Three-Switch Active-Clamp Forward Converter with Low Voltage Stress

Ki-Bum Park*, Chong-Eun Kim**, Gun-Woo Moon*, and Myung-Joong Youn*

* Department of Electrical Engineering and Computer Science, KAIST, Daejeon, Republic of Korea
** Samsung Electro-Mechanics Co. Ltd, Suwon, Republic of Korea

Abstract

A conventional active-clamp forward (ACF) converter is a favorable candidate in low-to-medium power applications. However, the switches suffer from high voltage stress, i.e., sum of the input voltage and the reset capacitor voltage. Therefore, it is not suitable for high input voltage applications such as a front-end converter of which the input voltage is about 400-V_{dc}. To solve this problem, three-switch ACF (TS-ACF) converter, which employs two main switches and one auxiliary switch with low voltage stress, is proposed. Utilizing low-voltage rated switches, the proposed converter is promising for high input voltage applications with high efficiency and low cost.

1. Introduction

To minimize the size and weight of pulse-width-modulation (PWM) converters, high switching frequency is generally required. However, the hard switching of power switch results in high switching loss and high EMI noise. Therefore, various types of soft switching DC/DC converters have been proposed [1],[2]. Among them, the active-clamp forward (ACF) converter, which employs active-clamp circuit (ACC) for transformer reset, shown in Fig. 1 is one of the most popular topologies in low-to-medium power applications because of its simple structure, small transformer size, and zero-voltage switching (ZVS) ability [1]-[4].

Both switches of the ACF converter suffer from high voltage stress, i.e., sum of the input voltage V_S and the reset capacitor voltage V_{Cc}, though its primary current is relatively low. Therefore, it is not suitable for high input voltage applications such as a front-end converter of which the input voltage is around 400-V. In this case, the voltage stress on switches can exceed 800-V with about half duty cycle, resulting usage of low performance and high cost switches. Especially, heavy burden is on the main switch which requires large load current capability and has narrow ZVS range. By selecting a small operating duty cycle, V_{Cc} (=$DV_S/(1-D)$) can be reduced, resulting low voltage stress on switches. On the other hand, the current stress on the main switch Q_M and the voltage stress on D_{S2} are considerably increased, contrary to the switch voltage stress to handle the same rated power. Moreover, the output filter size is also increased as the duty cycle is reduced. Consequently, it is hard to achieve low voltage stress on switch without side effects.

To relieve the above-mentioned limitations, a new three-switch ACF (TS-ACF) converter, which can have reduced voltage stress on switches with an optimal duty cycle, is proposed in this paper as shown in Fig. 2. The main switch is spilt into two i.e., Q_{M1} and Q_{M2}, and the ACC is repositioned, to distribute the voltage stress on switches. The clamp diode D_C limits the voltage stress on Q_{M2} by V_S and provides the conducting path of transformer magnetizing current I_{Lm} during the transformer reset operation. Since V_S contribute to the transformer reset to add to V_{Cc}, only a small value of V_{Cc} is required for the transformer reset. As a result,

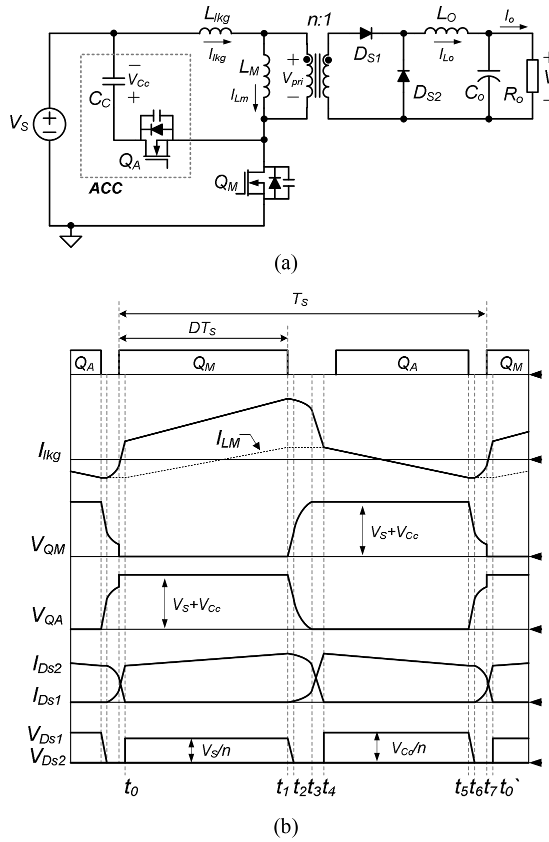


Fig. 1 Conventional ACF converter. (a) Circuit diagram. (b) Key waveforms.

the voltage stress on Q_{M1} and Q_A, i.e., V_S+V_{Cc}, is much less than those of conventional ACF converter accordingly. Thereby, utilizing low-voltage rated switches, i.e., high performance and low cost switches, the proposed converter can be adopted for high input voltage applications with high efficiency and low cost. It is noted that TS-ACF converter costs only additional one clamping diode D_C for distributing voltage stress among three switches. Moreover, Q_A in the repositioned ACC does not require a floating gate driver, though Q_{M1} should be floated. In addition, ZVS of Q_{M2} can be always achieved regardless of load condition as well as Q_A.

