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SIMULATION STUDIES OF FLYBACK DC/DC CONVERTER WITH ACTIVE CLAMP CIRCUIT

To yield energy from the low-voltage power source such as a photovoltaic panel or a fuel cell it is necessary to connect it with step-up DC/DC converter. Among many step-up topologies there are two basic types of converters: ones with and ones without galvanic isolation. Although both types provide voltage gain thanks to the turns ratio of transformer or coupled inductor, electrical isolation in some applications is essential. This paper presents an isolated DC/DC flyback converter using an active clamp and dual series resonance circuits. The converter operates as an isolated voltage amplifier with a voltage gain B dependent on duty cycle D and input voltage V_{in}. Through the use of transistors with low drain to source resistance $R_{DS(on)}$ conduction losses of main transistor switch can be reduced. The reverse recovery current of output rectifier can be omitted thanks to resonant tank consisted of transformer leakage inductance and voltage doubler capacitors. Active clamp circuit allows the energy transfer to the load in the two stages as in the forward converter. The 2-kW flyback converter simulation model was developed. Input voltage V_{in} varied from 12V to 48V and output voltage above 330V needed for 1-phase DC to AC conversion was achieved. Maximum converter efficiency was 92.3%.

KEYWORDS: Pspice simulation, flyback converter, active clamp

1. INTRODUCTION

In the applications with the output power of several kilowatt range and voltages between tens of volts large input currents increase the energy losses, and it is troublesome to maintain high efficiency of the converter. Moreover, the low voltage should be raised to the peak of a grid voltage. To achieve a high efficiency and voltage gain, converters based either on a transformer or coupled inductor have been considered. Compared with an isolation transformer, the coupled inductor has a simple and efficient structure, but its use is restricted to applications that do not require electrical isolation. Several circuits have been proposed from the two paths of development [1],[2]. Among many isolated converters good parameters (such as efficiency and voltage gain) have flyback topologies with soft-switching techniques applied [3],[4]. Unfortunately, one kilowatt of processed power is rarely

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exceeded in this type of systems. It is related to the low efficiency values of these converters working over a few hundred watts. In this study 2 kW flyback DC/DC converter with active clamp circuit will be presented and subjected to a thorough simulation analysis.

2. FLYBACK DC/DC BOOST CONVERTER TOPOLOGY

2.1. Electrical scheme

Flyback converter with active clamp and voltage doubler is depicted in Fig. 1. Converters main switch S_P is conducting input current i_{in} during on-state. When it is turned off clamp switch S_C turns on at zero voltage. Input power is delivered to the load even with main switch turned off. Dual series resonant tank consists of a voltage doubler capacitors C_1, C_2 and leakage inductance L_μ of transformer TR secondary side. This sub-circuit provide zero current turn-off of the output half-bridge diodes thus reverse recovery loss of the diodes can be omitted. Transformer *TR* assures galvanic isolation between two power stages and voltage step-up thanks to turns ratio *n*. The output diode rectifier D_1, D_2 with capacitors (C_1, C_2) double rectified AC voltage of transformer *TR* secondary windings.
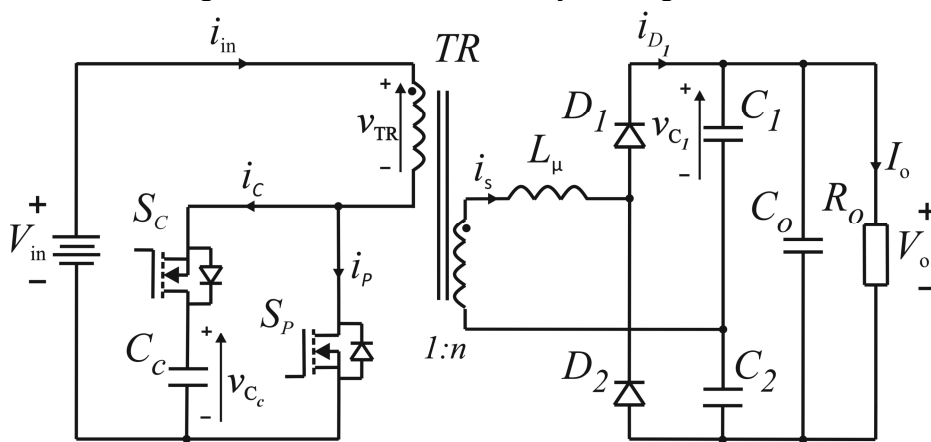

