REALIZING SOFT SWITCHING IN FLYBACK CONVERTER
BY APPROPRIATE TRANSFORMER DESIGN AND
COMPARISON WITH HARD SWITCHED SIMILAR
CONVERTER

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Abstract

AC-DC or DC-DC converters are today entirely dominated by switched-mode power converters, SMPCs. The industry today, in the race of meeting customers’ demands, is looking at packaging more and more power in lesser and lesser volumes. Hence the power supply designers are always engaged in devising new topologies and techniques to achieve power densities efficiently.

Soft switching is one such technique which aids the designers in finding a solution to increase power densities by raising the switching frequency. The present paper proposes the least complicated soft-switching technique in low power flyback converters. Flyback converter in the power range of 150W is taken as a study piece, and soft switching is demonstrated without adding any extra hardware and control overhead. The obtained results are compared with a hard switched CCM flyback converter.

Practical working models are built, tested, and evaluated to display the efficacy of the proposed scheme.

Keywords: Soft Switching, Flyback Converters, DCM, Hard Switching, low power, DC-DC Converter

I. Introduction

Soft Switching is an essential feature in power converters to achieve efficiency improvement and raise the switching frequency. In most of the practical applications, power levels of up to 200 watts are considered as low powered converters. For all such applications, the industry relies on flyback converter topology, which apparently has a simple structure and low component count.
In most of the large scale systems, many low power DC-DC converters are utilized to achieve specific tasks. Out of the total high power requirement of a system, different DC-DC converters of varying output voltages and smaller power stages deliver the power. All these DC-DC converters are fed with a semi-regulated DC bus, such as the output of a Power Factor Corrected converter module or any other intermediate bus voltage. Also, in most of the applications, the load on the DC-DC converters is constant. Under such conditions, the technique proposed [IV] achieves zero voltage and zero current switching for the power switch, without any additional hardware or control overhead.

This paper describes the design and fabrication of a practical soft switched flyback converter using the proposed technique. A hard switched CCM flyback converter is also built with identical specifications and components. Comparison of the performances of the converters under various operating conditions is presented. Results are tabulated and discussed.

II. Topology of Flyback Converter

As described above, the flyback converter is the first choice of designers for isolated low power applications due to its low component count and simple structure. The high-frequency transformer in a flyback converter can be viewed as an Inductor with two or more windings on a magnetic core. Energy from the input is initially stored in of the primary inductance of the transformer, and then it is released to the load through the secondary subsequently.

Flyback converter topology is a basic topology. This converter operates in one of the three modes: Continuous Conduction Mode (CCM), Discontinuous Conduction Mode (DCM) and Boundary Conduction Mode (BCM). The Flyback converter assumes different operating modes based on the output voltage, load conditions, and on the design of the transformer. The three modes have distinct operational advantages and disadvantages, and many books and application notes discuss these distinctions and give details offlyback converter circuit functioning and design [I] [III] [V] [X]. A functional circuit of the flyback converter is shown in figure 1.
While SW1 is ON, the $L_p$ stores energy. All along the ON period of SW1 $T_{ON}$, the primary current rises linearly. Because of the winding polarity, the diode $D_s$ in the secondary is off in this period. The power to the load is delivered by the output capacitor $C_o$.

When SW1 is turned OFF by the controller, the winding polarities reverse. The secondary diode starts conducting, and the energy in $L_p$ is delivered to the output through the secondary inductor. This energy is used to recharge $C_o$. The ON time of the switch SW1 is varied by a closed loop control to regulate the output voltage.

In DCM, the entire stored energy in $L_p$ during $T_{ON}$ is delivered to the $C_o$ and the load during the switch OFF time $T_{OFF}$. When SW1 is turned ON again in the subsequent period, the primary current starts from zero.

In CCM, only a part of the energy stored in $L_p$ is delivered to the output during the period $T_{OFF}$, and balance energy is stored in the transformer. Hence, when SW1 is turned ON by the controller in the subsequent operational period, the current in the primary starts from a residual value.

In BCM, the primary energy stored during the $T_{ON}$ is totally transferred to the load during $T_{OFF}$. SW1 is again turned ON immediately after the energy in the transformer goes to zero.

### III. Realizing Soft Switching

SW1 is either ON with zero voltage across SW1 or is OFF with zero current flow. With this, ideally speaking, the operational losses in SW1 of the converter will be zero.