2. Operational Principle

2.1. Mode Analysis

The key waveforms and topological states of TS-ACF converter are presented in Figs. 2(b) and 3, respectively. The basic operation is similar to that of ACF converter except for the transformer reset period. The operation of one switching period is subdivided into ten modes as follows.

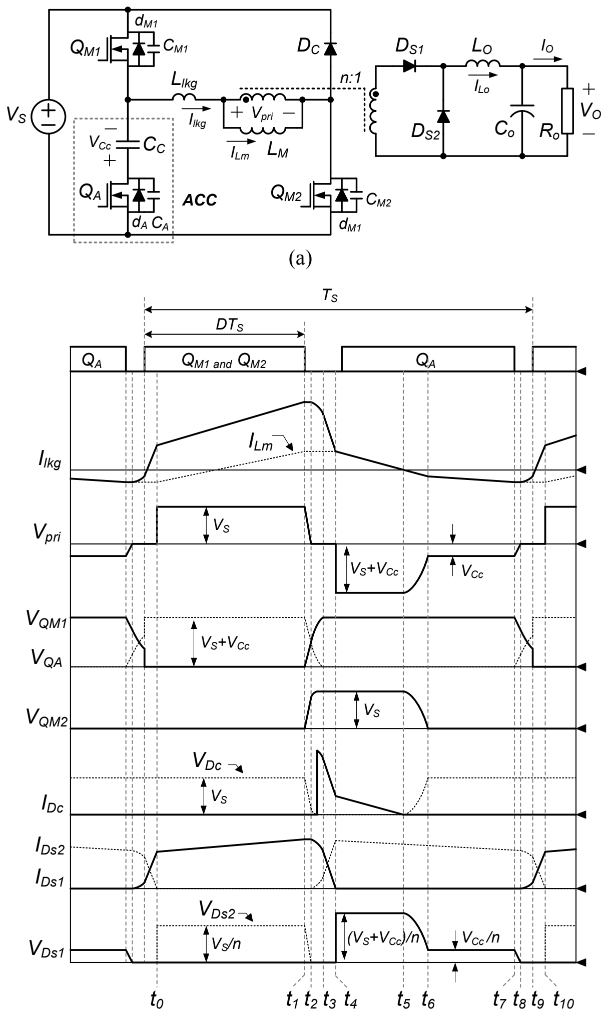


Fig. 2 TS-ACF converter. (a) Circuit diagram. (b) Key waveforms.

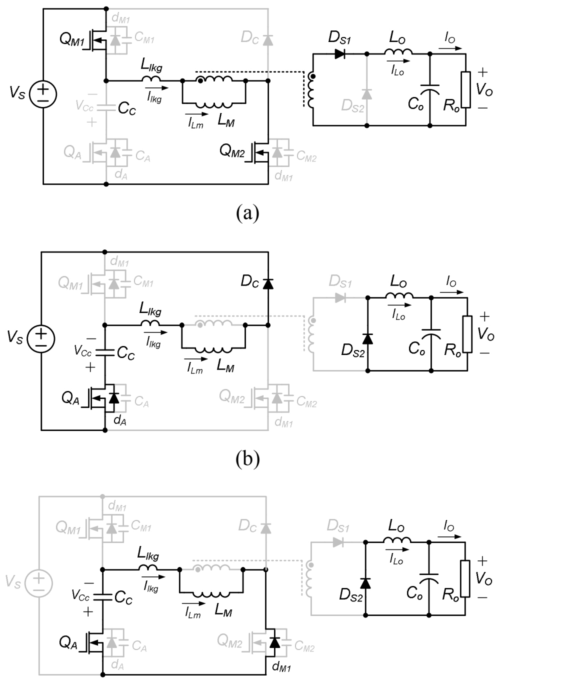


Fig. 3 Key topological states of TS-ACF converter. (a) Mode 1. (b) Mode 5. (c) Mode 7.