Fig. 1. Flyback DC/DC boost converter with active clamp circuit electrical scheme

2.2. Principle of operation

The converter operation time *T* can be divided into several time intervals. Primary and clamp transistor are driven alternately (Fig. 2). Duration of each transistor conduction time depends on the duty cycle *D*. In order to analyze different operation points of the converter *DT* and *(1-D)T* time intervals should be considered.
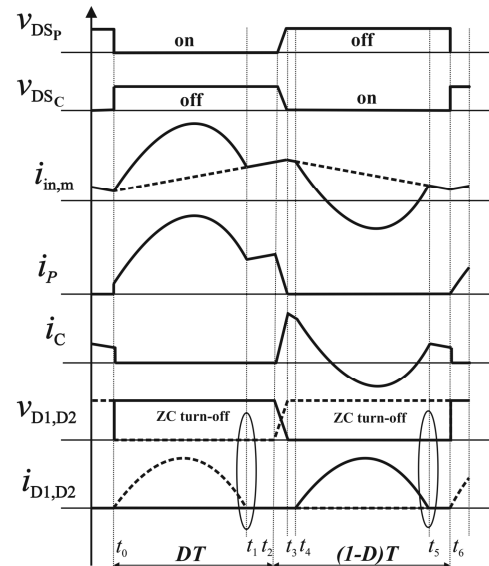
Fig. 2. Typical waveforms of flyback DC/DC boost converter with active clamp circuit

(t_0) - clamp transistor S_C is turned off, primary transistor S_P is turned on; output diode D_1 starts to conduct, D_2 is turned off;

(t_0-t_1) - primary transistor current i_P increases; resonance among C_1, C_2 and leakage inductance L_μ occur; transformer TR magnetizing inductance current i_m increases linear; power is transferred to the load through the transformer

t_1) - diode D_1 turns off at zero current;

(t_1-t_2) - C_1, C_2, L_μ resonance is terminated, magnetizing current i_m still increases; S_P is conducting; S_C is turned off; the input current i_{in} is falling, both diodes D_1, D_2 are turned off;

(t_2) - primary switch S_P is turned off;

(t_2-t_3) - main current i_{in} and magnetizing current i_m have approximately constant values; parasitic capacitance of the main switch is charged and clamp switch capacitance is discharged;

(t_3-t_4) - main current i_{in} and magnetizing current i_m are decreasing linearly; voltage across clamp switch S_C becomes zero; input current flows through clamp switch S_C parasitic diode;

(t_4) - clamp switch S_C is turned on at zero drain to source voltage;

(t_4-t_5) - clamp switch S_C is conducting; primary switch is off; magnetizing current decreases linearly; resonance between leakage inductance L_μ and voltage doubler capacitors C_1, C_2 occur;

(t_5) - diode D_5 turns off at zero current;

(t_5-t_6) - C_1,C_2, L_μ resonance is finished; clamp switch S_C is conducting; primary switch is off.

With regard to duty cycle D and voltage-second balance of primary transformer inductance we can determine the dependence of input voltage V_{in} and clamp capacitor voltage V_C which is

$$V_C = \frac{1}{1-D} V_{in}$$

(1)

Taking account to (1) and the transformer turns ratio n the voltage gain of overall converter B is obtained as follows

$$B = \frac{V_o}{V_{in}} = \frac{n}{1-D}$$

(2)