However, all practical solid-state switches have definite rise and fall times. During every ON-OFF-ON transitions, power loss occurs in the switch, and the losses increase as the switching frequency increases. The parameters governing the losses in switching components are well documented [VIII]. Besides, energy is stored in the
parasitic capacitances and inductances of the converter, and this energy is dissipated in
the switch.
To avoid or reduce the switching losses in the converter, soft switching techniques are
adopted. Soft switching makes the switch to turn ON and turn OFF when the voltage
across the switch is zero, or when the current through the switch is zero. Hence the
converter switching frequency can be increased without reducing the converter
efficiencies. Many soft-switching techniques for different flyback converter modes are
well presented in the literature [II], [IX].
Most of the techniques to realize soft-switching require additional devices and special
control algorithms to achieve soft switching in SMPCs to operate over entire input
voltage and load parameters [XII], [VII]. However, there are many requirements
wherein the load current, and the supply voltage are constant. In such conditions, the
proposed method [IV] can be used to realize total soft-switching obviating the need
for additional overhead for the converter operation with fixed line and load
requirements [XI].
The flyback converter would achieve overall soft-switching SW1 for a predefined
supply voltage and output current by implementing the simple design steps a) to d) give
below:

a) The power supply has to be in Discontinuous Conduction Mode of operation
b) A resonant capacitor $C_R$ is introduced across SW1.
c) Allow $C_R$ and $L_P$ to resonate while the switch is OFF and after the energy in the
transformer is wholly transferred to load.
d) Select the transformer turns-ratio such that the reflected voltage to the primary
side is the same as or higher than the operating supply voltage.

A 150 W soft switched converter operating at 220 V DC input voltage is designed and
built delivering 130 V DC to the load. An identical hard switched CCM converter is
also constructed to compare the performance.

III. DESCRIPTION OF THE PROPOSED SCHEME

Figure 2 shows the proposed scheme to achieve soft switching in the converter.
The converter is designed to operate in Discontinuous Conduction Mode. This enables the MOSFET SW1 to come ON at nil current during turn-ON in every operational period.

At turn ON of SW1, the current in LP linearly rises from zero to IP when SW1 is turned OFF. When SW1 is ON, Ds is in off state, and the load is supplied by the output capacitor Co.

When the PWM controller turns OFF SW1, the voltage at drain VD is zero. CR ensures that VD continues to be at zero until SW1 is fully turned OFF and thus ZVS is guaranteed.

Subsequently, the current flowing in LP and LS starts charging CR and VD rises. When VD reaches a point to induce sufficient secondary positive voltage, the diode DS starts to conduct, and the voltage in the secondary of the transformer is clamped to VOUT.

At this point, the energy stored in the primary starts transferring to the load through DS.

VD rises to a slightly higher value due to the energy stored in Ls and transfers to CR. CR and L1 resonate, and the VD settles down to VIN plus the reflected voltage.

As the converter is designed to operate in DCM, secondary current linearly falls to zero value at a constant voltage VOUT, well within the OFF period TOFF. Diode DS turns off with zero current when the secondary current becomes zero.

Subsequently, VD decreases in a sinusoidal fashion due to the resonance of CR with LP. At this stage, the energy in CR is transferred to Inductor LP, and the current in LP is in reverse direction of IP. When VD reaches the input voltage, the voltage across LP is zero, and the current in LP starts circulating within the circuit of VIN and VD. Consequently, VD starts decreasing and the energy stored in LP discharges CR to zero. The time taken for mutual transfers of energy from CR to LP and from LP to CR is half the resonant time of LP and CR. At the instant of SW1 turn ON, ZVS is guaranteed.
if the design ensures that remaining time of the switching cycle is greater than or equal to half resonant time.

IV. Computing the Primary and Secondary Inductance and Resonant Capacitor Values to Achieve ZCS and ZVS

The equations given below delineate the details explained earlier and enable to compute the required inductance and capacitor values. Table 1 presents the list of variables used in deriving the equations.

