A NEW SOFT SWITCHING FLYBACK-FORWARD PWM DC-DC CONVERTER

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Abstract- This paper presents a new soft switching flyback-forward PWM converter. The proposed circuit employs an auxiliary circuit to achieve soft switching condition for switches and also absorbs the voltage spikes caused by the leakage inductance of transformers in the converter. In the proposed converter main switch operates at ZVS and the auxiliary switch operates at ZCS. The proposed converter has some advantages such as the low output current ripple, sharing power between the magnetic elements and work at high power levels, soft switching condition in the both turn on and off switch. Soft switching condition is satisfied for both step-up (boost) and step-down (buck) in the proposed converter. Furthermore this converter has a high efficiency and low voltage stress. The converter is controlled by PWM.

Keywords- Zero Current Switching (ZCS), Zero Voltage Switching (ZVS), Soft Switching, and PWM.

I. INTRODUCTION

Isolated DC-DC converters are widely employed in the communication power system and industrial applications, fuel cell systems, etc. Isolation transformer links primary switching circuitry such as flyback, forward, push pull, half bridge or full bridge topologies with secondary rectifiers.

The well-known classical forward converter needs three windings. Two are used to transform the energy and the third one is used to rest the core. So far many of the flyback and forward transformers have been introduced. The new combined forward-flyback converter doesn’t need reset windings. The transformer is easier to manufacture, is smaller, has lower weight and is therefore cheaper. In the isolated interleaved ZVS flyback-forward boost type converter, the active clamp circuit is added in the interleaved two phases of the converter to recycle the leakage energy.

There are several ways to control the converters. In the PWM converter, switching frequency is fixed; and output converter controlled by controlling the duty cycle. Therefore PWM soft switching converters more than resonant and quasi-resonant converters are considered. In these converters, an auxiliary circuit is added to the switches of converter, so that converter control remains PWM. This paper describes a new soft switching flyback-forward PWM converter, which absorbed voltage spikes due to the leakage inductance of transformers.

The main switch operates at ZVS and the auxiliary switch operates at ZCS. Soft switching condition is satisfied for both step-up (boost) and step-down (buck) in the converter. In the both turn on and off switch, power is transferred to the output therefore this converter work at high power levels. Furthermore this converter is a high efficiency, low voltage stress and the low output current ripple.

II. PROPOSED CONVERTER AND OPERATIONAL PRINCIPLE

A. Proposed converter

The auxiliary circuit is shown in Fig1. The auxiliary circuit connected in parallel to the main switch. The auxiliary circuit consists of auxiliary switch Saux series diode Dav resonant elements La and Ca. This circuit when switched properly ensures lossless switching. The proposed flyback-forward converter is illustrated in Fig2; where Sa is the main switch, Cs is adopted to implement the ZVS soft switching performance, which includes the parasitic capacitance of the main switch. Cs is the block capacitor, C01 and C02 are the output capacitors, Vn1 and Vn2 are the input and output voltages, Da, Db and Dc are the proposed converter diodes, and R0 is the load.

There are two transformers in the proposed converter, which are named by flyback (T1) with 1: n turns ratio and forward (T2) with 1: m turns ratio and an inductance LT which is coupled with forward transformer by 1: m turns ratio. Lm1 and Lm2 are the magnetizing inductors; Lk1 and Lk2 are the leakage inductances of transformers.

![Fig 1. auxiliary circuit.](image-url)
B. Operation of proposed converter

To simplify the analysis of the converter in steady state, these assumptions are considered:

- The parasite elements are ignored.
- The output capacitors \( C_{O1}, C_{O2} \) are large enough, thus the output voltage \( V_o \) in one switching cycle is constant.
- The input voltage \( V_{in} \) in one switching cycle is constant.

Before \( t_0 \), the main switch \( S \) and the auxiliary switch \( S_a \) are in the off-state. The resonant capacitor \( C_a \) is charged to \( V_o \) by the current of the magnetizing inductors \( L_{m1} \) and \( L_{m2} \) (Equation (1)). The secondary side diodes \( D_1 \) and \( D_2 \) are both reverse-biased and other semiconductor devices are not conducts (see fig 4(a)). Equation (2) and (3) are gives the voltage across the primary of flyback transformer and forward transformer. Equation (4) gives the voltage across the coupled inductor \( (L_T) \).

\[
\begin{align*}
V_{ca} &= V_o + \frac{V_o}{2n} - \frac{2V_{C_b}}{m} \\
V_{L_{m1}} &= \frac{V_o}{2n} \\
V_{L_{m2}} &= -\frac{V_{C_b}}{m} \\
V_{L_T} &= -\frac{V_{C_b}}{m}
\end{align*}
\]

