Influences of magnetic inductance, leakage inductance and saturable inductance on an active clamp forward converter

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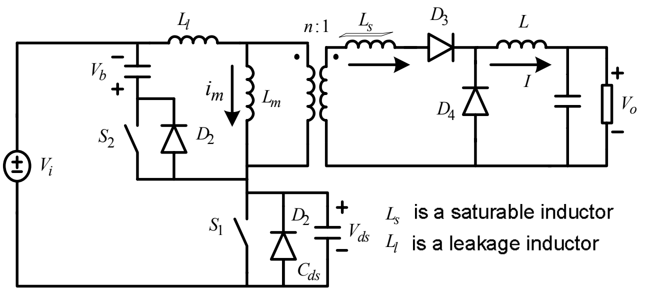
Abstract

In this paper, the influences of the magnetic inductance, leakage inductance and saturable inductor on the behaviour of the active clamp forward are analyzed, and their mathematic solutions are given. Based on the analysis, the other topology variant is proposed, which can be used to reduce the oscillation across the freewheeling switch and improve the ZVS condition of the auxiliary switch in primary side. This leads to improve the EMI behaviour and efficiency because the low voltage rectifier switches could be used. To verify these analyse, some experimental results are presented.

Introduction

The active clamp forward (ACF) converter is a better choice for low voltage power supplies within the range of 50 W to 500 W [1]-[5]. The topology has been studied and reported widely. ZVS condition can be improved with the energy of magnetic inductance and leakage inductance. But during these analyse of commutation process in most literatures, the leakage inductance is generally neglected. For the low voltage application, the turn ratio of the transformer is so high that there is a large leakage inductance, with which the commutation process of switches and its ZVS condition will be influenced. For the high frequency converter applications the influences can not be ignored. In addition, ZVS condition can be improved with a saturable inductor in series with the rectifier switch. But, during the saturable state, the parasitic inductance induced by the saturable inductor will be increased, which will lead to a strong oscillation voltage across the freewheeling rectifier diode so as to deteriorate the EMI behaviour and efficiency. Also, due to the high oscillation voltage, sometimes a higher voltage rectifier switch has to be required so as to further reduce the efficiency. To alleviate the high oscillation voltage, improve EMI behaviour and efficiency, an improved method will be proposed in this paper.



S1: main switch
S2: auxilary switch
D3: rectifier switch
D4: freewheeling switch

Fig. 1 Circuit of the active clamp forward (ACF) converter

This paper contains the following. First, analytical equations including leakage inductance and saturable inductance will be given in detail. Then, the other topological variant is proposed based on these analyse. Finally, experimental results are presented.

Basic principle including leakage and saturable inductance

Fig. 1 shows an active clamp forward converter circuit, L_l denotes the leakage inductance and L_s denotes the saturable inductance. In general, there are six modes during a switching cycle. The equations under the idea operation, which do not include the leakage and saturable inductors, have been reported. In low voltage power supplies, the leakage inductance is large, which can not be ignored. And the efficiency can be improved with a saturable inductor in series with a rectifier switch. Hence, the equations including them will be given. Because only in the third and sixth mode there is more important influence on the ZVS condition for Switch S_1 and S_2, we will only give the equations in the modes.

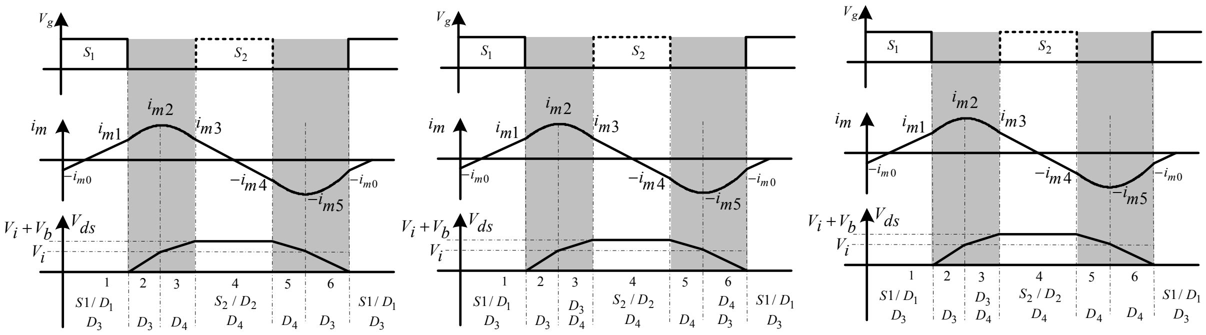
In sixth mode, if the leakage inductance is very small and the saturable inductor can be ignored, the commutation process between D4 and D3 could be neglected. Fig. 3 (a) shows the equivalent circuit in this mode. Thus we can get the following:

$$V_{ds}(t) \approx V_i + (-i_{m5} + \frac{I}{n}) z \sin \omega t \quad (1a)$$

$$i_m(t) = -\frac{I}{n} + (-i_{m5} + \frac{I}{n}) \cos \omega t \quad (1b)$$

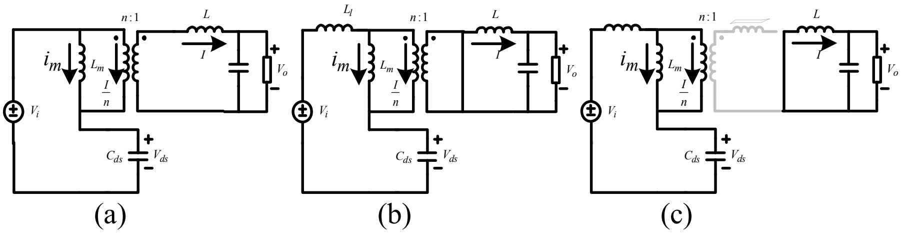
Duration time can be gotten as

$$T_6 = \frac{1}{\omega} \tan^{-1} \frac{V_i}{(i_{m0} - \frac{I}{n}) z} \quad (2)$$



(a) (b) (c)

Fig. 2 Operation waveforms of consideration for (a) only the magnetic inductance, (b) leakage inductance or (c) saturable inductance



(a) (b) (c)

Fig. 3 Equivalent circuits of mode 6 for consideration of (a) only the magnetic inductance, (b) leakage inductance or (c) saturable inductance.

Where $z = \sqrt{\frac{L_m}{C_{ds}}}$, $\omega = \frac{1}{\sqrt{L_m C_{ds}}}$

ZVS boundary condition is

$$i_{m5} > \frac{V_i}{z} + \frac{I}{n} \tag{3}$$

In sixth mode, if the leakage inductance is very large, the commutation process between D_3 and D_4 could not be neglected. Fig. 3 (b) shows the equivalent circuit in this mode. Thus we can get the following:

$$V_{ds}(t) = V_i - i_{m5} z_2 \sin \omega_2 t \tag{4a}$$
$$i_m(t) = -i_{m5} \cos(\omega_2 t) \tag{4b}$$

Duration time can be solved as

$$T_6 = \frac{1}{\omega_2} \sin^{-1} \frac{V_i}{i_{m5} z_2} \tag{5}$$

Where $z_2 = \sqrt{\frac{L_l}{C_{ds}}}$, $\omega_2 = \frac{1}{\sqrt{L_l C_{ds}}}$

Hence ZVS condition can be solved as

$$i_{m5} > \frac{V_i}{z_2} \tag{6}$$

If there is a saturable inductance in series with D_3, the equivalent circuit in this mode can be shown in Fig. 3 (c). There are the same equations for the voltage across switch S_1, the current through magnetic inductance and duration time as (4) and (5).but the impedance and frequency are

$$z_3 = \sqrt{\frac{L_m + L_l}{C_{ds}}} \tag{7a}$$

$$\omega_3 = \frac{1}{\sqrt{(L_m + L_l) C_{ds}}} \tag{7b}$$

ZVS boundary is

$$i_{m5} > \frac{V_i}{z_3} \tag{8}$$

From the above equations, we can know the following.

- If there are no leakage inductance and saturable inductor, the magnetic current is very high due to the reflected current from secondary side. This will lead to a high conduct loss to keep a ZVS condition.
- If there is a large leakage inductance, ZVS can be kept with the energy of the leakage inductance. Hence, conduct loss of the primary side can reduce with a high magnetic inductance. But in fact the oscillation during the commutation is very strong due to the large

leakage inductance and the junction capacitor of the switches. Sometimes this will deteriorate the EMI behaviour and efficiency.

