**Rafał WIDÓREK[1], Sławomir LIGENZA[2], Cezary WOREK[1]**

AGH University of Science and Technology (1), Fideltronik IMEL Sp. z o.o. (2)

# Magnetic component design and switching technique in high efficiency flyback SMPS

***Abstract.*** *In the article analysis of energy losses in the flyback converter as function of transformer design and operating frequency is presented. An introduction of a resonant snubber circuit on the secondary side of the flyback transformer, combined with controlled switching time of the transistor is discussed.*

***Streszczenie.*** *W artykule zaprezentowano analizę strat w zasilaczu w funkcji parametrów transformatora oraz częstotliwości pracy. Przedstawiono wpływ zastosowania tłumika rezonansowego w połączeniu z kontrolowanym czasem przełączania tranzystora kluczującego. (**Projekt składowej magnetycznej I technika przełączania układu SMPS**).*

**Keywords:** flyback, transformer losses, switching optimization, efficiency.
**Słowa kluczowe:** flyback, straty transformatora, optymalizacja przełączania, sprawność.

## Introduction

The LED lighting market is growing rapidly, so there is a demand for high efficient, not expensive power supplies. The power requirements are usually between 30 W - 200 W. The flyback SMPS converter offers a low component count design while still being able to deliver power in the aforementioned range. The reduced component count, in comparison with e.g. forward converter, allows for a lower cost, high efficiency and small-sized design of the power supply.

This paper will focus on improving the design of the flyback converter and will present a modification to the switching scheme. In the article an analysis of energy losses in the flyback converter as function of operating frequency will be presented. The analysis includes transformer winding losses resulting from current conduction, air gap influence, core losses, transistor switching losses and conduction losses, as well as losses in other components (e.g. rectifier diode). This analysis will be concluded with a search of a point of operation, i.e. operating frequency, at which the overall energy losses in the converter are minimal, thus achieving high efficiency. The paper will contain both calculation and measurement results presentation and comparison.

A modification of the flyback circuit, which improves both efficiency and lowers electromagnetic interference, will be presented. An introduction of a resonant snubber circuit on the secondary side of the flyback transformer, combined with controlled switching time of the transistor will be discussed. The quasi-resonant switching takes advantage of the shape of the transistor VDS voltage and ID current, so switching losses can be largely reduced. The paper will present a description of the circuit that implements this technique as well as a description of the switching cycle of semiconductor elements.

## Modelling power losses

The converter has many sources of power loss. The most critical components are: flyback transformer, the switching transistor and rectifier diode. These components produce a major part of total power loss in flyback converter. Output current shunt resistor and primary side resistor in series with the switching transistor are also included in the analysis. The most difficult part to model is the flyback transformer. There are three major sources of losses here: ferrite core losses, winding conduction losses and winding losses resulting from the core air gap. The core losses will be modelled by the following function provided by Ferroxcube [1]:

(1) $P_{vmloss} = C_m f^x B_{peak}^y (ct_0 + ct_1 T + ct_2 T^2) \cdot 10^3$ , W/cm$^3$

where: $C_m$, $x$, $y$, $ct_0$, $ct_1$, $ct_2$ – coefficients (obtained empirically); $f$ – operating frequency, Hz; $B_{peak}$ – half of the peak to peak flux excursion in the core, Tesla; $T$ – core temperature, ºC.

Current conduction winding losses calculation is obtained from

(2) $P_{curloss} = R_0 (1 + \alpha \cdot \Delta T) \cdot I_{RMS}^2$ , W

where: $R_0$ – resistance value at 20ºC including fundamental component skin effect; $\alpha$ – copper temperature coefficient, 1/ºC; $\Delta T$ – temperature difference from 20ºC,ºC; $I_{RMS}$ – RMS value of the current, A. The current flowing through the windings is a triangular waveform, thus the RMS value is equal to:

(3) $I_{RMS} = I_{pk} \cdot \sqrt{\frac{D}{3}}$ , A

where: $I_{pk}$ – peak value of the current, A, $D$ – duty cycle of the waveform.

