RT_1=RT_2 \).
The time \(t_0, t_1, t_2\) and \(t_3\) 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 \(t_1\) and \(t_2\) or time delay “\(T_D\)” is equal to 2 micro-seconds.

**A. Converter working process during period of \(t_0~t_4\)**

1) During this period of time, it can be seen from Figure 2 that both the control signals \(V_{SD}\) and \(V_{SD}\) are valid positive voltage, so the situation in this period is the steady condition that IGBT1 and IGBT4 are “ON” and the main power \(U_d\) transmits energy to the load by way of IGBT1 to main transformer to IGBT4. During this steady period of time, the parallel LC snubber circuits of IGBT1 and IGBT4 are in zero voltage state because of the “ON” state of IGBT1 and IGBT4. This is because:

\[
U_L + U_C = 0 \quad (1)
\]

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:

\[
U_L = \frac{dL}{dt} = 0 (v) \quad (2)
\]

So: \(U_C = 0 (V)\)

2) During this period of time, the parallel LC snubber circuits of IGBT2 and IGBT3 are also in steady state, their voltages are:

\[
U_C = U_{th}, \quad U_L = 0.
\]

This is because IGBT2 and IGBT3 are in “off” state, so:

\[
U_L + U_C = U_d \quad (3)
\]

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

\[
U_L = \frac{dL}{dt} = 0 (v) \quad (4)
\]

\[
U_C = U_d
\]

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

(a) \(L_0RT_1\) Circuit: During this period of time \((t_0\sim t_1)\), this circuit is in energy-storing state because IGBT1 is “ON”. The voltage division between \(C_{81}\) and \(C_{82}\) makes \(U_L = U_d/2\), so, its differential equation is:

\[
L_0\frac{di_{L1}}{dt} + RT_1i_{L1} = \frac{U_d}{2} \quad (5)
\]

The answer to it is:

\[
i_{L1} = \frac{U_d}{2RT_1}(1 - e^{-RT_1t}) \quad (6)
\]

The reason to add this circuit is to use the energy stored in inductor \(L_0\) 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:

\[
\frac{1}{2} L_0 I_p^2 < C U_d^2 \quad (7)
\]

The converter will not realize ZVS when the load current is low, however, the converter can use the total energy stored in the leak inductor of the main transformer when one IGBT in the lagging leg of this circuit is to protect inductor \(L_0\) when one IGBT in the lagging leg of this circuit is to protect inductor \(L_0\) when one IGBT in the lagging leg of this circuit is to protect inductor \(L_0\) when one IGBT in the lagging leg of this circuit is to protect inductor \(L_0\) when one IGBT in the lagging leg of this circuit is to protect inductor \(L_0\). When use series circuit \(L_0RT_1\), 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 \(L_0\) 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 \(L_0\) 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:

\[
\frac{1}{2} L_L I_p^2 + \frac{1}{2} L_0 \frac{I_{L1}^2}{L_1} \geq C U_d^2 \quad (8)
\]

where

- \(L_L\) : Leakage inductance, it is equal to 4μH
- \(L_0\) : The added inductance, it is 400μH
- \(I_p\) : The current of the primary winding of the transformer when one IGBT in the lagging...
It is well known that the current changing rate in \( L_{oi} RT_1 \) 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 ZVS in full load range. When the resistance of \( RT_1 \) is equal to zero, its differential equation is:

\[
\frac{di_{i1}}{dt} = \frac{U_d}{2}
\]

The answer to it is: \( I_{i1_i(t)} = \frac{U_d}{2 L_{oi1}} t \)

Substituting the corresponding values in formula (8),

\[
\frac{1}{2} \times 4 \times 10^{-6} \times I_1^2 + \frac{1}{2} \times 400 \times 10^{-6} \times \frac{T^2}{4} \leq 0.003446
\]

Because the frequency of the converter is equal to 25kHz, \( T = 1/f = 4 \times 10^{-5} \) (s). Substituting this value in formula (11),

\[
\frac{1}{2} \times 4 \times 10^{-6} I_1^2 \geq -0.029689
\]

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:

\[
\frac{1}{2} L_0 I_1^2 \geq C U_d^2
\]

Substituting the corresponding values in formula (13)

\[
\frac{1}{2} \times 400 \times 10^{-6} I_1^2 \geq 0.003446
\]

So, \( I_1 \geq 4.15 \) (A)

This \( L_0 RT_1 \) circuit will always be in the magnetic charged when IGBT1 is “ON” in a half period \( (T/2) \). Therefore, the magnetic charging time for this circuit is:

\[
T = 2 \times 10^{-5} \text{ (s)}
\]

Substituting this value in the formula (6),

\[
\frac{514.86}{2 RT_1} (1 - e^{-\frac{RT_1}{400 \times 10^{-6} + 2 \times 10^{-5}}}) \geq 4.15
\]

Its answer is: \( RT_1 = 25.55 \) (Ω)

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

\( L_0 RT_2 \) Series Circuit:

In the period of \( (t_0 \sim t_1) \), the IGBT4 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 “\( t_0 \sim t_1 \)”

Both IGBT1 and IGBT4 are all “ON” from time \( t_0 \) to \( t_1 \) \((t_0 \sim t_1)\), so its differential equation is:

\[
U_{c04} + (L_c + L_o) C_{c04} \frac{d^2 U_{c04}}{dt^2} = U_d
\]