- If there is a saturable inductance in series with the rectifier diode, ZVS condition can be improved due to no reflected current from secondary side. Furthermore, because of this saturable inductance, there is no strong oscillation during the commutation from the rectifier diode (D3) to the freewheeling diode (D4). But during the commutation from the freewheeling diode to the rectifier diode the oscillation is stronger than that without the saturable inductance because of the larger parasitic inductance induced by the saturable inductance. Hence, this will deteriorate the EMI behaviour. Also, because of the stronger oscillation, a higher voltage freewheeling switch has to be used so as to reduce the efficiency when the voltage across D_4 is higher than that across D_3.

Hence, to alleviate the above problem, we can use a saturable inductance in series with D_4 other than that in series with D_3 when the voltage across D_4 is higher than that across D_3, as shown in Fig. 4. It should be noted that in mode 3 the rectifier diode D_3 does not turn off and the freewheeling diode D_4 does not turn on because of the saturable inductance, and in mode 6 the both diode will turn on because of the parasitic inductance induced by the saturable inductance. In the sixth mode, there are the same equations as the case, in which the leakage inductance is very large. In the third mode, the equations can be solved as

$$V_{ds}(t) = V_i + (i_{m2} + \frac{I}{n}) z_4 \sin \omega_4 t \qquad (9a)$$

$$i_m(t) = -\frac{I}{n} + (i_{m2} + \frac{I}{n}) \cos(\omega_4 t) \qquad (9b)$$

Duration time can be written as

$$T_3 = \frac{1}{\omega_4} \sin^{-1} \frac{V_b}{(i_{m2} + \frac{I}{n}) z_4} \qquad (10)$$

where $z_4 \approx z$ and $\omega_4 \approx \omega$ for $L_m \gg L_l$.

The equations in mode 3 for the cases in Fig. 2 (b) and (c) can be solved as

$$V_{ds}(t) = V_i + (i_{m2}) z_2 \sin \omega_2 t \qquad (11a)$$

$$i_m(t) = i_{m2} \cos(\omega_2 t) \qquad (11b)$$

The duration time of this mode can be written as

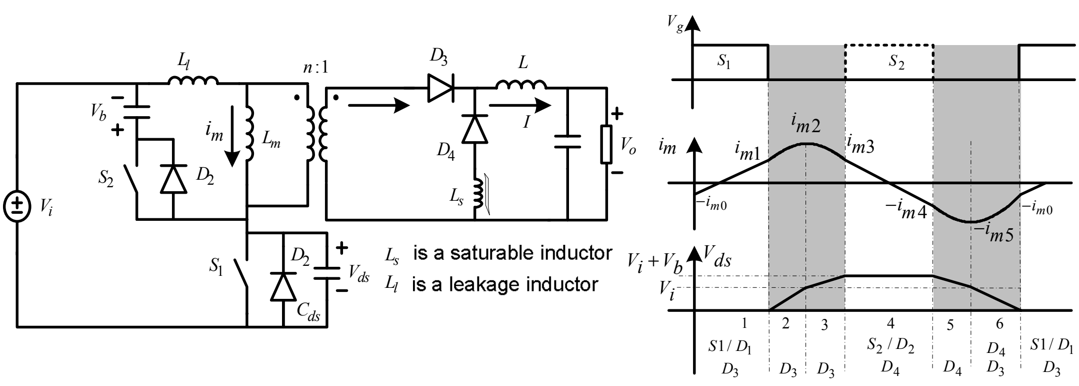


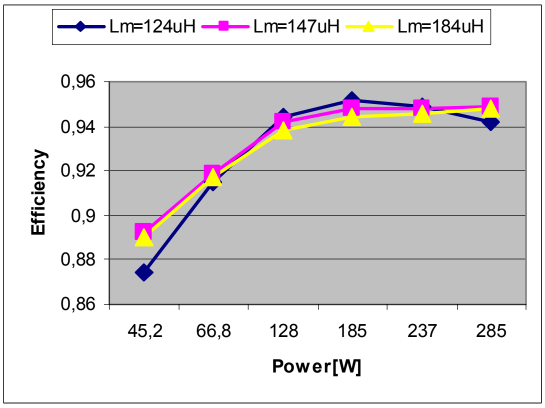
Fig. 4 The proposed circuit and its operation waveforms