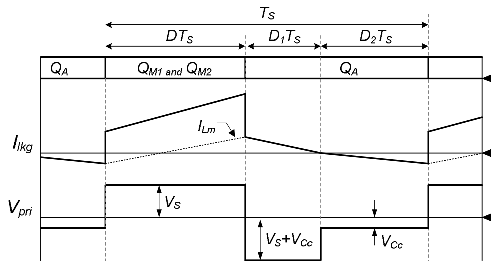


Fig. 4 Simplified waveform

Mode 1 [t_0~t_1] : Both Q_{M1} and Q_{M2} conduct, and V_S is applied to the transformer primary side V_{pri}. I_{Lm} is increased linearly and the power is transferred to the output.

Mode 2 [t_1~t_2] : Both Q_{M1} and Q_{M2} are turned off at t_1. The reflected output inductor current I_{Lo}/n and I_{Lm} charges output capacitance of switches C_{M1} and C_{M2}, while discharging C_A. Therefore, V_{pri} is decreased linearly.

Mode 3 [t_2~t_3] : V_{pri} reaches zero at t_2, then the transformer leakage inductor L_{lkg} resonates with C_{M1}, C_{M2}, and C_A. V_{QM2} reaches V_S and D_C is conducted. The commutation between secondary diodes D_{S1} and D_{S2} begins.

Mode 4 [t_3~t_4] : V_{QA} reaches V_S+V_{Cc} and V_{QM1} reaches zero at t_3. I_{lkg} flows through d_A. To achieve ZVS, Q_A should be turned on while d_A conducts. V_S+V_{Cc} is applied to L_{lkg}, thus I_{lkg} decreases linearly and the commutation is accelerated.

Mode 5 [t_4~t_5] : I_{Ds1} reaches zero at t_4 and the commutation is finished. I_{Lm} flows to the input side through d_A, C_C, and D_C. Therefore, V_S as well as V_{Cc} contributes to the reset operation. That is, V_S+V_{Cc} is applied to L_M, which result in small value of V_{Cc} for the transformer reset.

Mode 6 [t_5~t_6] : I_{Lm} reaches zero at t_5. L_M resonates with C_{M2}, therefore V_{QM2} is decreased.

Mode 7 [t_6~t_7] : V_{QM2} reaches zero at t_6 and d_{M1} is conducted. I_{Lm} flows through C_C, Q_A, and d_{M1}. To achieve ZVS, Q_{M2} should be turned on while d_{M2} conducts. V_{Cc} is applied to L_M and I_{Lm} is decreased slowly than before.

Mode 8 [t_7~t_8] : Q_A is turned off at t_7. I_{Lm} charges C_A while discharging C_{M1}. Thus, V_{pri} is increased linearly.

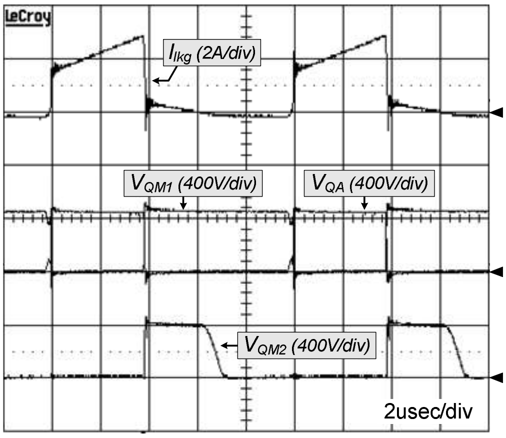
Mode 9 [t_8~t_9] : V_{pri} reaches zero at t_8 and L_{lkg} resonates with C_A and C_{M1}. The commutation between secondary diodes begins.

Mode 10 [t_9~t_{10}] : Both Q_{M1} and Q_{M2} are turned on at t_9. V_S is applied to L_{lkg} and I_{lkg} increases linearly. I_{Ds2} is decreased to zero and the commutation is finished at t_{10}.

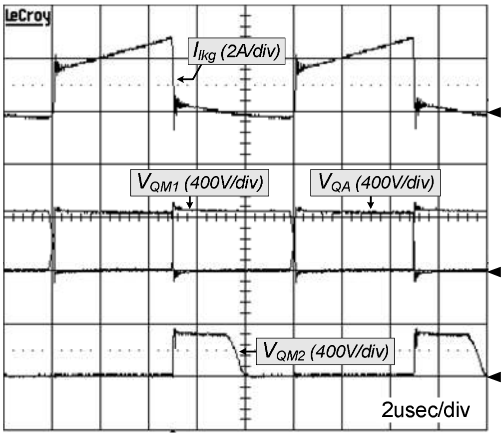
2.2. Steady-State Equations

For the analytic purpose, the simplified waveform shown in Fig. 4, which ignores the transition period, is used. Utilizing the volt.-sec. balance of L_M and cur.-sec. balance of C_C, the steady state equations are obtained as (1)-(3). It is noted that V_{Cc} of TS-ACF converter presented in (1) is much less than that of ACF converter, i.e., $DV_S/(1\text{-}D)$, by the help of V_S in the transformer reset operation as expected. Moreover, if the resonant period between L_M and C_{M2}, i.e., t_5~t_6, is considered, V_{Cc} would be reduced further than (1).