Choose D as 0.33 to ensure adequate interval for $L_P$ and $C_r$ resonance. Hence design the converter with $T_{ON} = T/3$ and $T_{SD} = T/3$

Select N from

$$N \geq \frac{V_{IN}}{V_{OUT}}$$  \hspace{1cm} (1)

The load current $I_o$ is equal to the secondary average current, hence compute $I_{SP}$ with

$$I_{SP} = \frac{6* I_o}{N}$$  \hspace{1cm} (2)

$$I_{PP} = \frac{I_{SP}}{N}$$  \hspace{1cm} (3)

To achieve DCM, $I_{SP}$ has to fall to nil value in a time of $T_{SD}$ and as per design it is equal to 0.33 T

$$V_{OUT} = 3* L_S* I_{SP} / T$$  \hspace{1cm} (5)

Compute $L_S$ using
\[ L_S = V_{OUT} * T / (3 * I_{SP}) \]  \hfill (6)

Derive \( L_P \) from
\[ L_P = L_S * N^2 \]  \hfill (7)

Finally, determine \( C_R \) with
\[ \pi \sqrt{L_P * C_R} = T / 3 \]
\[ C_R = (T / (3\pi))^2 / L_P \]  \hfill (8)

V. Timing Chart

Total time period \( T \) can be divided into five intervals to understand soft switching. Figure 3 depicts the Voltage at drain and current through the drain over the time period \( T \).

![Figure 3 Timing Chart](image)

Just before \( t_0 \), the SW1 is in OFF condition, the current in the transformer is zero, \( D_S \) is OFF, and \( C_O \) supplies power to the load. The MOSFET is turned ON at \( t_0 \).

**INTERVAL A:**
The SW1 is turned ON by the controller at \( t_0 \), the current in SW1 is zero, and the primary current rises linearly up to \( t_1 \). The peak primary current \( I_P \) at \( t_1 \) is computed by
\[ I_P = (T / 3) * (V_{IN} / L_P) \]
The drain voltage \( V_D \) is zero throughout this interval. This period ends at \( t_1 \), wherein \( t_1 - t_0 \) is equal to about \( T / 3 \). The controller turns off SW1 at \( t_1 \).

**INTERVAL B:**
SW1 turns OFF at zero voltage due to \( C_R \). Current flowing in the primary inductor \( I_P \) is redirected to \( C_R \), which is charged linearly. \( V_D \) builds up gradually, and when \( V_D \) equals \( 2 * V_{IN} \), this interval ends at \( t_2 \). This interval duration is less than a microsecond and is given by
\[ t_2 - t_1 = 2 * V_{IN} * C_R / I_P \]
INTERVAL C:
The secondary voltage at time $t_2$ is equal to $V_{OUT}$. $D_s$ starts conducting and clamps the secondary to $V_{OUT}$. The stored energy is transferred to load and charges output capacitor $C_o$. When $I_s$ falls to a nil value, this interval ends at $t_3$, and $D_s$ switches OFF with zero current.

INTERVAL D:
At $t_3$, the resonance between $C_R$ and $L_p$ starts. The stored energy in resonant capacitor $C_R$ with a voltage at $2*V_{IN}$ starts transferring to $L_p$. The direction of primary current $I_p$ reverses during this interval. $V_D$ decays in a sinusoidal mode, and when $V_D$ falls to $V_{IN}$ this interval ends at $t_4$.

Interval $D = 0.5\pi \sqrt{C_R * L_p}$.
The interval is chosen as $T/6$ to ensure proper operation.

INTERVAL E:
$L_p$ voltage is zero at $t_4$, and the $I_p$ circulates within the circuit. This circulation results in a further decrease of $V_D$ and $C_R$ starts discharging using the energy stored in $L_p$. When $V_D$ reaches zero at $t_5$, this interval ends.

Interval $D+E = 0.5\pi \sqrt{C_R * L_p}$.
This interval $t_5 - t_4$ is chosen as $T/6$. $t_5$ and $t_6$ of the next cycle are the same. Hence, at $t_5$ the controller turns ON SW1 resulting in ZVS turn ON.

VI. PROTOTYPE DESIGN AND RESULTS
To verify the proposed technique of deriving soft switching, a prototype 150W DC-DC converter operating from 220VDC input is designed and fabricated. The component values were arrived using the equations above for three different switching frequencies.