$$T_3 = \frac{1}{\omega_2} \sin^{-1} \frac{V_b}{i_{m2} z_2} \qquad (12)$$

With the analysis, we can know the duration time in mode 3 for the proposed circuit is shorter than the other cases shown in Fig. 2 because of the reflected current from secondary side. It is helpful for the auxiliary switch S_2 to attain the ZVS condition. And the oscillation across the freewheeling diode can be suppressed because of the saturable inductor. The efficiency could be improved if the lower voltage freewheeling switch is used.

Experimental results

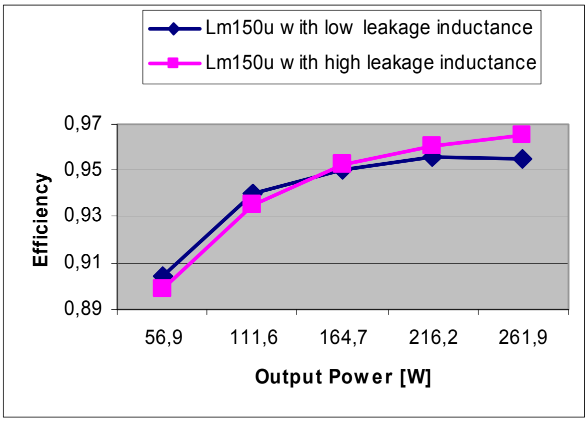
Fig. 5 shows the efficiency curves with different magnetic inductances. From the curves, we can know the efficiency can be improved for the high output power with a low magnetic inductance, but the efficiency is deteriorated for low output power with a low magnetic inductance as predicted. The



Experiment Conditions:

Switching frequency: 260 kHz
Input voltage: 380V
Output voltage: 12V
Turn ratio of the transformer: 9.5
Switches in primary side: SPP17N80C3
Synchronous switches in secondary side: FDP 047AN 08A0

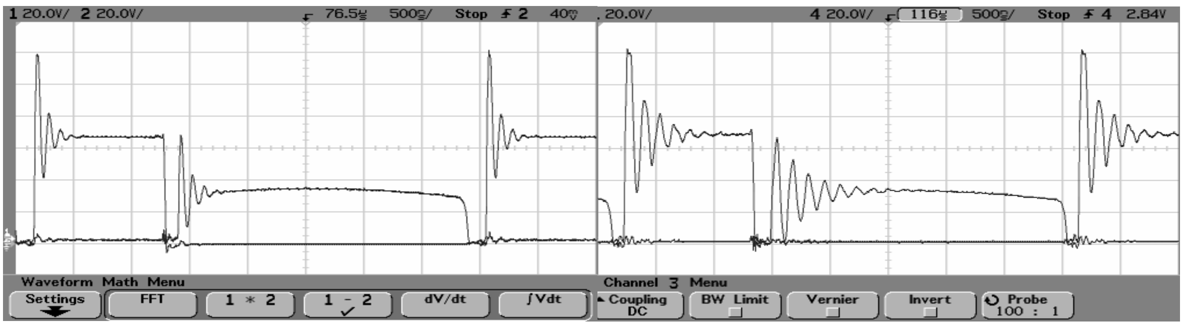
Fig. 5 Influence of magnetic inductance on the efficiency



Experiment Conditions:

Switching frequency: 250 kHz
Input voltage: 380V
Output voltage: 19V
Turn ratio of the transformer: 6
Switches in primary side: SPP11N80C3
Synchronous switches in secondary side: FDP 3652