$$V_{Cc} = \left[\frac{\sqrt{1+4D^2/(1-D)^2}-1}{2} \right] V_S \tag{1}$$



(a)



(b)

Fig. 5 Experimental waveforms at full load condition. (a) V_S=385-Vdc. (b) V_S=300-Vdc.

$$D_1 = D - \frac{(1-D)}{2}\left[\frac{\sqrt{1+4D^2/(1-D)^2}-1}{2}\right] \quad (2)$$

$$D_2 = 1 - D - D_1 \quad (3)$$

2.3. ZVS operation

In ACF converter, although the ZVS of auxiliary switch is always achieved by I_{Lm}, the ZVS range of main switch is narrow because L_{lkg}'s energy for ZVS is insufficient. On the other hand, it is remarkable that the ZVS of Q_{M2} in TS-ACF converter can be always achieved by the resonant between L_M and C_{M2} during the transformer reset operation as in t_5~t_6 naturally. However, the ZVS range of Q_{M1} is still narrow similar to conventional one.

3. Experimental Results

To verify the validity of the TS-ACF converter, a 300-W converter prototype with 300~390-Vdc input and 48-Vdc output operating at 100kHz has been built. To employ same voltage rating main switches, the nominal duty cycle at the maximum input voltage 390-Vdc is selected at about 0.4. The prototype of the TS-ACF converter has the following parameters: transformer: PQ3230, transformer turn ratio n=38/13, transformer magnetizing inductance L_M=2.1mH, transformer leakage inductance L_{lkg}=9.3uH, main switches Q_{M1} and Q_{M2}: SPP11N60, an auxiliary switch Q_A: FQP6N60, clamping diode D_C: RHRP1560, secondary diodes D_{S1} and D_{S2}: MUR2020, output inductance L_O=150uH.

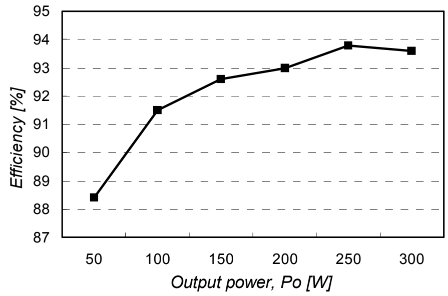


Fig. 6. Measured efficiency

Fig. 5(a) shows the key experimental waveforms of TS-ACF converter with 385-Vdc input voltage at full load condition (300-W). V_{QM1} and V_{QA} are limited to V_S+V_{Cc}, which are slightly higher than 400-Vdc since V_{Cc} is small as expected. V_{QM2} is limited by V_S and is decreased to zero during the transformer reset operation allowing ZVS of Q_{M2}. Fig. 5(b) shows the case of 300-Vdc input voltage, where V_{QM1} and V_{QA} also ensure low voltage stress.

Fig. 6 shows the measured efficiency of TS-ACF converter. Since the proposed converter adopts low-voltage rating switches which has a small drain-source resistance, its primary conduction loss can be reduced. Moreover, ZVS of Q_A and Q_{M2} reduces the switching loss, though Q_{M1} still suffers from hard switching as conventional one.

4. Conclusions

A conventional ACF converter, a favorable topology in low-to-medium power applications, suffers from high voltage stress on switches. Therefore, it is not suitable for high input voltage applications such as a front-end converter of which the input voltage is about 400-V_{dc}. Although relatively low voltage stress can be achieved using small duty cycle, the current stress would be considerably increased and causing other side effects.

To relieve these problems, TS-ACF converter, which employs two main switches and the repositioned ACC with one additional clamping diode, is proposed in this paper. The voltage stresses of all switches are considerably reduced compared with those of ACF converter. Therefore, the TS-ACF converter can be operated by an optimal duty cycle with high-performance and low-voltage rated switches. Moreover, ZVS of lower side main switch can be always achieved regardless of load and line conditions as well as auxiliary switch. Consequently, the TS-ACF converter is promising for high input voltage applications with high efficiency and simple structure.

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