Tool for Design and Simulation of Flyback Converters

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Abstract: *In this paper is presented a mathematical method to design of switching mode power supply with galvanic separation. Also, the intent of this paper is to present a tool for designing of Flyback converter. Using a combination between differential mathematical equation and linear equations implemented in Matlab, a tool for simulation and design of this type of converter was implemented. This tool allows the introduction of minimal number of input data in order to design the converter and returns all the circuit parameters and the characteristic waveforms of the Flyback converter. This tool for designing and simulating of Flyback converter can have a wide range of users, from switching mode power supply design engineers, in order to reduce the time necessary for design this type of converters, to students that learn these kinds of dc-dc power supply. In order to validate the results obtained with the mathematical model implemented in this Matlab tool, a Spice model simulation was also implemented.*

1. Introduction

Starting from the idea that any electronic circuit, for operation, needs a power source and that switching mode power supply are an important object of study in electronics, this paper aims to address both the problem of designing such a converter and problem understanding through its simulation in the teaching activities. From years of teaching experience in this field, we can say that one of the simplest methods for understanding the operation of switching converters by students consists in analysis converters based on mathematical equations and their characteristic waveform with the following measurements of interest. So this paper aims to submit a tool for design and simulation of power converters based on mathematical equations that can be set during operation. In most application when the power DC-DC converters is presented is necessary to introduce in their configuration a transformer in order to achieve galvanic insulation between input and output. Starting from the idea of designing a converter to provide such isolation between input and output, the Flyback converter topology was chosen because of its peculiarity. Compared to other converters that provide isolation between input and output the advantage of Flyback converter consists mainly in the fact that it is the cheapest and simple converter with galvanic isolation, needing only one inductive element.

This type of converter operates similarly like Buck-Boost converter, except that the magnetic circuit consists of a transformer secondary winding wound in the opposite direction to the primary winding, generally used in relatively small power up to 200 W (due to the large volume required at high power transformer). So, we can say that the Flyback converter is a DC-DC converter that provides isolation between input and output and this converter can be easy controlled in order to obtain a good stability of voltage or current in load. The schematic diagram of Flyback converter is shown in figure 1, which shows the presence transformer that serves as energy storage device, and as an advantage over other converters, we could specify the presence of a single inductive element.

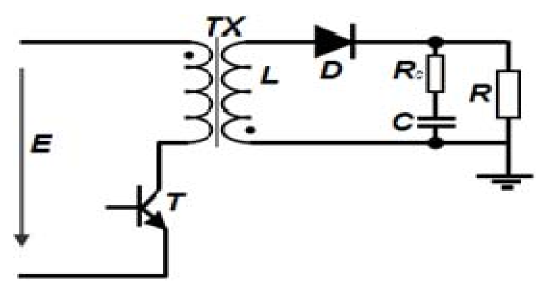

Fig. 1. The schematic diagram of a Flyback converter.

In figure 1 is presented the schematic diagram of a Flyback converter as a simply mode in order to extract the mathematical equation of this converter to be presented and used in the implementation chapter. As it can be seen that the converter topology is relatively simple, consisting of several elements that make it cheap in price and easy to control. By applying a DC input voltage with E value, as shown in Figure 1, it is passed through a transformer which has windings in opposite phases. Therefore a positive voltage through is obtained. The capacitive filter at the output of the converter is designed to smooth the waveform of the voltage on the load. To create a mathematical model very solid, the parasitic elements of components were also taken into account. For example in figure 1 is presented the equivalent series resistance (ESR) of a capacitive filter.

2. IMPLEMENTATION

As we previously mentioned purpose of the paper is to present a design and simulation platform for Flyback converter. To develop a solid platform for simulation of these converters we chose for implementing this tool the Matlab software. Use of this software is based on the fact that it is used by our students in teaching activities and this software represents a solid understanding of the waveforms based on mathematical relationships. So, the first step in the development of the Matlab platform consists in writing the mathematical equations for the Flyback converter. In order to implement the simulation and design platform is necessary to write a mix between differential mathematical equation (to represent the graphical solution of current and voltage across the circuit) and linear mathematical equation (to calculate all the parameters). The mathematical analysis of Flyback converter is based on the conduction and blocking states of the power element (power transistor). Using this states of operation of power converter we can develop our tool in order to allow modeling a continuous conduction mode (CCM) and the discontinuous conduction mode (DCM) (in power supply field is very important to know in what regime of operation wants to operate the converter; therefore, a complete platform must allow its operation in both cases).