3. PSPICE SIMULATION MODEL OF FLYBACK DC/DC CONVERTER WITH ACTIVE-CLAMP CIRCUIT

Flyback isolated DC/DC converter model (Fig. 3) is supplied from DC source V_{in}. Transistor S2 and capacitor C3 (560 µF) form active clamp circuit. Transformer TR ensures galvanic isolation, its turns ratio is n = 1:4. Output AC voltage of the transformer is rectified by diode half-bridge. Voltage doubler output capacitors C1 and C2 (2.2 µF both) and leakage inductance Lu (1.5 uH) of the transformer form resonant tank. Output filter capacitor is 560µF. Output voltage V_o varies with input voltage V_{in} and duty cycle D. Gate driving circuit was introduced in order to improve the quality of transistor switching. In order to accelerate turning off of the transistor BAV20 Schottky diode, 10 nF capacitor and 10 Ω resistance were connected parallel forming the gate circuits at both transistors gates.
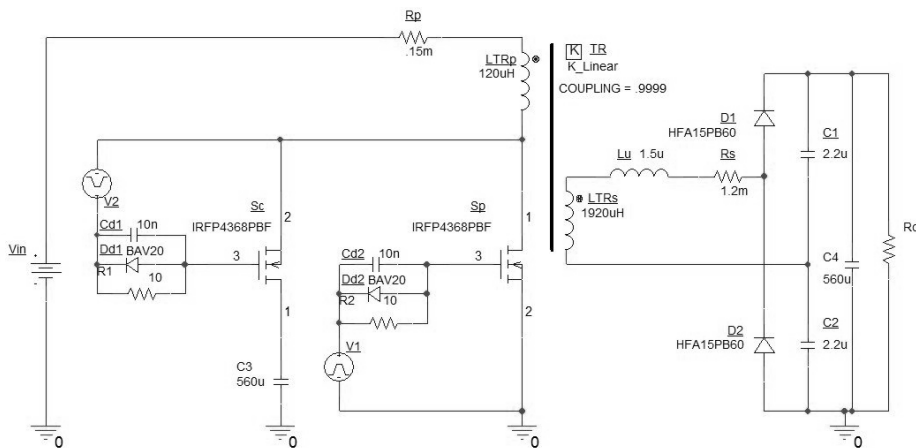
Fig. 3. Pspice model of DC-DC flyback converter with active clamp

The value of driving voltage was constant and equal 20 V. As input voltage was up to 48 volts it was possible to apply low drain to source resistance MOSFET transistors - IRFP4368 ($R_{DS(on)}$ = 1.46 m Ω, 75 V maximum drain to source voltage) [5]. Energy losses of the transistor increase with current square and they are expected to decrease with use of single mili-Ohms drain to source resistance. In output rectifier silicon HFA15PB60 Schottky diodes [5] simulation models were used. The reverse recovery time specified by the manufacturer was 18 ns. Reverse recovery current thanks to C1,C2,Lu resonant tank was significantly reduced. This is a concurrent solution for the application of silicon carbide (SiC) diodes. The values of primary and secondary windings resistances (Rp, Rs) and inductances (LTRs, LTRp) of isolation transformer TR were equal: 0.15 mΩ, 120 μH and 1.2 mΩ, 1920 μH respectively.

4. SIMULATION RESULTS

Transient waveforms of proposed flyback converter are presented in Fig. 4 for fixed frequency 45 kHz, duty cycle of D = 0.6 and load resistance R_o = 70 Ω. The transistors currents and voltages waveforms shapes are associated with the control strategy.
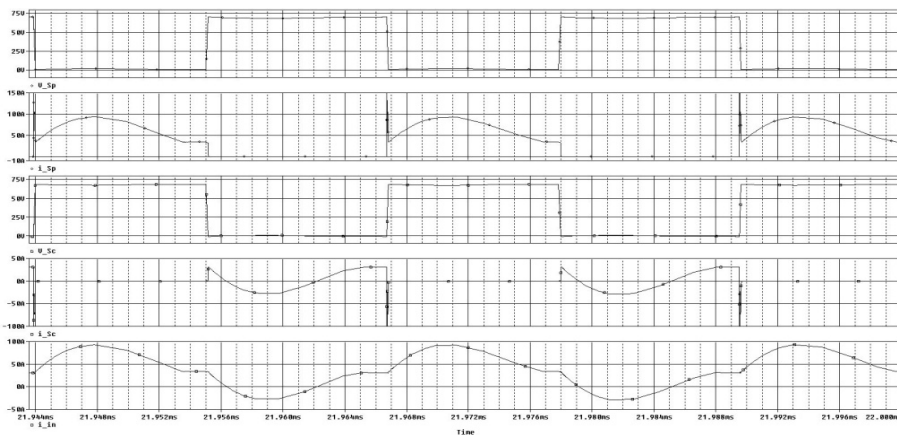

