Letters to the Editor

Analysis and Design for RCD Clamped Snubber Used in Output Rectifier of Phase-Shift Full-Bridge ZVS Converters

Song-Yi Lin and Chern-Lin Chen

Abstract— **Detailed analysis and parameter design for a resistor-capacitor-diode (RCD) clamped snubber used in the output rectifier of phase-shift full-bridge zero-voltage-switching (PS-FB-ZVS) converters are presented. Design equations and some properties of the clamped circuit are highlighted.**

Index Terms—**Phase-shift full-bridge zero-voltage-switching converters, snubber.**

I. Introduction

Phase-shift full-bridge zero-voltage-switching (PS-FB-ZVS) converters [1] have been widely used in high-voltage high-power applications. These converters have advantages over resonant-type converters for fixed-frequency operations and the minimization of switching losses and switch stresses. A problem with these converters used in high-output-voltage applications is the secondary parasitic ringing, which greatly increases the voltage stress of the rectifier diodes. The traditional *RC* damping snubber cannot be used because of the large snubber loss in high-voltage high-frequency applications. An RCD clamped snubber [2] circuit is commonly used to prevent the secondary voltage from exceeding a desired level with acceptable loss. The goal of this letter is to analyze the snubber circuit operations and to develop design equations to choose the value of R.

II. Circuit Description

Shown in Fig. 1(a) is the power circuit of a PS-FB-ZVS converter. According to the switching patterns of a PS-FB-ZVS converter, its primary voltage waveform is similar to V_p' in Fig. 1(b), but with different amplitude V_{in}, the input dc voltage. The primary side is loaded by a transformer with turns ratio $1:N$ in serial connection with an inductor L_p used to achieved ZVS for primary switches. Modeling the primary side by an ideal voltage source and excluding the transformer, we get the simplified equivalent circuit in Fig. 1(b), in which $L_1 = L_p * N^2$ and $V_d = V_{\text{in}} * N$.

The simplified circuit in Fig. 1(b) can be used to realize the ringing mechanism of the secondary side. Before t_0, the output current I_o flows through the four rectifier diodes, and V_s is held at zero. After t_0, V_p' turns from zero to V_d and I_s increases with slope V_d/L_1. When I_s reaches I_o, D_2 and D_3 stop conducting, and the excess current, $I_s - I_o$, flows into the parasitic capacitance C between node V_s and ground. The mechanism described above will cause V_s to rise because of resonance between L_1 and C. Note that C is composed of the junction capacitance of the unconducted rectifier diodes and the stray capacitance of the isolated transformer. Assuming that L_f is large enough to be a constant current source and solving the differential

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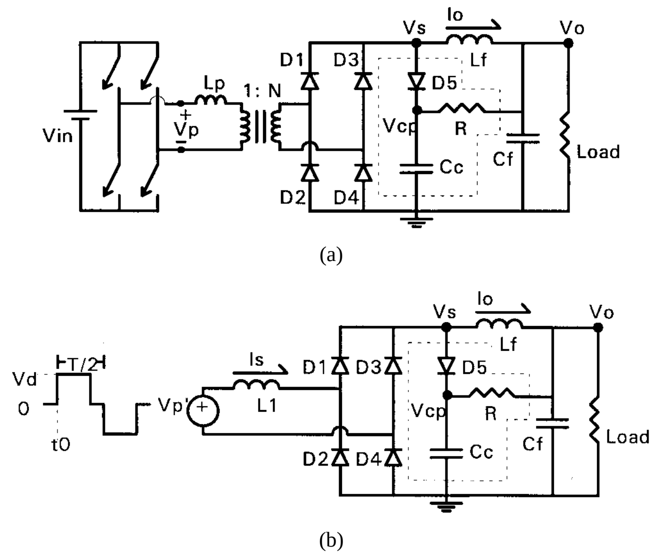

Fig. 1. PS-FB-ZVS converter and its associated simplified circuit, including the RCD clamped snubber. (a) PS-FB-ZVS converter. (b) Simplified circuit of PS-FB-ZVS converter.

equations of the resonant circuit with initial conditions $V_s(0) = 0$ and $I_s(0) = I_o$, we have

$$V_S = V_d - V_d \cos\left(\frac{t}{\sqrt{L_1 C}}\right)$$
$$I_S = I_O + \frac{V_d}{\sqrt{\frac{L_1}{C}}} \sin\left(\frac{t}{\sqrt{L_1 C}}\right). \tag{1}$$

The maximum value of V_s in (1) is $2 * V_d$. Take $V_d = 500$ V, for example; V_s will reach 1000 V and it will be very difficult to choose appropriate rectifier diodes.

As shown in Fig. 1, an RCD snubber consisting of R, C_c, and D_5 is used to overcome the aforementioned problem. C_c is assumed large enough to be a constant voltage tank with amplitude V_{cp}. When V_s reaches V_{cp}, D_5 will conduct, and the excess current, $I_s - I_o$ will flow through it until $I_s - I_o = 0$. Additionally, R provides a discharge path for charge balance of C_c. Note that one terminal of R is connected to node V_o, so that a portion of snubber loss can be recovered to output.

III. Analysis

Below, we will deduce the relation between R, V_{cp} and losses of the snubber. At the steady state, the average current through C_c must be zero, so that C_c can be a constant voltage tank.