During the conduction of the transistor, diode is blocked and all energy is stored in the transformer's primary winding. The differential mathematical relation of current through the coil L (i_L) (secondary winding) and the capacitor voltage (u_c), which can be derived for this operating range, are presented in equation 1, where L_p and L_s denotes the inductance of primary respectively secondary transformer and R_c is the capacitor series resistance.

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{E}{\sqrt{\dfrac{L_s}{L_p}} \cdot L} \\ \dfrac{du_c}{dt} = -\dfrac{u_c}{(R+R_c)\cdot C} \end{cases} \tag{1}$$

When the transistor is blocked, the voltage on the transformer windings is reversed and the diode enters conduction. The energy stored in the preceding interval in the primary winding is now delivery to the load. Mathematical equations that describe the variation of current coil and voltage across on the capacitor which can be derived for this operating range are expressed in relation presented below:

$$\begin{cases} \dfrac{di_L}{dt} = -\dfrac{R}{R+R_c} \cdot \dfrac{u_c + R_c \cdot i_L}{L} \\ \dfrac{du_c}{dt} = \dfrac{R \cdot i_L - u_c}{(R+R_c)\cdot C} \end{cases} \tag{2}$$

These two situations presented above describe the CCM mode of operation of power converter when the transformer secondary current value is great than zero. The output voltage (u_s) of the Flyback converter in this case can be expressed as:

$$u_s = \frac{E}{\sqrt{\dfrac{L_s}{L_p}}} \cdot \frac{D}{1-D}, \tag{3}$$

and the load current which is the average current through the diode is given by:

$$I_s = \frac{I_{L\max} + I_{L\min}}{2} \cdot (1-D) \cdot f_{com} \tag{4}$$

From equations 3 and 4 we can conclude that for continuous conduction mode the output voltage is independent of the load. Also, the current form of transformer's secondary windings does not change with load current, it is increased or decreased with I_s. The transformer of Flyback converter does not work like a traditional transformer, but combines the functions of a shock transformer, which aims to accumulate the energy. The minimum value of inductance L of the secondary winding of the transformer TX must avoid discontinuous regime, and it is determined from the relation:

$$
\begin{aligned}
L_{\min} &= \frac{E_{\max} \cdot T}{2 \cdot n \cdot I_S} \cdot D_{\min} \cdot (1 - D_{\min}) \\
&= \left(\frac{u_S \cdot E_{\max}}{n \cdot u_S + E_{\max}} \right)^2 \cdot \frac{T}{2 \cdot P_{S\min}}
\end{aligned}
, \qquad (5)
$$

where n is the transformation ratio, D is the duty cycle, T represents the switching period and P_s is the output power.

The DCM regime results in a new period characterized by the fact that the current in secondary winding reaches zero value. During this time, both switches, transistor and diode are blocked, so the current in transformer's secondary winding is zero. Mathematical equations that can be derived for this period are:

$$
\begin{cases}
\dfrac{di_L}{dt} = 0 \\
\dfrac{du_c}{dt} = -\dfrac{u_c}{(R + R_c) \cdot C}
\end{cases}
\qquad (6)
$$

In this case the output voltage of the Flyback converter is:

$$
\begin{cases}
D' = D \cdot \sqrt{0.5 \cdot T \cdot \dfrac{R}{L}} \\
u_s = D' \cdot \dfrac{E}{\sqrt{\dfrac{L_s}{L_p}}}
\end{cases}
, \qquad (7)
$$

where D' represents the old duty cycle witch will be incremented in the next switching period in a closed loop case.

Since the platform is meant to be both simulation and design, a series of calculations must be performed in order to determine the optimal parameters of the power converter. In table 1 it can be seen the equations for maximum current across the transistor, the current across diode and the value of capacitance, etc.

Tab. 1. Equations for optimal parameters.