Fig. 4. Transient characteristics of flyback DC/DC boost converter; drain to source transistors voltages V_Sp,V_Sc; transistor Sp current i_Sp ; transistor Sc current i_Sc; input current i_in

Parasitic current overshoots on both transistor currents are associated with switching processes. This phenomenon will affect the efficiency of the converter enlarging transistors switching losses. It most likely can be eliminated by introducing a small time shift between control signals. Drain to source voltages of both transistors are free of parasitic oscillations. In Fig. 5 output rectifier voltages and currents waveforms are presented. Both diodes are turned off at zero current so reverse recovery turn off losses can be neglected.
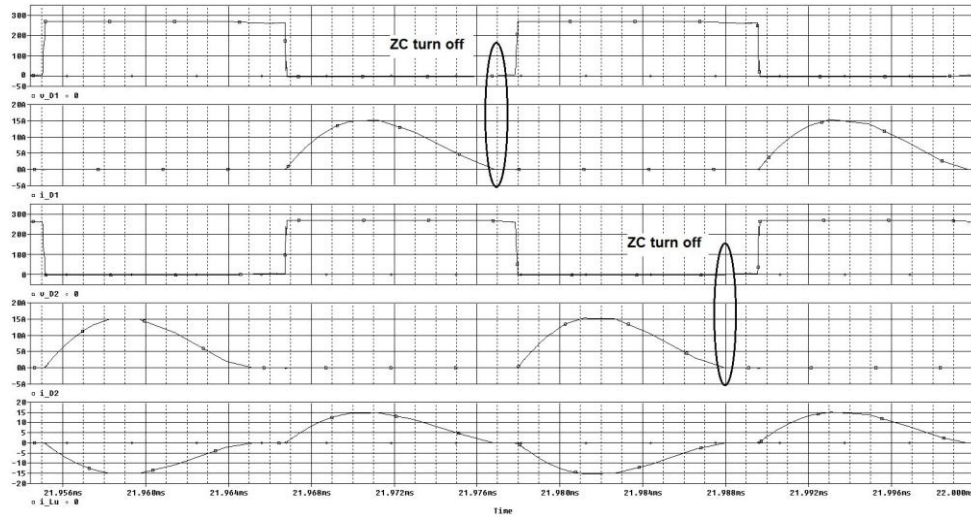
Fig. 5. Transient characteristics of flyback DC/DC boost converter; output diode voltages
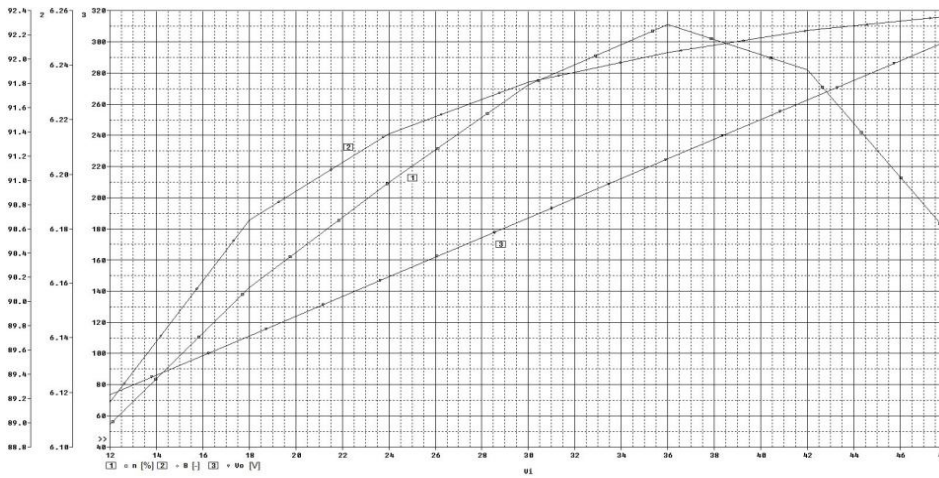V_D1,V_D2; diode D1, D2 currents i_D1; leakage inductance current i_Lu