Due to air gap in the flyback transformer, the flux will generate losses in the windings located in close proximity to the gap. An approximation method is presented in [2, 3] and [4]. Assuming conditions given in [2]

(4) $P_{cueddy} = \frac{\pi l_w d^4 k_f}{192 \rho_c} \left( \frac{N \mu_0}{w} \frac{di(t)}{dt} \right)^2$ , W

where: $l_w$ – length of the conductor, m; $d$ – diameter of the copper wire, m; $\rho_c$ – resistivity of the copper, $N$ – winding count, $\mu_0$ – permeability of free space, $w$ – copper layer width, $i(t)$ – current in the winding.

From (1), (2) and (4) the transformer losses are calculated

(5) $P_{transloss} = P_{vmloss} \cdot V_e + P_{curloss} + P_{cueddy}$ , W

where: $V_e$ – core volume, cm$^3$.

There are two sources of losses in the transistor: current conduction losses and switching losses. These are calculated from [5]:

(6) $P_{tcloss} = R_{DSon} \cdot I_{RMS}^2$ , W

(7) $P_{tswloss} = 2 V_{DC} I_{pk} \frac{T_{sw}}{T}$ , W

where: $R_{DSon}$ – transistor on resistance, Ω; $I_{RMS}$ – RMS current flowing through transistor, A; $V_{DC}$ – transistor voltage in off state, V; $I_{pk}$ – transistor peak current, A; $T_{sw}$ – transistor switch time, s; $T$ – converter switching period, s.

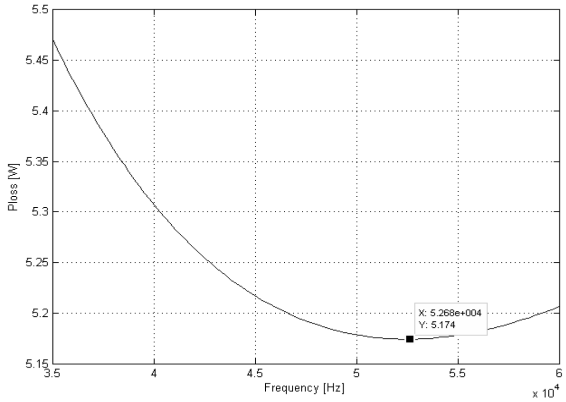


Fig.1. Converter power loss vs. operating frequency

The efficiency at this point is approximately 88.29%, which can be observed in figure 2.

The losses in the rectifier diode can be obtained by similar methods as for the transistor. Switching losses in the diode in discontinuous mode flyback can be omitted.

(8) $$P_{dloss} = U_F I_{avg} + r_F I_{RMS}^2 \text{, W}$$

where: $U_F$ – diode forward voltage, V; $I_{avg}$ – average current flowing through diode, A; $r_F$ – diode dynamic resistance, Ω; $I_{RMS}$ – RMS current, A.

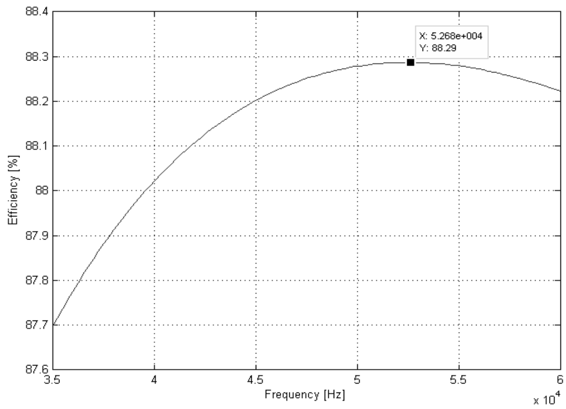


Fig.2. Converter efficiency vs. operating frequency

Analysis has been performed using the equations to calculate total power losses in the flyback converter at varying operating frequency. Figure 1 presents the calculated results of the converter losses. At around 53 kHz the converter losses reach its minimum.

