A Comparative Study of Operation Characteristics of Active Clamp Forward Converter Based on Loss Analysis

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ABSTRACT - In this paper, operation characteristics of the Zero-Voltage-Switching (ZVS) mode and Non-Zero-Voltage-Switching (NZVS) mode of the active clamp (ACL) forward converter are compared through the loss analysis. The losses of semiconductor devices, transformer and passive elements of the converter are analyzed and compared for each type of operation mode. In order to verify the validity of the analysis, we have built a 50W ACL forward converter and measured the losses of the converter. From the experiment it is known that the ACL forward converter shows nearly same loss distribution for both of operation modes.

1. INTRODUCTION

The forward converter is one of the most popular switching converter topologies for medium and small DC regulation power applications. However, compared with other circuit topologies, this topology has not only transformer but also inductor as energy accumulation device. In order to reduce the size of energy accumulation devices, the converter needs a high switching frequency but it causes to higher voltage stress and further higher switching loss at the main switch of the converter. And, owing to resonance between the leakage inductance of the transformer and the parasitic capacitor of the switch, the noise is increased and the reliability of the switch is decreased after all.

One example of forward converter topologies is an active clamp forward converter which has characteristic of zero-voltage-switching operation. The converter has also an ability to reset the magnetizing energy by the active clamp circuit. This active reset of the magnetizing energy extends the maximum duty cycle of the switch beyond 50%. And it allows wider range of input voltage and relatively constant voltage stress at the main switch over the full range of input voltage.

Operation characteristics between the zero-voltage-switching (ZVS) mode and the non-zero-voltage-switching (NZVS) mode of the converter are compared through the loss analysis. The losses of semiconductor devices, transformer, and passive elements are analyzed and compared for each type of operation mode. For an experiment we have built 50W ACL forward converter, in which the input voltage is Vin=50V and the output voltage Vo=5V, and measured the losses of the converter. The experimental results show that the ACL forward converter has nearly same loss distribution characteristics for both of operation modes.

2. REVIEW OF OPERATION PRINCIPLES

Basic ACL Forward DC/DC Converter

Figure 1 shows the circuit diagram of the active clamp forward converter. The clamp switch (Q_2) is used. Its first purpose is to clamp the primary to the clamp capacitor. A second function is to allow a controlled transfer of energy back from the clamp capacitor to the primary side power stage of the converter (to provide a path for recycling the magnetizing energy in a lossless manner).

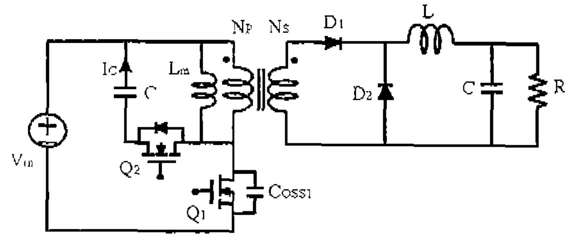


Fig.1 The active clamp forward converter circuit diagram

When Q_1 turns off, the magnetizing inductance of the transformer starts to resonate with the parasitic capacitance of the switches (Q_1, Q_2). When the inductive energy in the leakage and magnetizing inductance is larger than the capacitive energy in the MOSFET output capacitance, the converter operates in ZVS mode. So the operation mode (ZVS or Non ZVS) of converter is determined by the magnetizing inductance.

Non-ZVS operation mode

Key waveforms of the Non ZVS active clamp forward converter are shown in Fig. 2. The main switch, Q_1, is turn-off at t1. C_S (sum of MOSFET's output capacitance) is then charged by the reflected output current, and the switch voltage, V_{DS1}, increase. When V_{DS1} reaches Vin, the freewheeling diode D_2, turns on. This short-circuit the secondary of the transformer and starts the current commutation from the forward diode, D_1 to D_2. When D_1 turns off, Lm starts resonate with C_S. At t_3, V_{DS1} reaches Vin+Vc, and the body diode of the clamp switch, Q_2, turns on, The magnetizing current, i_M, in now the clamp current, Ic, and it decrease with the slope Vc/L_m. At t_4 $Ic(i_M)$ reverse the direction and continuously decrease with the same slope. Q_2 is turned off at t_5. This starts a new L_m-C_S resonance, in which C_S delivers energy to Lm. During the time interval t_5-t_0 V_{DS1} decreases to Vin. D_1 turns on, providing a path for the freewheeling of i_M at the secondary. Q_1 is turned on again at t0, starting as new switching cycle.