The initial values for equation (16) are:

\[
i_p(0+) = 0, U_{c04}(0+) = 0
\]

This is because the energy of \( C_{c04} \) and \( L_c \) had released totally and the energy of \( L_0 \) 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),

\[
U_{c04}(s) + (L_c + L_o) C_{c04} [s^2 U_{c04}(s) - s U_{c04}(0+)] = \frac{U_d}{s}
\]

\[
\therefore U_{c04}(s) = \frac{1.1486 \times 10^{-11}}{(5.71 s^2 + 10^3) s}
\]

Substituting these values in formula (17)

\[
U_{c04}(s) = \frac{1.1486 \times 10^{-11}}{(5.71 s^2 + 10^3) s}
\]

Make Laplace reverse-conversion for formula (18).

\[
U_{c04(t)} = 514.86 \times 514.86 \cos 13229 t
\]

Therefore, the current of primary winding in “\( t_0 \sim t_1 \)” is:

\[
i_p(t) = C_{c04} \frac{dU_{c04}(t)}{dt} = 10 \times 10^{-6} \times 514.86 \times 13229 \sin 13229 t = 68.1 \sin 13229 t
\]

In the period of “\( t_0 \sim t_1 \)”, we can get the oscillation frequency of the primary current \( i_p(t) \) from formula (20):

\[
f = \frac{13229}{6.28} \approx 2106.53 \text{ (Hz)}
\]
The frequency of the converter is: \( f = 25 \text{kHz} \), therefore: \( f_c = 0.08426 \text{f} \).

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

**B. Period of "t1-t2"**

At the time \( t_1 \), Control signal \( V_{s3} \) reduces to zero, so, IGBT1 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 \( L_0 \) 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 \( L_{o2} \) will be used to charge \( L_0C_3 \) snubber circuit and discharge \( L_1C_1 \) snubber circuit. Generally speaking, the energy stored in output filter inductor \( L_0 \) is much more than the energy stored in \( L_1 \) and \( L_{o2} \). Therefore, the energy needed to realize ZVS for the leading leg is enough. Certainly, the turning off of IGBT4 is finished under the zero-voltage state. \( T_1 \) is assumed to be the time for capacitor \( C_1 \) to discharge completely. The current \( ip(t) \) is nearly two times of current through \( L_1C_1 \) snubber circuit in this period of time. In the period of \( T_2 \), the capacitor \( C_1 \) will be discharged totally, so, the voltage \( U_{c1} \) will be equal to zero at \( t_1 + T_1 \). Certainly the voltage \( U_{L1} \) is equal to zero at this time. This is because: "\( U_{L1} = 0 \)" means that \( i_{L1} \) reaches its peak value, \( U_{L1} = L \frac{di_{L1}}{dt} \) causes \( V_{ce1(t)} \) to be zero. 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 \( D_1 \) turn on, so, IGBT1 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 IGBT1 is still "ON", these will make the diode \( D_1 \) continue to be "ON". Therefore, this constitutes a free – wheeling period of time. During this period of time, the energy stored in \( L_{o1}, L_{o2} \) and \( L_0 \) will continue to release and the voltage of the secondary winding will continue to reduce. In fact, the free-wheeling period begins at "\( t_1 + T_1 \)".

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 "t2-t3"**

The control signal \( V_{s1} \) will become zero at \( t_2 \) and IGBT1 will turn off. The remaining energy in \( L_1 \) and \( L_{o1} \) will begin to charge the \( L_1C_1 \) snubber circuit and discharge the \( L_0C_3 \) snubber circuit. At this time, the voltage of the secondary winding has already reduced to zero; so, inductor \( L_0 \) 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 \( L_1 \) 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 \( L_0RT_1 \) to guarantee the ZVS realization in full load range. When the resistance of \( RT_1 \) is lower than 20 \( \Omega \), it will be no problem to realize ZVS in full load range. Certainly, the capacitor \( C_2 \) in \( L_2C_2 \) snubber circuit will have released its stored energy completely before \( t_2 \) we assume the time needed to do so is "\( T_2 \)". After the time "\( t_2 + T_2 \)"; the parallel diode \( D_3 \) will be "ON" and this enables IGBT2 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 \( L_{o1} \) and \( L_0 \) return their remaining energy to the input supply. The control signals for IGBT2 and IGBT3 become high at \( t_3 \) and the inductors have already released their energy totally at \( t_3 \), so, IGBT2 and IGBT3 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 "\( V_{ce1(t)} \)" and "\( V_{ce4(t)} \)" during the whole period are as following: (The unit for "\( ip(t) \)" is "Amperes"; The unit for "\( V_{ce1(t)} \)" and "\( V_{ce4(t)} \)" is "Volts").

![Fig. 3: \( Ip(t) \) and \( V_{oa} \) of IGBT waveforms](image-url)
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.

In Fig. 5, the square wave is \( V_{ce} \) of IGBT\(_1\); the approximate sine wave is \( I_p(t) \).

In Fig. 6, the square wave is \( V_{ce} \) of IGBT\(_3\); the approximate sine wave is \( I_p(t) \).

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.

From this curve, it can be seen that \( I_{max} \) is A8 (4.31074V)
and $I_{\text{in}}$ 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 ($S \leq 0.001$) very well. From all of these experimental results, it can be seen that this method is successful in widening 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.

REFERENCES