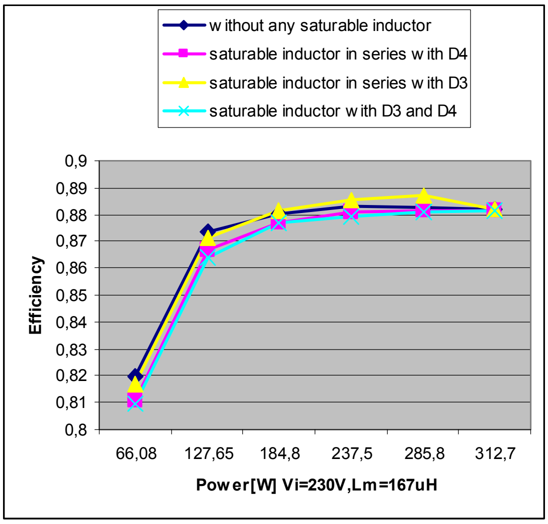
Fig. 6 Influence of leakage inductance on the efficiency



(a) (b)

Fig. 7 Voltage across D3 and D4 with (a) low and (b) high leakage inductance (20V/div) reason is the following. With a small magnetic inductance, ZVS condition is improved so as to a high efficiency for high output power. But the low magnetic inductance leads to a high magnetic current so as to reduce the efficiency for low output power.

Fig. 6 shows the compared efficiency curves with different leakage inductances. There is higher efficiency for high output power and lower efficiency for low output power with the low leakage inductance. The reason can be explained in the following. ZVS can be attained with the energy of the leakage inductance. There is more energy for a high power with the high leakage inductance. Hence, there is a high efficiency for this case. But there is a stronger oscillation during commutation. This will lead to reduce the efficiency under low output power. In addition, it should be noted the EMI behaviour will be deteriorated and sometimes the reliability will be reduced due to the strong oscillation induced by the high leakage inductance. Fig. 7 shows the compared waveforms across the rectifier switches in secondary side. The rating voltage of the switches is 100V. As shown in this figure, there is a stronger oscillation with higher leakage inductance. Moreover, due to the unclamped inductive switching (UIS) capability of the selected rectifier switches, dynamic avalanche is generated. This will lead to reduce the reliability. If the energy induced by the leakage inductance is enough high, the switches will be broken down.

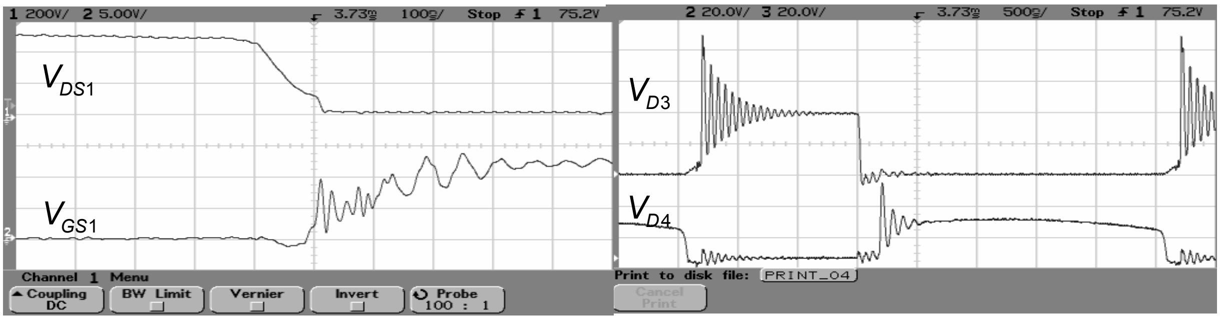


Experiment Conditions:

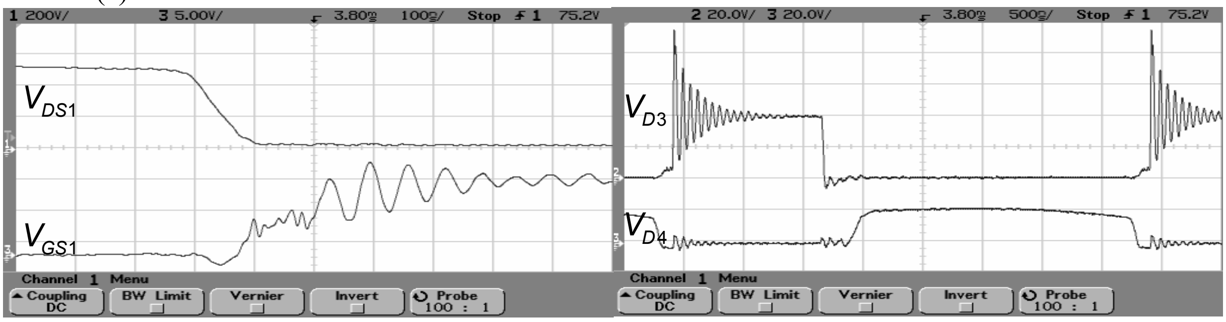
Switching frequency: 260 kHz
Input voltage: 230V
PFC output voltage: 380V
Output voltage: 12V
Turn ratio of the transformer: 9.5
Switches in primary side: SPP17N80C3
Synchronous switches in secondary side: FDP 047AN 08A0