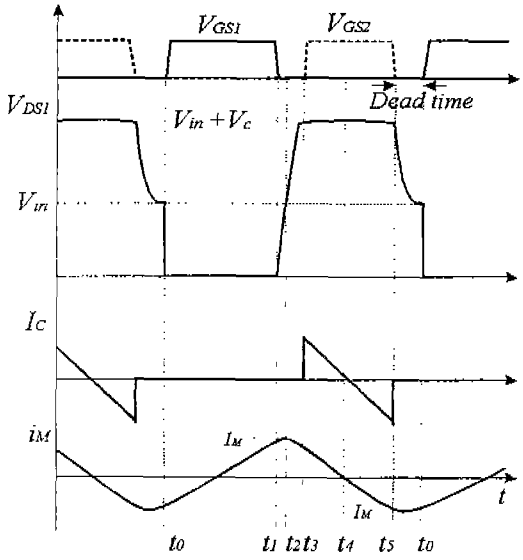


Fig. 2 Key waveforms of the Non ZVS mode

ZVS operation mode

Characteristic waveforms for ZVS mode ACL forward converter are shown in Fig. 3. ZVS is accomplished by reducing L_m. i_M is increased due to the reduction of Lm, so that in the time interval t_5-t_0 it con both support the output current and discharge C_S. Therefore, the ZVS condition is given by :

$$\frac{1}{2}L_m\left(I_{m\,pk}-\frac{I_o}{N}\right)^2 \ge \frac{1}{2}C_sV_{in}^2 \qquad (1)$$

During time interval t_0-t_5, operation of the circuit is

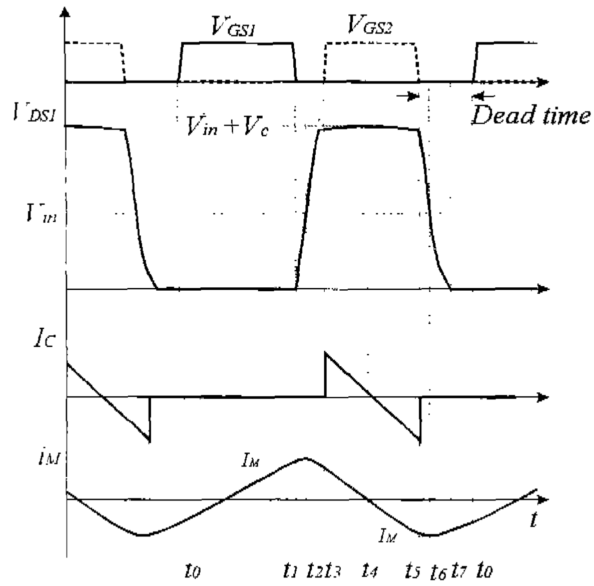


Fig. 3 Key waveforms of the ZVS mode

identical to that of the Non ZVS mode ACL forward converter. The clamp switch Q_2 is turn off at t_5. V_{DS1} decrease to Vin. The transformer voltage becomes zero at t_6. It changes the flowing path of output current form D_2 to D_1. Thus the reflected output current Io/N and magnetizing current i_M continues to discharge C_{OSS1}, and the V_{DS1} decreases towards zero voltage.

3. LOSS ANALYSIS

The total losses of a ACL forward converter can be attributed to conduction losses on both switches and diodes, switching losses and transformer losses (including the core loss and copper loss). For different operation conditions each part accounts for the total losses differently.

Conduction Losses

Conduction losses can be divided into two portions, the conduction losses due to the channel resistance of the active switch and those due to the forward voltage drop of the diodes, provided the resistance of the PC board conduction traces are negligible.

The conduction losses caused by channel on resistance of the MOSFET are

$$P_Q = R_{DS(on)} * I_{DS(rms)}^2 \tag{2}$$

where $R_{DS(on)}$ is the channel resistance of a MOSFET and $I_{DS(rms)}$ is the rms current through the corresponding switch.

The diodes (forward diode and freewheeling diode) also have conduction losses, which are

$$P_D = V_D * I_o \tag{3}$$

where V_D is the forward voltage drop on the diodes and I_O is the load current.

Switching Losses

The switching losses depend on the operation mode of the circuit. If the circuit works with ZVS, the turn on loss may be eliminated completely. In addition to the turn on loss, there are also turn off loss. To completely describe the switching losses, we need to know not only the operation waveforms, but also the turn on and off characteristics of the switches used in the circuit. The switching losses is given by :

$$P_s = f_s * energy(turn\ on + turn\ off) \tag{4}$$

where f_s is the switching frequency.

Losses in Magnetic devices

The transformer and inductor in a ACL forward converter is another loss source, which consists of core loss and copper loss.