Parameter	Equation form
I_T (transistor current)	$\frac{I_{L\max}}{n} = \frac{P_{S\max}}{n \cdot u_S} \cdot \left(\frac{n \cdot u_S + E}{E_{\min}} \right) + \frac{E_{\min} \cdot T}{2 \cdot n \cdot L_s} \cdot \frac{n \cdot u_S}{n \cdot u_S + E_{\min}}$
I_D (current across diode)	$\frac{I_{T\max}}{n}$
U_D	$\frac{E_{\max}}{n} + u_S = \frac{E_{\max}}{n} + \frac{E_{\max}}{n} \cdot \frac{D}{1-D} = \frac{E_{\max}}{n \cdot (1 - D_{\min})}$
V_e (shock volume)	$\mu_o \cdot \mu_e \cdot \frac{I^2_{L\max} \cdot L}{B^2_{\max}}$
ΔB	$\frac{(I_{L\max} - I_{L\min}) \cdot B_{\max}}{I_{L\max}}$
C (output capacitive filter)	$\frac{I_{S\max} \cdot T}{\Delta u_S} \cdot \frac{n \cdot u_S}{E_{\min} + n \cdot u_S}$
I_C	$\frac{I_S^2}{1-D} \cdot \left[D + \left(\frac{I_S}{I_S \cdot \sqrt{3}} \right)^2 \right]$

3. RESULTS

Based on the mathematical equations presented above, the Matlab platform is developed to design and simulate the Flyback converters and returns the optimal values of the components of the converter and the waveforms characteristics. The following figure shows all the three windows the design tool returns. So, the firsts figure presents the waveforms of the converters and permits the user to introduce the minimal parameters in order to simulate the converter. Starting from differential equation presented in table 1, a Matlab platform for design and simulation of these converters was made. The approach of differential equations allows us to graphically represent the characteristic waveforms of this converter. In figure 2 and figure 3 are presented the preliminary results extracted from the Matlab simulation platform.

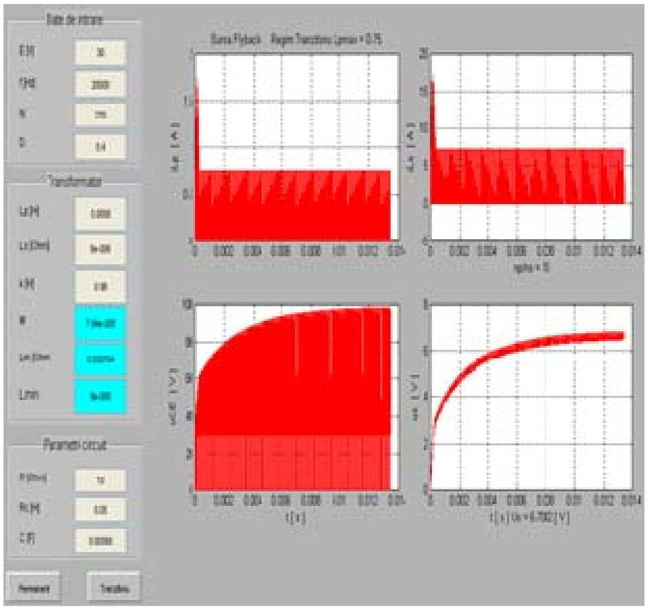

Fig. 2. The Matlab tool for Flyback convertor. Waveforms in transited regime.

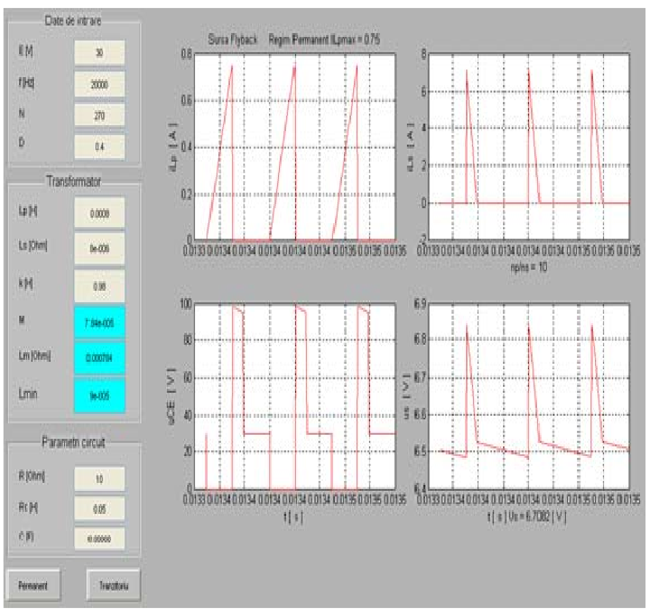

Fig. 3. The Matlab tool for Flyback convertor. Waveforms in steady state regime.