Fig. 6. Efficiency η, voltage gain *B* and output voltage V_o as a function of the input voltage V_{in}
for fixed output resistance R_o = 70 Ω, frequency f = 45 kHz and duty cycle *D* = 0.6

   As it can be seen in Figure 6 peak converter efficiency was 92.3% for 36 V
input voltage and 293 V of output voltage. The converter maintained voltage step
up ratio over 6 in the 1.3 kW range of output power. Above 24 volts system
provided efficiency over 90%. Output power regulation and changes of circuit
energy associated are shown in Figure 7. Output voltage and power are decreasing
with duty cycle *D* increase. For 2 kW of output power efficiency was 89% which is

a good result for flyback converter. Peak efficiency 91,5% remained at 0.6÷0.65 duty cycle range. Voltage above 330 volts needed for 1-phase DC to AC conversion was maintained for 1.7kW to 2kW with the efficiency over 80% Converter reached 89.1 %, 373 V output, 8.9 voltage gain and efficiency for 2 kW.
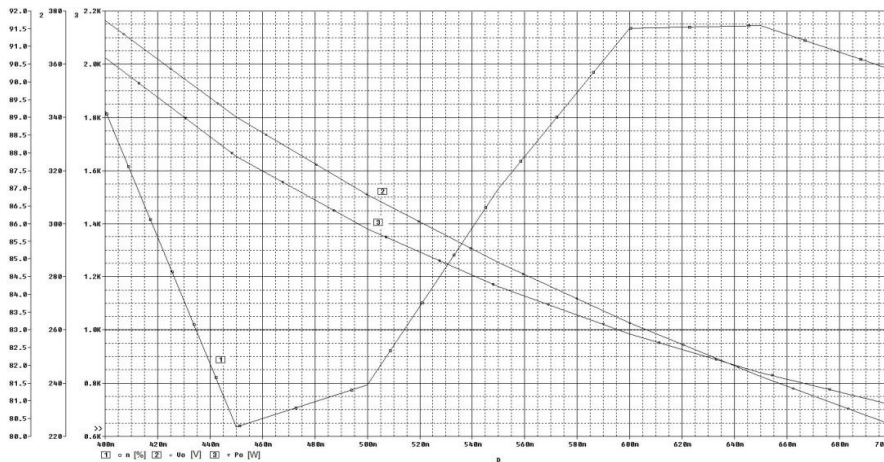

Fig. 7. Efficiency η, output voltage and output power P_o as a function of duty cycle D for fixed output resistance R_o = 70 Ω, frequency f = 45 kHz and input voltage V_{in} = 42

In order to achieve the best possible conditions for converter operation control strategy needs to be adjusted according to the power supply and load demands.

6. CONCLUSION

The 2 kW flyback converter simulation model was proposed. The use of soft-switching techniques and active clamp circuit enabled to achieve high efficiency and high voltage step-up ratio rarely encountered in this type of circuits. Despite the power range rarely encountered in such solutions the efficiency reported for 2 kilowatts was 89.1%. Reverse recovery of output diode and connected with it turn-off energy losses have been omitted. Application of low $R_{DS(on)}$ MOSFET transistors reduced transistors conduction losses. For input voltages more than 24V converter maintained the efficiency above 90%. Reported peak converter efficiency was 92.3% for 700 watts of output power. Since the PSpice model does not fully reflect the real parameters of real circuit it is expected that the results of laboratory tests may vary slightly.

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