Core loss

The core loss increases in all core materials increases with increases in ac flux density, B_{ac}, and operating or switching frequency, f_s. The general form of the loss per unit volume, P_{core}, is

$$P_{core} = k * f^a B_{ac}^d \tag{5}$$

where k, a, d are constants that vary form one material to another. The flux density B_{ac} in (5) is the peak value of the ac waveform as shown in Fig. 4, (a) if the flux density waveform has no time average. When the flux density waveform has a time average B_{avg} as shown in Fig. 4, (b), then the appropriate value to use in (5) is $B_{ac} = \hat{B} - B_{avg}$

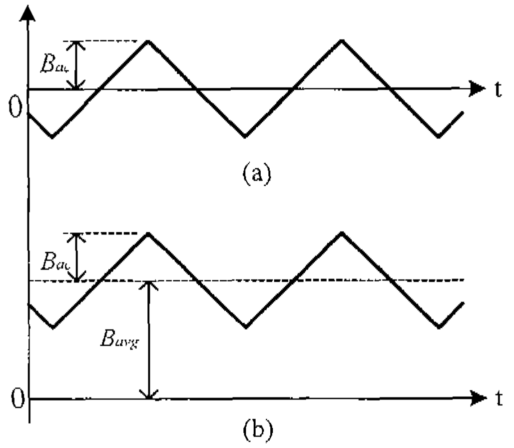


Fig. 4 Magnetic flux density waveforms having (a) no time average (b) with a time average

For the TDK alloy PC40, the core losses are given by:

$$P_{fe} = 3.817\times10^{-16} * f^{1.88} * B_{ac}^{2.6206} \tag{6}$$

Copper loss

In computing the copper loss of the transformer, the following formula may be applied

$$P_{cu} = I_{rms}^{2} R_{DC} \tag{7}$$

where I_{rms} is the rms value of the current in the windings and R_{DC} is the DC resistance computed simply from geometry and material resistivity. However, as is well known, the actual power loss in copper windings increases above the DC value as the frequency of the current increase. This is mainly due to two effects: (a) skin effect and (b) proximity effect. Both effects result in a non-uniform distribution of the current through the cross section of the conduction wire. At higher frequencies, the current will concentrate at the outer surface of the conductor thereby increasing the effective resistance of the wire (known as AC resistance) and in turn elevation the power loss. When several current carrying conductors are placed in the same vicinity, the various currents in each conductor will induce eddy currents in the surrounding conductors. These extra eddy currents will give rise to extra loss and will result in an alteration of the current distribution. These AC loss is given by:

$$P_{cu} = I_{rms}^{2} R_{AC} \tag{8}$$

4. EXPERIMENT RESULTS

To experimentally verify and compare the modes in ACL forward converter , two 50W converters were constructed to following specifications:

- Vin=50Vdc,
- Vo=5Vdc,
- *fs*=200, 400kHz
- Load current: 0.1 ~ 10A

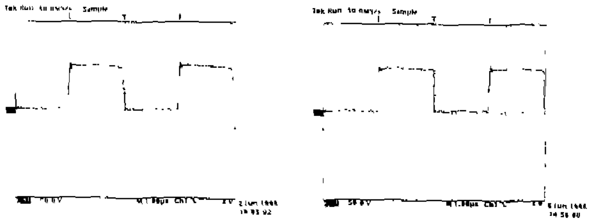
Based on the specifications, the power stage components were chosen: IRF 640 for the power, clamp switches and 60CNQ035 rectifier and TDK PQ3230 PC40 as the transformer core.

In case ZVS mode, transformer with magnetizing inductance (L_m) = 60.48μH was employed to achieve ZVS. The value of the clamp capacitance is C_L = 200 nF.

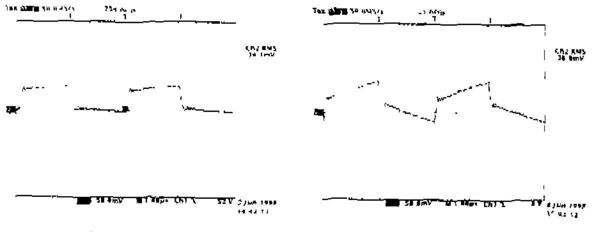
In case Non ZVS mode, the measured value of the magnetizing inductance is L_m = 273.78 μH. The value of the clamp capacitance is C_L = 47 nF.

The experimental waveforms of the main switch (Q_1) drain-source voltage, the transformer primary and secondary current, as well as the clamp switch (Q_2) current, are shown in Fig. 4. These waveforms are measured at full load (200 kHz).