The efficiency was also measured in a built flyback converter. The converter produces an 115 V output with 39W power capability. The measurement results are presented in table 1.

Table 1. Comparison of calculated and measurement data

| Operating frequency [kHz] | Input power [W] | Output power [W] | Measured efficiency [%] | Measured power losses [W] |
|---|---|---|---|---|
| 39.27 | 37.102 | 32.59 | 87.84 | 4.51 |
| 42.29 | 39.66 | 35.07 | 88.43 | 4.59 |
| 45.74 | 43.29 | 38.09 | 87.99 | 5.2 |
| 47.11 | 44.25 | 39.55 | 89.38 | 4.7 |
| 50.48 | 46.45 | 41.24 | 88.78 | 5.21 |
| 52.89 | 48.68 | 43.35 | 89.05 | 5.33 |
| 55.09 | 48.22 | 43.34 | 89.88 | 4.88 |
| 58.1 | 48.69 | 43.34 | 89.02 | 5.35 |

**Effects of addition of the resonant snubber circuit**

Typical flyback converter has high electromagnetic emissions due to hard switching of the transformer current. Connecting a resonant snubber circuit to the secondary winding can significantly reduce ringing, thus improving efficiency and reducing the EM emissions. Figure 3 shows the flyback circuit with the attached resonant snubber circuit.

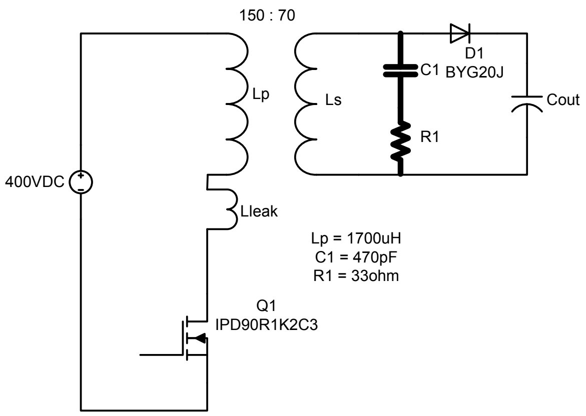


Fig.3. Circuit of the flyback converter with resonant snubber circuit

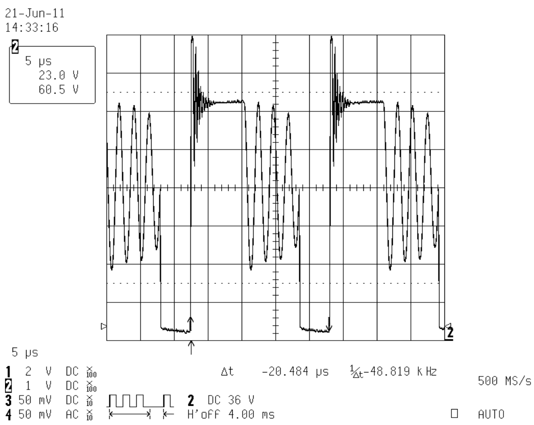


Fig.4. Circuit of the flyback converter without resonant snubber circuit

The modifying circuit consists of components *C1* and *R1*. The addition of the capacitor allows the transistor to switch in quasi-resonant mode. The capacitance transfers to primary side and is connected in parallel with transistor capacitance for ac currents. At the transistor turn off the current forced by transformer leakage inductance is diverted to this capacitance. The transistor current falls to zero at low $U_{DS}$ voltage, thus reducing turn off switching losses. Additionally, the current change d$i$/d$t$ in transformer leakage inductance is lowered, which results in lower voltage spikes and lower amplitude of ringing.