$V_{IN} = 220V$ DC
$V_{OUT} = 130V$ DC
$P_0 = 150W$

Table 2 depicts the computed values of primary inductance $L_p$, secondary inductance $L_s$, and resonant capacitor $C_R$ for three different operating frequencies 100KHz, 150 kHz, and 200KHz using the formulae presented above.
Table 2 Computed Values of $L_P$, $L_S$, and $C_R$

The core of the transformer is chosen as EE25/13/7 double stack made by EPCOS. The ferrite material is N87. The number of primary turns $N_P$ of the transformer is calculated using standard design equations. The adequate gap is provided in the core to realize the required inductances $L_P$ and $L_S$. UCC3844 is chosen as the controller IC.

The observed waveforms of the Drain and gate are presented in the following figure 4 and figure 5.

![Figure 4 Drain and gate waveforms](image)

Figure 4 Drain and gate waveforms

Figure 4 captures gate and drain waveforms of the main switch indicating the soft switching phenomenon.

![Figure 5 Zero drain voltage at turn ON and turn OFF](image)

Figure 5 Zero drain voltage at turn ON and turn OFF

Figure 5 clearly depicts the SW1 coming on with zero voltage with the $V_D$ reaching zero volts before the gate waveform rises above the cut in the threshold. It also
captures the condition of ZVS during turn OFF. $V_D$ starts at zero voltage and gradually increases.

![Drain voltage and current at transitions](image)

The drain voltage and drain current are shown in figure 6 clearly indicating ZVS and ZCS at transitions.

Table 3.03 presents the losses measured in the soft-switched DCM converter at three operating frequencies.

| Description         | Switching Frequency (KHz) |
|---------------------|---------------------------|
| Input Voltage VDC   | 220                       |
| Output Voltage VDC  | 130                       |

It can be seen from the above table that the losses in the converter are reasonably constant over the operating frequencies. The minor increase in the losses can be attributed to the transformer and other circuitry.

Figure 7 shows the image of the Soft Switched Flyback converter.
VII. HARD SWITCHED CCM CONVERTER DESIGN AND RESULTS

A CCM flyback converter is designed to deliver 150W to the load at an input voltage of 220V and output voltage of 130V. Turn OFF snubber is provided to absorb the energy in the leakage inductance of the transformer and protect the MOSFET switch.

The CCM transformer was designed with the following parameters.

- Operating Frequency: 100 to 200 KHz
- Duty Cycle: 40%
- $\Delta I = 20\%$ of the peak current
- Minimum converter efficiency: 90%

With the above, the primary inductance value arrives at 2.1mH. The turns-ratio is 1.12. Hence, secondary inductance is 1.7mH.

The number of turns $N_p$ and $N_s$ are derived from transformer design methodology for a flux swing of 200mT.

With these values, a converter is fabricated, and the test results are presented here. The resultant drain and gate waveforms are shown in figure 8. Drain voltage and current are shown in figure 9.
It can be observed from the above data in Table 4 that the losses in the converter increase with the increase in the operating frequency. Figure 10 shows the image of the Soft Switched Flyback converter.
VIII. COMPARISON OF SOFT SWITCHED AND HARD SWITCHED CCM CONVERTERS

Table 5 Performance of the hard switched CCM converter

| Description                        | Switching Frequency KHz |
|------------------------------------|-------------------------|
| Input Voltage VDC                  | 220                     |
| Output Voltage VDC                 | 130                     |
| Output Power W                     | 150                     |

Table 5 presents the losses in both the converters at various switching frequencies. The overall losses are higher in the hard switched converter compared to the soft-switched converter.

A saving of 4.0 W to 6.5 W is achieved because of the soft switching in the flyback converter.

IX. Conclusions

A 130 V 150 W flyback DC-DC converter operating from 220 V DC input was designed and built to validate the scheme. An identical hard switched CCM converter is also built for comparison. The results are tabulated and presented for operation at switching frequencies of 100, 150, and 200 KHz. The results clearly demonstrate the achievement and advantages of total soft switching.

The results clearly demonstrate a saving of 4.0 W to 6.5 W in the soft-switched DCM converter compared to the CCM Hard switched converter.

Due to the inherent properties of DCM flyback converter design, the proposed technique is applicable to products requiring low power and less current in the load.
While many soft-switching flyback converters require auxiliary switches and associated control and drives, this scheme does not use any additional switches. But this scheme is limited to constant input and fixed load.

All hard switched flyback converters incorporate a dissipative snubber. This design eliminates the need for such a dissipative snubber along with realizing soft switching.

In many practical requirements such as LED power supplies operating from battery sources, bias generators, fan power supplies, etc., the present technique is useful.

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