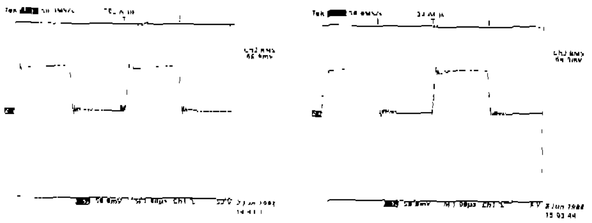
The power stage efficiency was measured under



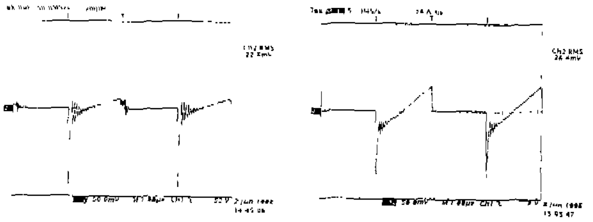
(a) V_{DS},Q_1 (50V/div) (b) V_{DS},Q_1 (50V/div)



(c) I_{T1} (2.5A/div) (d) I_{T1} (2.5A/div)



(e) I_{T2} (5A/div) (f) I_{T2} (5A/div)



(g) I_{Q2} (500mA/div) (h) I_{Q2} (1A/div)

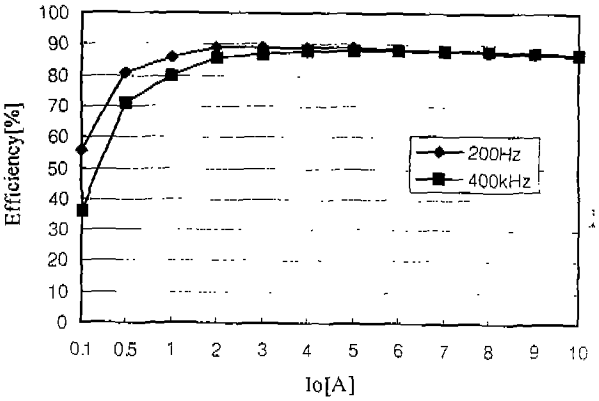
Fig. 4. Experimental wave forms at full load I_o = 10A

(a), (c), (e), (g) : Non-ZVS mode

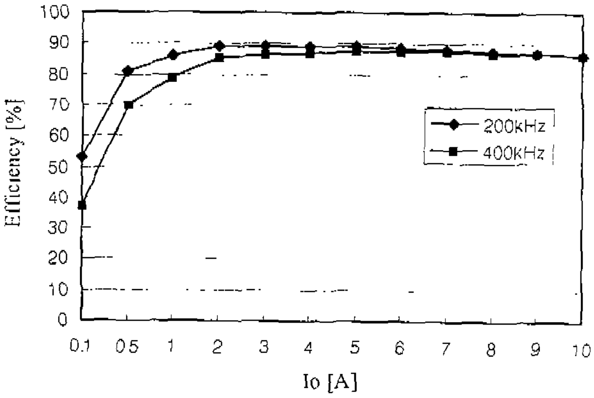
(b), (d), (f), (h) : ZVS mode

different load conditions, as shown in Fig. 5. When operating at full load, the efficiency was 86.25% (Non-ZVS 200kHz), 86.15% (ZVS 200kHz), 86.93%% (Non-ZVS 400kHz), 86.27% (ZVS 400kHz). The maximum efficiency was measured to be 89.31% (Non-ZVS 200kHz), 89.25% (ZVS 200kHz), 88.25% (Non-ZVS 400kHz), 87.64% (ZVS 400kHz). The detailed test results of the losses are summarized in table 1 (at f_s = 200kHz).

The experimental results show that both types of the operation have nearly same distribution of loss. The major sources of this loss distribution are conduction loss (Q_1, diode) and copper loss (transformer, inductor).



(a) Non-ZVS mode



(b) ZVS mode

Fig. 5. The efficiency measurement

Table 1. Loss of the Non-ZVS and ZVS ACL FC (Io = 10A)

Loss		Non-ZVS		ZVS	
		mW	%	mW	%
Transfo-rmer	Core	26.65	0.3	26.10	0.3
	Copper	1160.41	14.5	1196.70	14.8
Switch	Q1	2231.00	27.9	2296.40	28.5
	Q2	94.59	1.18	532.33	6.6
Inductor	Copper	1579.30	19.7	1563.80	19.4
	Core	0.033	0	0.042	0
Diode		2500.00	31.3	2300.00	28.5
Filter Capacitor(ESR)		5.80	0.1	4.78	0.1
Unknown Loss		398.60	5.0	146.40	1.8
Total Loss		8.00[W]	100	8.07[W]	100

5. CONCLUSION

Reviewing the operation principle of the ACL forward converter it is identified that there are two operation modes, Non-ZVS operation mode and ZVS operation mode.

Operation characteristics of the two modes are compared through the loss analysis. The losses of semiconductor devices, transformer and passive elements of the converter are analyzed and compared for each type of operation mode.

From the result, it is known that the ACL forward converter has nearly same loss distribution characteristics for both of operation mode. The validity of the analysis is verified by an experiment.

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