# Modelling of Switched Mode Fly-back Supply for Engineering Education

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Abstract—This paper presents a modelling method useful in the education process for the study of DC-DC power conversion principles using pulse width modulation converters. In this paper, the proposed modelling method is applied to a switched mode Fly-back supply. The model of the supply circuit includes the main parasitic elements of its component parts. To analyze the operation mode of the switched mode Flyback supply its model is implemented with the help of MATLAB programming environment. The implementation of the model is used to simulate the behaviour of the Fly-back supply for both continuous conduction and discontinuous conduction modes, in transient and steady state conditions. The model and its implementation offer to the users an easier way to understand and analyze the operation principle of the switched mode power supplies. Moreover, the authors developed a graphic user interface dedicated to this study. The paper includes simulation and experimental results that validate the model of the supply.

Index Terms—circuit modelling, DC-DC power conversion, engineering education, pulse width modulation, switched mode power supply

#### I. INTRODUCTION

One of the most important problems in the education is to establish a reliable connection between theory and practice [1]. For this reason, the future graduates have to gain, during their vocational training in universities, both theoretical and practical skills. Generally, the same affirmation is also valid for engineering education and mostly in the field of electrical and electronics specializations.

An important connection between the two aspects of the vocational training mentioned above is the modelling process of the real problems. It is also important to mention that the practical activity in laboratories can be made by investigating a physical circuit using proper measurement apparatus or by simulations due to the performances of the computers and the specialized software developed for specific purposes and applications. The modelling activity completes the learning process. When a model is created, implemented and then validated, the student has the proof that he understand the operation principle of the analysed circuit and detains a strong tool of investigation or design, because it save important costs related to the materials, devices and specific measurement apparatus used in practical experiments, but also precious time.

This work presents how the modelling activity and its results can be applied in the learning process, to successfully interweave the theoretical knowledge and practical aptitudes of the students, when the students follow courses dedicated to the study of the DC-DC power conversion. In the study of the electronic power converters are currently used analysis techniques [2], [4], [5] and [6] such as: time domain analysis, state space analysis and state averaging technique. In the case of the switched mode DC-DC supply it is advantageous to use the time domain analysis due to the periodical operation of the supply.

In order to perform time domain analysis one can use for example simulation programs, such as PSPICE [3], [12] and Simulink [9] with SimPowerSystems [10].

Considered by many researchers as a reference simulation program, PSPICE offer a friendly graphic user interface and libraries that comprise very accurate device models. Nowadays, there is a trend among electronic devices producers that offer for their products PSPICE models. For this reason, the results of the time domain analysis using simulation program are very close with PSPICE experimental results obtained with real electronic circuits. Despite of its performances, PSPICE return convergence errors when it is used to simulate circuits with many time constants whose values are much different. This situation appear also in the case of the switched mode DC-DC supply where the switching period is smaller than the time constant of the output filter. To overpass this problem, it is necessary to simplify the topology of the converters with the lack in the results precision.

Another simulation environment is Simulink used at the analysis of the dynamic systems. Simulink offer also a user friendly graphic interface and different sets of predefined block libraries such as SimPowerSystems. The models of the power electronic devices included in SimPowerSystems are more plain then their counterparts from PSPICE.

In spite of many facilities of the simulation programs mentioned above, in the learning process, when the students use them, they comprehend heavily the connection between the relations derived theoretically at course which explain the operation of a circuit and the circuit topology.

In order to facilitate the knowledge assimilation for the students in the education process, related with the study of switched mode power supplies, the authors propose a modelling method showing its sequences in the case of a Fly-back supply. The model of the supply takes into account the main parasitic elements of its electronic component parts. The model is implemented using only basic functions of MATLAB programming environment [8]. The modelling and implementation procedure can be used to analyze more complex DC-DC converters. The article includes also experimental results obtained with a low power switched mode Fly-back converter that is able to supply a high output

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DC voltage because its transformer has the turns ratio greater than one. The experimental results are useful to validate the model of the Fly-back converter presented hereinafter.

### II. BRIEF DESCRIPTION OF FLY-BACK SUPPLY

The circuit diagram of a switched mode Fly-back supply is shown in Fig.1. The primary winding of  $T_r$  acts as an inductor when the transistor is in on state. In the off state of  $T_l$ , the transformer assures the isolation between the load and the input power supply. It provides also an output voltage as load circuit request as long as there is energy stored in the magnetic core. The turns ratio is  $n = n_l / n_2$ .



Figure 1. Fly-back topology.