In figures 2 and 3, the tool returns the characteristic waveforms for current across the primary and secondary windings, the transistor voltage and the output voltage in transient or steady state regime. The user may select the input voltage, switching frequency and the output power and the Matlab tool return the waveforms and the optimal parameters of power converters.

The second image of the tool, in figure 4, refers to the optimal parameters calculated and determined with the Matlab tool. The maximum value of current across diode and transistor and the transformer ration are presented. Also, for a minimal number of input parameters the platform returns the optimal parameters and the characteristic waveforms for transistor and diode current and for voltage across transistor.

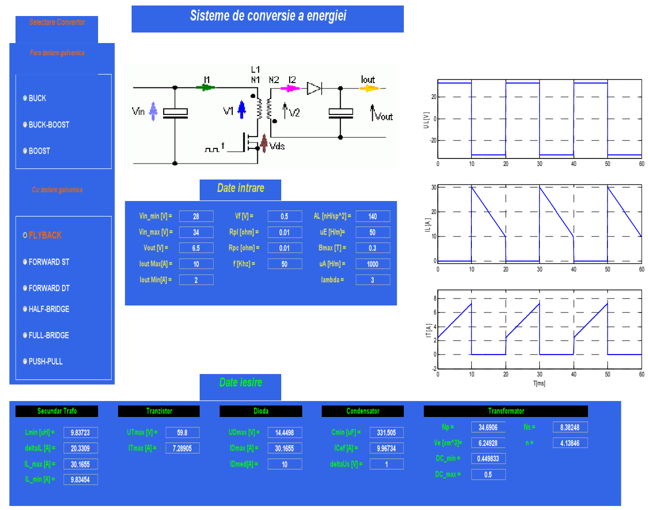

Fig. 4. Optimal parameters of power converters determinated of Matlab tool.

The third image of this tool shows the characteristic of these converters in CCM and DDM regime, as seen in figure 5.

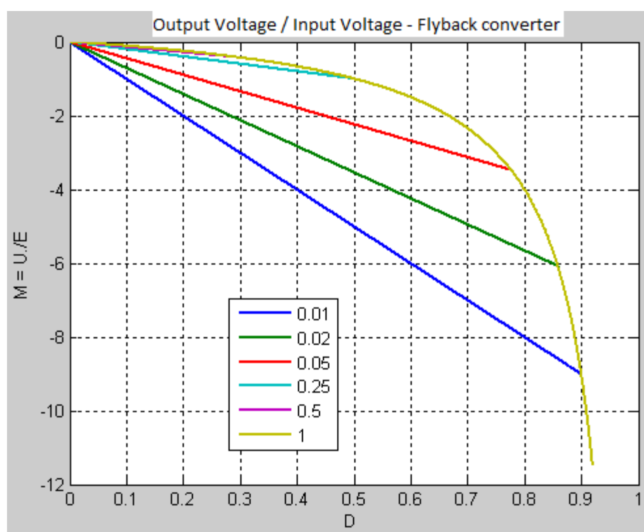

Fig. 5. The CCM and DCM caracteristics of Flyback converter.

In figure 5, a caracteristics of the Flyback converter is presented. This feature shows the operation of the converter both in CCM and DCM regime. The mathematical analysis of both operation modes of the Flyback converter determined the voltage control characteristic. By graphically representting it in Matlab it can be observed that: for discontinuous conduction mode we obtain a linearity of the voltage transfer factor, the slope depending on the circuit's component values; for the continuous conduction mode, a nonlinearity exists which leads to instability.

4. CONCLUSION

As you can see in figure 2, 3, 4 and 5 the Matlab tool returns the characteristic waveforms for current across the primary and secondary windings, the transistor voltage and the output voltage in transient or steady state regime. The user select the input voltage, switching frequency and the output power and the Matlab tool return the waveforms and the optimal parameters of power converters. Because the purpose of this tool is to assist both the switching mode power supply engineers and students, the Matlab tool will run as an executable that can be downloaded without requiring Matlab program. Using a combination between differential mathematical equation and linear equations implemented in Matlab, a tool for simulation and design of the Flyback converter was implemented. This tool allows the introduction of minimal number of data input in order to design the converter and returns all the circuit parameters and the, characteristic waveforms of the Flyback converter. This tool for design and simulation of Flyback converter can have a wide range of users, from switching mode power supply design engineers in order to reduce the time necessary for design the Flyback converters to students that the meaning of dc-dc power supply.

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