Mode1: This interval begins when the auxiliary switch \( S_a \) is turned-on with ZCS at \( t=t_0 \). The equivalent circuit is shown fig 4(b) with \( I_{L_a}(t_0) = 0 \) as the initial current of resonant inductor \( L_a \). The current in the auxiliary switch \( S_a \) increase linearly as in (6).

\[
I_{S_a}(t) = \frac{V_{C_a}}{L_a} (t-t_0)
\]

\[
I_{S_a}(t) = \frac{V_o}{2n} - \frac{2V_{C_b}}{m} (t-t_0)
\]

At \( t=t_1 \), current \( I_a(t) \) reaches \( I' \). During this condition is equivalent to:

\[
(t-t_0) = \frac{IL_a}{V_o + \frac{V_o}{2n} - \frac{2V_{C_b}}{m}}
\]

Mode2: When the current in the auxiliary switch \( S_a \) reaches \( I' \), the diode \( D_1 \) is turn off with ZCS at \( t=t_1 \). The resonant elements \( L_a \) and \( C_a \) are resonating during this interval. The current in the auxiliary switch \( I_{S_a}(t) \) will raises sinusoidal as shown in 4(d). Equation (8) and (9) gives the current through the resonant inductor and the voltage across the resonant capacitor respectively. This interval ends, when the voltage across the resonant capacitor \( V_{C_a}(t) \) decreases to zero. This forward biases the body diode of the main switch \( S \) at time \( t=t_2 \). Body diode of the main switch \( S \) is turned-on and it can be now turned-on with zero voltage.
switching (ZVS). The current of the main switch and the voltage of \( C_a \) in resonant state are shown in below.

\[
I_{S_a}(t) = I' + \frac{V_{C_a}}{Z} \sin(w_o(t-t_1)) \tag{8}
\]

\[
V_{C_a}(t) = V_{ca} \cos\left(w_o(t-t_1)\right) \tag{9}
\]

\[
w_o = \frac{1}{\sqrt{L_a C_a}} \tag{10}
\]

\[
Z = \frac{L_a}{\sqrt{C_a}} \tag{11}
\]

During this condition is equivalent:

\[
t_2-t_1 = \frac{\pi}{2} \sqrt{\frac{L_a}{C_a}} \tag{12}
\]

Mode3: Body diode of the main switch (S) turns on, therefore main switch (S) can be turn on with zero voltage switching (ZVS). In this interval, the resonant stop and the current of the main switch (S) raise linearly to zero with white slit slope of \( \frac{V_{ca}}{m L_a} \).

The important equations introduce as following:

\[
V_{L_{m1}} = \frac{V_o}{2n} \tag{13}
\]

\[
V_{L_{m2}} = \frac{V_{Cb}}{m} + \frac{V_o}{2m} \tag{14}
\]

\[
V_{L_T} = \frac{V_{Cb}}{m} + \frac{V_o}{2m} \tag{15}
\]

\[
V_{C_a} = V_{in} + \frac{V_o}{2n} - 2\left( \frac{V_{Cb}}{m} + \frac{V_o}{2m} \right) \tag{16}
\]

\[
I_{S_a}(t) = -\frac{V_{Cb}}{m L_a} (t-t_2) + I' \tag{17}
\]

\[
I_S(t) = \frac{V_{Cb}}{m L_a} (t-t_2) + I' \tag{18}
\]

Mode4: In this interval, the current of the main switch S is zero, the current of inductor \( L_T \) transfer from the body diode S to the main switch S. Therfore diode \( D_1 \) turns on by ZVS and diode \( D_2 \) turns off by ZCS. During in this interval, the current of auxiliary switch \( S_a \) decrease to zero with the pervious slope. Thus the auxiliary switch \( S_a \) is turned off on ZCS. According to KCL equation (17), from the moment, the current of main switch S will be obtained.

\[
I - I_{S_a} = I_S \tag{19}
\]

\[
\Delta T_4 = t_4 - t_3 = \frac{I L_m}{V_B} \tag{20}
\]

\[
V_B = \frac{V_{C_b}}{m} \tag{21}
\]

The equivalent circuit condition is shown in fig4 (e).

Mode5: At \( t=t_4 \) i.e., at the end of DTS, the main switch S is switched-off. The turn off of the main switch is at zero voltage (ZVS), because of snubber capacitor across the main switch.

The voltage across the main switch raises slowly whereby the turn off transition losses reduced. In this condition the diodes \( D_1 \) and \( D_2 \) turn on under ZCS. The voltage across the primary of flyback and forward transformers for this situation is as follows:

\[
V_{L_{m1}} = -\frac{V_o}{2n} \tag{22}
\]

\[
V_{L_{m2}} = \frac{V_{C_b}}{m} \tag{23}
\]

\[
V_T = \frac{V_{C_b}}{m} \tag{24}
\]

This equation circuit is shown in fig4 (f).