The main theoretical wave forms that describe the operation modes of the switched mode Fly-back supply are shown in Fig.2.



Figure 2. Wave forms for DCM and CCM.

If the supply operate in steady state continuous conduction mode CCM (which means the energy that exists in transformer is greater or at least equal with zero during the operation of the supply) and if input  $U_i$  and output  $U_o$  voltages are considered for simplicity both constant, using the volt-second balance for the primary winding, one can derive the next relation:

$$U_O = n^{-1} \frac{\alpha}{1 - \alpha} U_i. \tag{1}$$

In (1)  $\alpha$  is the duty cycle of the pulse width modulated command voltage  $u_{cd}$  which has a constant *T* period.

When the transistor  $T_i$  is turned on, the current  $i_i$  can be described by the next equation:

$$i_{1\max} - i_{1\min} = \frac{Ui}{L_1} \alpha T \tag{2}$$

The average current through diode D reflected in the primary winding of the transformer  $T_r$  is obtained with the next relation:

$$\frac{i_{1\max} + i_{1\min}}{2} = n^{-1} \frac{U_O}{(1-\alpha)R}$$
(3)

From (2) and (3) one can derive the minimum value of the primary winding inductance at the boundary condition between continuous conduction mode CCM and discontinuous conduction mode DCM, when  $i_{lmin} = 0$ , with the following relation:

$$L_{1\min} = \frac{1}{2}n^2 (1-\alpha)^2 RT .$$
 (4)

The last relation is useful in the design of the switched mode Fly-back supply. Similar results were reported in [4] and [6].

#### III. MODEL OF FLY-BACK SUPPLY

The first step in the modelling of the Fly-back supply is to use an equivalent circuit for the transformer  $T_r$  shown in Fig.1. This device was replaced by two inductors and an ideal electrical transformer. The two inductors represent the leakage inductance  $L_s$  and magnetizing inductance  $L_M$  of the real transformer. For the ideal transformer, the turns of the primary and the secondary windings are  $n_1$  respectively  $n_2$ . Tacking into account the model of the real transformer, one can obtain a new equivalent topology of the switched mode supply, as is shown in the next figure.



Figure 3. Equivalent topology of Fly-back supply.

In each operation cycle, there are three operation modes that are reliant with the state of the electronic power devices and the evolution in time of the state variables. For the operation period of each mode a first order differential equations system can be written with a set of initial conditions. The initial conditions used to solve the differential equations systems are the values of the state variables, obtained at the end of the previous operation mode [6].

In the first operation mode, transistor  $T_1$  is turn on with the help of  $u_{cd}$  and diode D is turned off due to the polarity of the voltage on the secondary winding. The equivalent circuit of this operation mode is shown in Fig.4.



Figure 4.

The currents don't pass through dashed circuits, which mean that their value is zero. The next system describes the operation principle for this mode of operation and it includes the parasitic elements  $L_S$  and  $L_M$  of the transformer as well as the voltage drop  $u_{CEon}$  of  $T_I$  in its on state. In the system, the states variables are the current  $i_I$  through the leakage inductance, magnetizing current  $i_M$  and capacitor voltage  $u_C$ .

$$\begin{vmatrix} L_S & L_M & 0 \\ 0 & 0 & C \end{vmatrix} \frac{d}{dt} \begin{vmatrix} i_1 \\ i_M \\ u_C \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & -1/R \end{vmatrix} \cdot \begin{vmatrix} i_1 \\ i_M \\ u_C \end{vmatrix} + \begin{vmatrix} U_i - u_{CEon} \\ 0 \end{vmatrix}$$
(5)

The currents through the two parasitic inductances are equal while the currents through the windings of the ideal transformer i and  $i_2$  are zero. The capacitor C assures the energy for the load.

In the second operation mode, the command voltage  $u_{cd}$  brings the transistor  $T_l$  in off state and diode D is turned on due to the energy from the magnetizing inductance  $L_M$ .

In Fig.5 is shown the equivalent circuit of the Fly-back supply from which result (6) where  $U_D$  represents the voltage drop over the diode when it is in on state. The currents flow only in the circuits marked with solid line.



Figure 5.

$$\begin{vmatrix} 0 & 0 & 0 \\ 0 & L_M & 0 \\ 0 & 0 & C \end{vmatrix} \frac{d}{dt} \begin{vmatrix} i_1 \\ i_M \\ u_C \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & -n_1/n_2 \\ 0 & n_1/n_2 & -1/R \end{vmatrix} \cdot \begin{vmatrix} i_1 \\ i_M \\ u_C \end{vmatrix} + \begin{vmatrix} 0 \\ 0 \\ U_D \end{vmatrix}$$
(6)

During the period of this operation mode two things could happen. If the magnetizing current  $i_M$  becomes zero before to start a new operation cycle, the Fly-back supply operates in DCM. If the value of the magnetizing current  $i_M$  is greater than zero the Fly-back supply runs in CCM.