Referring to Fig. 2, notice that $I_r = I_s - I_o$. When V_s reaches V_{cp}, D_5 starts to conduct as I_r decreases linearly with the slope $(V_{cp}$-$V_d)/L_1$ until I_r reaches zero. After that, resonance starts again with the initial condition $V_s = V_{cp}$ and $I_s = I_o(I_r = 0)$. Solving the differential equation, we find that the next voltage peak will never reach V_{cp} due to the finite copper losses. The clamping action takes place only once, and its duration is

$$\Delta_t = \frac{L_1 * I_r(f_1)}{V_{cp} - V_d}. \tag{2}$$

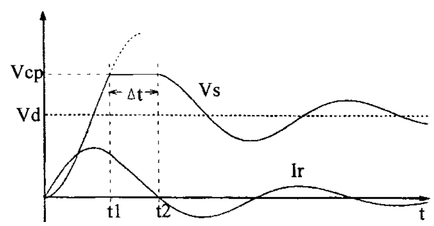

Fig. 2. Voltage and current waveforms of the clamped snubber.

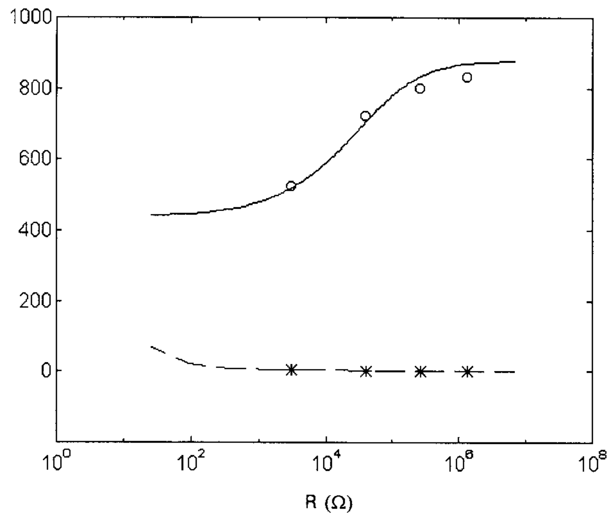

Fig. 3. Measured and calculated results about R versus V_{cp} and associated loss. ○: Measured V_{cp} (V); −: Calculated V_{cp} (V); ∗: Measurd loss (W); −−: Calculated loss (W).

The time integral of current flowing through D_5 per cycle is

$$\int_{f_1}^{t_2} I_r(t)\, dt = \frac{I_r(t_1)}{2}\Delta_t = \frac{1}{2}L_1 * I_r^2(t_1)\left(\frac{1}{V_{cp} - V_d}\right). \tag{3}$$

Substituting $V_s(t_1) = V_{cp}$ into (1), we have

$$I_r^2(t_1) = \frac{C}{L_1}V_{cp} * (2V_d - V_{cp}). \tag{4}$$

The time integral of current flowing through R per cycle is

$$\left(\frac{V_{cp} - V_o}{R}\right) * \frac{T}{2}. \tag{5}$$

Since the average current through C_c must be zero at steady state, (3) and (5) must be equal. Substituting (4) into (3) and then equating (3) and (5), we get

$$R = \frac{T(V_{cp} - V_o)(V_{cp} - V_d)}{C * V_{cp}(2V_d - V_{cp})}. \tag{6}$$

Fig. 3 depicts the relationship between R, V_{cp} and the associated snubber loss, $(V_{cp} - V_o)2/R$. Both experimental and calculated results are shown with the specified case $V_d = 440$ V, $V_o = 400$ V, $T = 11.2$ μs, and $C = 185$ pF. It is observed that a smaller value of R will lower V_{cp}, but increase snubber loss.

One comparison can be made with another snubber configuration, in which R is connected to ground. Following a similar calculation, it is found that, for the same level of V_{cp}, the loss of the proposed snubber is only a portion, $(V_{cp} - V_o)/V_{cp}$, of that of the snubber type just mentioned above.

For general application, V_d, V_o, and T are known. C can be estimated by measuring the ringing frequency, $w = (L_1 * C)^{-1/2}$. There are two alternatives to choose V_{cp} and R. One is to pick a reasonable value of V_{cp} (for example, $V_{cp} = 1.5 * V_d$) and then use (6) to calculate R and associated loss. If the loss is too high, then increase V_{cp} to lower the snubber loss until a compromise is achieved. Another way is to specify snubber loss, $(V_{cp} - V_o)2/R$, and use (6) to solve for V_{cp} and R. C_c must be in the order of tens of nanofarads, such that it can be approximated by an ideal voltage source.

IV. Conclusion

Detailed analysis and parameter design for the RCD clamped snubber has been presented. It has been shown that a compromise is needed between clamped voltage and snubber loss for the choice of R.

References

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Speed Sensorless Vector Control of Induction Motor Using Kalman-Filter-Assisted Adaptive Observer

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***Abstract*—This letter presents a new method of estimating rotor speed of an induction motor. The new method is based on an adaptive flux observer. A second-order Kalman filter is then employed to modify the estimated rotor flux. Experimental results show that the new method has better accuracy in following the speed command under heavy loads.**

***Index Terms*—Adaptive observer, induction motors.**

I. Introduction

In recent years, applications of vector-controlled induction motor drives have widely proliferated. Conventional approaches for vector control [1], [2] require motor speed as a feedback signal. In order to obtain the speed information, speed transducers, such as shaft-mounted tachogenerators, resolvers, or digital shaft position encoders are used, which degrade the system's reliability, especially in hostile environments.

Sensorless vector control has, therefore, been developed to meet this need. In the literature, various approaches of sensorless vector control have been presented. Kubota *et al.* [3] proposed an adaptive flux observer to estimate the rotor flux and speed. The computation process of estimating the rotor speed is simple, and the estimated rotor flux is used to calculate the vector rotation angle. However,

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