It is observed that turn on and turn off of main switch and auxiliary switch by the auxiliary circuit are loss-less.

### III. DESIGN GUIDELINES

In this section, guidelines for the design of the proposed flyback-forward PWM converter are presented.

- Selection of resonant inductor \( L_r \) and resonant capacitor \( C_r \).
- The slope of current in the auxiliary circuit in \( T_1 \) depends on \( L_r \).
- The value of \( L_r \) and \( C_r \) together decides the resonant interval \( T_2 \). The resonant interval should be minimum.

This interval minimizes the conduction losses in the auxiliary switch; maximizes the effective duty cycle as well. The length of the resonant interval is approximately a quarter of the resonant period (Equation (25)).

\[
\frac{\pi}{2} \sqrt{L_r C_r} = (5to10)%of T_{on}(\text{max}) \tag{25}
\]

- Larger values of \( C_r \) increase the peak of auxiliary circuit current. Lower values of \( C_r \) increases voltage slope of main switch. Value of \( C_r \) is so
selected that voltage across the main switch does not exceed the specified limit. The \( C_r \) value is obtained below.

\[
C_r = \frac{I_I}{2V} \quad (26)
\]

\( I_I \) is the on-state current, \( V \) is the off-state voltage, \( t_f \) is the fall time of the main switch.

A. Selection of auxiliary switch \( S_a \), Diodes \( D \) and \( D_a \)

- The device used for the auxiliary switch should have low output capacitance.
- The diodes \( D \) and \( D_a \) are fast recovery diodes.
- The gating signals to \( S \) and \( S_a \) are as shown in fig.3 to ensure ZVS and ZCS transitions of the main and auxiliary switch, respectively.

- The turn-on of auxiliary switch is \( t_s = t_1 + T_2 + T_3 \). This ensures that the turn-off transition of the auxiliary switch \( S_a \) is at zero current.
- The minimum delay \( T_d \) for the turn-on of the main switch \( S \) is \( t_s = T_1 + T_2 \). In several ZVS schemes, the delay is a function of load and other operating conditions.

**IV. SIMULATION RESULTS**

The flyback-forward PWM converter is simulated shown in fig.5 fig.6 and fig.7. The circuit parameters and specifications of proposed converter are summarized in Table.1. As you can see in Fig. 5 the current in turns on instant is negative therefore body diode is on and ZVS condition is provided. Also the voltage at turn off instant raises slowly due to snubber capacitor therefore ZVS condition exists. In Fig. 6 the current of auxiliary switch is zero at turn on and turn off instant therefore ZCS conditions are provided. In Fig. 7...
the voltage and current waveforms of D1 is presented. As you can see ZCS condition exists for turn on and off instant.

### TABLE 1

Utilized components and parameters in the proposed flyback-forward PWM converter

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty cycle</td>
<td>0.52µs</td>
</tr>
<tr>
<td>Input voltage</td>
<td>24V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>48V</td>
</tr>
<tr>
<td>Output power</td>
<td>50W</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>100KHZ</td>
</tr>
<tr>
<td>Snubber capacitor</td>
<td>4.7nf</td>
</tr>
<tr>
<td>Resonant capacitor</td>
<td>1nF</td>
</tr>
<tr>
<td>Block capacitor</td>
<td>10µf</td>
</tr>
<tr>
<td>Output capacitors</td>
<td>47µF</td>
</tr>
<tr>
<td>Resonant inductor</td>
<td>4 µH</td>
</tr>
<tr>
<td>Coupled inductance</td>
<td>30µH</td>
</tr>
<tr>
<td>Magnetizing inductor of Lm1</td>
<td>200 µH</td>
</tr>
<tr>
<td>Magnetizing inductors of Lm2</td>
<td>100 µH</td>
</tr>
<tr>
<td>Turns ratio</td>
<td>1</td>
</tr>
</tbody>
</table>

**Fig. 5.** simulated and experimental results ZVS performances of the main switch (S).

**Fig. 6.** shows the simulated and experimental results ZCS performances of the auxiliary switch (S).

**Fig. 7.** shows the simulated and experimental results the current waveform of (D1).

### CONCLUSION

This paper presents a new soft switching flyback-forward PWM converter. The main switch operates under ZVS condition and the auxiliary switch operates under ZCS condition (turn on and off). Soft switching condition is satisfied for both step-up (boost) and step-down (buck) in the converter. Simulation results are presented for a 50 w, 100KHZ flyback-forward converter.

### REFERENCES