The resistor *R1* is used to lower the quality factor of the resonant circuit. It helps in damping the turn off oscillations on the transistor *Q1*. Moreover it also reduces ringing on the rectifier diode *D1*. Figures 4 and 5 presents the transistor *Q1* voltage waveforms with and without the resonant snubber circuit.

For static loads, such as power LEDs, additional technique can be used. The value of the capacitor *C*1 can be selected to switch on the transistor *Q1* at the valley of the voltage oscillations. The turn on $U_{DS}$ amplitude can be reduced from 400 V to approximately 200 V - 250 V. This significantly reduces the transistor switching losses.

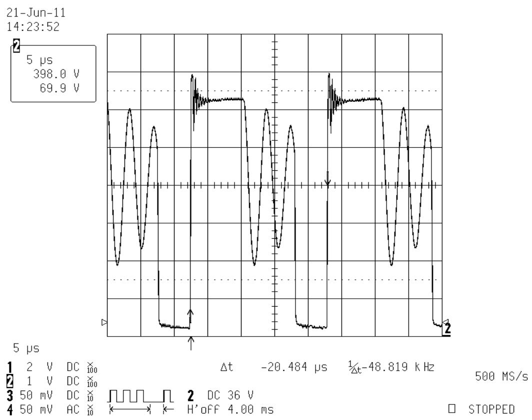


Fig.5. Circuit of the flyback converter with resonant snubber circuit

Measurements show that after introducing the resonant snubber circuit the efficiency is round 2% higher. Table 2 presents a comparison of the measurements for the circuit with and without the resonant snubber circuit.

Table 2. Comparison of efficiency in two circuit versions

| Circuit | Without snubber | With snubber |
|---|---|---|
| Pin [W] | 45.76 | 46.24 |
| Pout [W] | 39.58 | 40.98 |
| Efficiency [%] | 86.49 | 88.62 |
| Ploss [W] | 6.18 | 5.26 |

**Conclusions**

The paper presented a method of evaluating the losses in the flyback converter as a function of the operating frequency. The calculations can be used to define the power losses distribution among the components and it gives a good estimation of the converter efficiency as a guide choice. The improvement achieved by using the resonant snubber circuit is significant while the cost of the modification is extremely low.

REFERENCES


[1] Design of Planar Power Transformers. Ferroxcube Application Note

[2] Van den Bossche A., Cekov Valchev V., Improved calculation of winding losses in gapped inductors. *Journal of applied physics*, (2005)

[3] Nan X., Sullivan C.R., An Improved Calculation of Proximity-Effect Loss in High-Frequency Windings of Round Conductors, *IEEE Power Electronics Specialists Conference*, (2003), 853-860

[4] Popenda A., Concept of modelling of induction machine core losses, *Przegląd Elektrotechniczny*, 86 (2010), n.12, 120-123

[5] Shiroyama H., Matsuo H., Ishizuka Y., Quasi-resonant converter with divided resonant capacitor on primary and secondary side, Telecommunications Energy Conference - INTELEC 2009

[6] Park K.-B., Kim C.-E., Moon G.-W., Youn M.-J., PWM Resonant Single-Switch Isolated Converter, *IEEE Transactions on power electronics*, 24 (2009), n.8

[7] Feng T., Chen F., Rustom K., Batarseh I., Pulse Frequency Modulation with Soft-switching Flyback Single-stage Inverter, Telecommunications Energy Conference - INTELEC 2010



***Authors:** mgr inż. Rafał Widórek, dr inż. Cezary Worek, Akademia Górniczo-Hutnicza, Wydział EAIiE, al. A. Mickiewicza 30, 30-059 Kraków, E-mail: widorek@agh.edu.pl; worek@agh.edu.pl; mgr inż. Sławomir Ligenza, Fideltronik IMEL Sp. z o.o., ul Cystersów 19, 31-553 Kraków, E-mail: slawomir.ligenza@fideltronik.com.pl.*