Fig. 8 Influence of saturable inductance on the efficiency

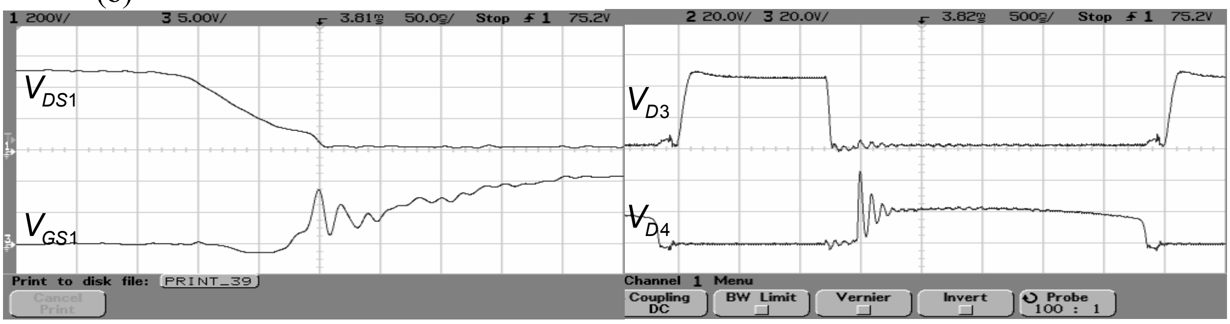
Fig. 9 (a) shows the voltage waveforms across D_3 and D_4 without any saturable inductor. Fig. 9 (b) shows the compared waveforms for the case with a saturable inductor in series with the rectifier switch. It can be seen that the ZVS for the main switch is attained with this saturable inductor. As shown in Fig. 8 the efficiency for this case is improved. But there is very strong oscillation for the voltage across the rectifier switch due to the large leakage inductance of the transformer and parasitic inductance induced by this saturable inductor during its saturable state. In addition, due to the strong oscillation, the EMI behaviour is deteriorated. Moreover, it can be seen dynamic avalanche is generated. To improve the reliability, the rating voltage of the freewheeling switch should be higher than 80V. Fig. 9 (c) shows the other compared waveforms for the case with a saturable inductor in series with freewheeling switch. It can be seen the oscillation across the freewheeling switch is suppressed. EMI behaviour is improved. Moreover, a lower voltage (<60V) freewheeling switch can be used so as to improve the efficiency. Fig. 8shows the compared efficiency curves with the same freewheeling switch. It can be seen there is little difference between them.



(a)



(b)



(c)

Fig. 9 Voltages across D3 and D4(P=306W, 20V/div) (a)without any saturable inductor, (b) with a saturable inductor series with D3 and (c) with a saturable inductor series with D4.

Conclusion

- The efficiency for high power can be improved with a small magnetic inductance, but it for low power will be deteriorate with the small magnetic inductance.
- ZVS condition can be improved with the leakage inductance so as to improve the efficiency for high power. But it will cause the strong oscillation during commutation. This leads to reduce the efficiency for low power and deteriorate the EMI behaviour.
- ZVS condition of the main switch can be improved with a saturable inductor in series with the rectifier switch in secondary side. A higher voltage freewheeling switch has to be used due to the stronger oscillation caused by the parasitic inductance of the saturable inductor.
- ZVS condition of the auxilary switch can be improved with a saturable inductor in series with the freewheeling switch in secondary side. A lower voltage freewheeling switch could be used so as to improve the efficiency and EMI behaviour.

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