The third operation mode begin when the value of the magnetizing current  $i_M$  become zero. It is obvious that this operation mode appear only when the Fly-back supply operates in DCM. This operation mode is absent in CCM. For DCM, the third operation mode can be followed with the help of the equivalent topology shown in the Fig.6.



Figure 6.

For this operation mode one can write the next system.

$$\begin{array}{cccc} 0 & 0 & 0 \\ 0 & 0 & C \\ \end{array} \begin{vmatrix} i_{1} \\ i_{M} \\ u_{C} \\ \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 \\ 0 & 0 & -1/R \\ \end{vmatrix} \cdot \begin{vmatrix} i_{1} \\ i_{M} \\ u_{C} \\ \end{vmatrix}$$
(7)

Using (5), (6) and (7), it was implemented in MATLAB programming environment a program that is used to simulate the operation of the Fly-back supply in time domain. This program is able to simulate the CCM and DCM as well as transient period and steady state operation of the Fly-back supply. The principles used to implement the simulation program in the MATLAB programming environment are briefly shown in the following chapter.

#### IV. IMPLEMENTATION OF THE MODEL

The differential equation systems from the previous chapter are particular cases of the next general form:

$$\mathbf{y}' = \frac{dy}{dt} = f(t, y). \tag{8}$$

MATLAB programming environment offers "ode" functions able to solve ordinary differential equations such as (8). Knowing the differential equations that show the behaviour of the Fly-back supply for every operation mode and the method of use the "ode" functions, the effort of the students is concentrated now not on solving the systems of differential equations but to the implementation of a simple program. This program is able to accomplish transient and steady state analysis, both for CCM as well as DCM. Using this method of work the students understand easier the connection between theoretical analysis and simulation results.

In order to use "ode" function it is important to mention the following information: the name of the function that describes each operation mode, period of every operation mode, initial and integration conditions. In the next example was chosen *ode45* function:

[t, y] = ode45( 'mode function', period, init, opt, P1, P2, ... )

where *t* is a column vector that shows the integration time, *y* is an array that hold the solutions (each row in the array *y* corresponds to a certain time returned in the vector *t*), *mode\_function* is the name of the function that describe (5), (6) or (7), *period* represent the integration time interval, *init* shows the initial conditions of the state variables at the beginning of the period, *opt* mention the integration conditions and P1, P2, ... is a list of parameters. These last parameters list describe the operation condition and the circuit shown in Fig.1.:  $U_i$ , *R*, *C*,  $L_S$ ,  $L_M$ ,  $U_i$ ,  $n_1$ ,  $n_2$ , number of operation cycles and so on. As an example, the next lines of code show the implementation of *mode\_function* for (5).

function dy = mode\_1(t, y, P1, P2, ...); dy = zeros(3, 1); dy(1) = y(2); dy(2) = Ui / (lm + ls); dy(3) =  $-(1 / (r^{*}c)).*y(3);$ 

A similar implementation is made for (6) and (7). It is important to notice that for the second operation mode (6), the implementation of mode\_function has to include an event function that must find out if the Fly-back supply operates in CCM or DCM. During the second operation mode, the event function tests the value of the magnetizing

current. If iM current is smaller or equal to zero, the program integrates (7) else the program integrates (5) with new initial conditions.

The event function is used in the program implementation as follow:

function [value, isterminal, direction] = events( t, y, P1, P2, ...)
value = y(2);

isterminal = 1; % integration stop when y(2) become 0

direction = -1; % y(2) pass through zero from positive to % negative values

where y(2) represent the magnetizing current  $i_M$ . The results are displayed using "plot" functions.

In the education process, is a good practice to make also experiments with a circuit that has similar parameters with those used in the simulation, in order to proof that the simulation results are in good agreement with the experimental results.

# V. SIMULATION AND EXPERIMENTAL RESULTS

For simulation and experiments was used a transformer that presents the next characteristics: maximum output power 9W, inductance of primary winding is about  $30\mu$ H (including leakage inductance) when the secondary winding is floating and finally and  $n_2 = 9*n_1$ . The switching period of the transistor is  $T_c = 21\mu$ s and the input voltage is  $U_i = 12$ V. The output filtering capacitor is C = 940 nF/630V.

In the first part of the laboratory course, students will perform a set o simulations by the help of MATLAB programming environment based on the model described before. First of all, tacking into consideration (4), students determine the boundary conditions between continuous and discontinuous conduction mode. In this case if load resistance is about 411  $\Omega$  and  $\alpha = 0.25$  magnetizing current reaches to zero at the beginning and at the end of each switching time period, Fig.7.



Figure 7. The limit between CCM and DCM for  $R = 411\Omega$  and duty cycle  $\alpha = 0.25$ .

For CCM and DCM can be used resistors with values smaller respectively greater. In the next two figures are presented simulation results for CCM when  $R = 270 \Omega$  and  $\alpha = 0.25$ , Fig.8 respectively simulation results for DCM when  $R = 1.5 \text{ k}\Omega$  and duty cycle keep its value, Fig.9.

Due to the fact that in many applications the Fly-back supply operates in DCM, the students could focus then on this mode of operation. To limit the output power at 5W, the load of the switched mode Fly-back supply is a resistor



**Figure 8.** CCM for  $R = 270\Omega$  and  $\alpha = 0.25$ .



**Figure 9.** DCM for  $R = 1.5 \text{ k}\Omega$  and  $\alpha = 0.25$ .

In the Fig.10, Fig.11 and Fig.12 are shown simulation results for different values of the duty cycle  $\alpha$ . The peak of the current through magnetizing inductance and average value of the output voltage increase their values gradually with the duty cycle of the command voltage for the transistor  $T_I$ .

One can observe that the output ripple also increase but is limited to few hundred of mV that is acceptable for a switched mode supply.



**Figure 10.** DCM for  $R = 2.7 \text{ k}\Omega$  and  $\alpha = 0.14$ .

After the simulation stage, the students make experiments with a supply which has similar parameters like the model mentioned before.

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**Figure 11.** DCM for R = 2.7 K  $\Omega$  and  $\alpha = 0.19$ .



**Figure 12.** DCM for R = 2.7 K and  $\alpha = 0.25$ .

In order to make the study of the switched mode supply easier, a graphic user interface was created. As one can see in Fig.13 and Fig.14, the main simulation parameters can be inserted or changed in their counterparts input fields of the graphic user interface.



Figure 13. Transient operation mode for DCM

Then, the transient and steady state operation modes can be selected. In Fig.13 is presented the transient operation mode of a Fly-back source for the first 30 time periods. In Fig.14 one can observe a detail of a steady state operation mode of the supply with the same parameters.



Figure 14. Steady state DCM operation mode.

This graphic user interface is very useful because it can be used to test the operation mode for different parameters, to verify the results of the students that designed such switched mode power supplies and so on.

First practical experiments consist of an investigation of the electrical signals from the circuit, as one can see in Fig.15, where  $R = 2.7 \text{ k}\Omega$  and  $\alpha$  is set at 0.14. In Fig.13 is shown above  $u_{CE}$  voltage and below the current through primary winding.



Figure 15. Voltage and current for primary winding in DCM for  $n_2 = 9*n_1$ .

After the signal investigation, the students make another set of measurements in order to obtain different kind of characteristics. One of them is the efficiency of the supply. To determine the efficiency of the supply, the students have to measure the input and output power,  $P_i$  and  $P_O$  of the supply for different values of the duty cycle and than to

draw a characteristic similar with the one depicted in Fig.16.



Figure 16. Efficiency  $(P_O/P_i)$  of the supply vs. duty cycle  $\alpha$ .

## VI. CONCLUSION

The authors presented in this article a modelling procedure applied to a switched mode Fly-back supply and using the standard functions from MATLAB programming environment they implemented a program able to simulate the operation of this supply. This procedure can be used also to analyze, in time domain, more complex switched mode DC-DC converters.

In the last part of the paper, the authors presented a laboratory work procedure for students and a set of simulations results for the continuous and discontinuous conduction modes of the Fly-back DC-DC converter, in both transient and steady state operation. Using the simulation program developed by the authors, no convergence errors were reported like in the case of PSPICE used to the time domain analysis of the switched mode power supply.

To test in a fast manner the operation of the supply, for different conditions and parameters, a graphic user interface was also implemented. The simulation program and its graphic user interface are useful in special when the transient analysis is desired because this analysis is difficult to be derived analytically.

The paper presents also experimental results that validate the accuracy of the proposed model.

As one can see, the authors try by means of this paper to presents a possible procedure of achievement of an easy, intuitive and useful connection from the theoretical aspects presented at courses to the practical approaches.

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