A NEW SINGLE SWITCH ISOLATED DC-DC CONVERTER WITH TWO FORMS OF TRANSFERING ENERGY OPERATING IN CCM

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***Abstract* – This work present a new single switch isolated DC-DC converter whose particularity is the way it processes the energy: direct transference and inductive accumulation. The analysis considers operation in continuous conduction mode (CCM) of current in the output inductor L_2. Theoretical analysis, design methodology, and experimental results taken from a 250 [W], 50 [KHz] laboratory prototype are presented in this paper.**

KEYWORDS

DC-DC converters, flyback converters, forward converters, SMPS.

I. INTRODUCTION

It is possible to identify two forms of transfer or processing energy in the isolated DC-DC converters. On the one hand: inductive accumulation (Flyback Transformer), where, in one stage, the converter accumulates the energy in the inductor core and delivering it afterward to the load, and on the other hand the direct transference (Forward Transformer) where the converter delivers the energy directly to the load.

Both forms of processing energy can be observed simultaneously in the Flyback-current-fed Push-Pull DC-DC converter [1], also. At the time when the load is being fed directly from the source, the flyback connection stores energy. This accumulated energy is delivered to the load in the following stage. This work presents the single switch version of the Flyback-Push-Pull converter, this fact explains why it has been called: "New Flyback-Forward Converter" and its structure is presented in figure 1.

II. DESCRIPTION OF THE CIRCUIT

The New Flyback-Forward Converter is conformed, in its power section, by an active switch S_W, which together with the output diodes D_1 and D_2 defines the stages of operation of the converter. Moreover a transformer, operating in high frequency, formed by the primary and secondary inductances, L_3 and L_4, respectively, denominated Forward transformer, which provides galvanic isolation between the source (Ve) and the load (Vs). This transformer also separates the coupled inductors L_1 and L_2 that form the denominated "Flyback transformer". These coupled inductors are those that provide the Flyback characteristic of the converter, storing energy when the switch is on and delivering it to the load when the switch is off.

Since the circuit is obviously asymmetric it is necessary to provide a path for the magnetization current of the Forward transformer. This function is assumed by LC snubber, formed by L_f, C_f, D_{11}, D_{12}. The LC snubber circuit absorbs and recovers the magnetization energy of the Forward transformer without auxiliary winding.

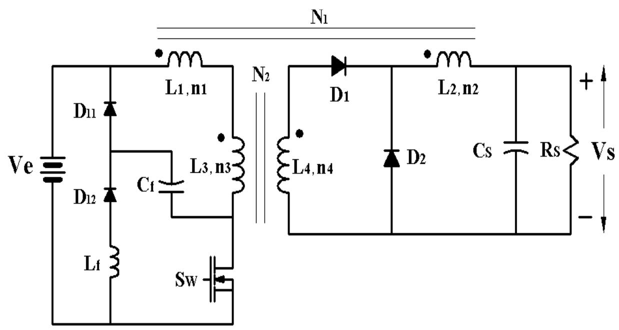

Fig. 1- New Flyback-Forward Converter with LC snubber.

In summary, the elements of the power stage of the new Flyback-Forward converter are:

S_W	: Active power switch
D_1, D_2	: Output Diodes
Cs	: Output filters capacitor
Rs	: Equivalent load resistance
L_1, L_2	: Flyback Transformer Inductances.
n_1, n_2	: L_1 and L_2 turn number
L_3,L_4	: Forward Transformer Inductances.
n_3, n_4	: L_3 and L_4 turn number
D_{11}, D_{12}	: Snubber circuit diodes.
L_f	: Snubber circuit inductance
C_f	: Snubber circuit capacitance

On the other hand, it is defined:

N_1	: Flyback transformers turns ratio
N_2	: Forward transformer turns ratio
L_e	: Equivalent inductance of coupling between L1 and L2, reflected to the secondary.

III. OPERATION IN STEADY STATE

Since it has been assumed a continuous conduction mode in L_2, the existence of only two stages of operation is guaranteed. In order to simplify the analysis of the proposed converter, the effect of the demagnetization of the core of the Forward transformer will be omitted, also the components are considered ideal and operating in steady state.

Stage 1 (t_0-t_1): At the instant t = t_0, when S_W is turns on, the current flows through L_1, L_3 and S_W. The voltage across L_3 is reflected across the forward secondary winding (L_4), the diode D_1, is turned on. The Flyback Transformer does not transfer any power to the load (Rs) only acts as an inductor storing energy. The load receives energy from the forward transformer and the output capacitor. (Fig. 2) This stage finish when S_w, is turned off, therefore the duration of this stage is D·T.

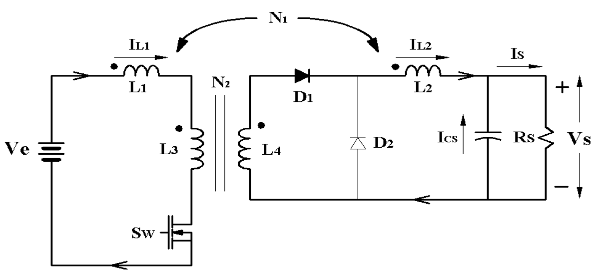

Fig. 2- First stage of operation

The magneto-motive force, mmf, during this stage is represented by the following expression:

$$mmf\big|_{\Delta ton} = i_{L2}\big|_{\Delta ton} \cdot \left(\frac{n_1}{N_2} + n_2\right) \tag{1}$$

Second Stage (t_1-t_2): At t=t_1, S_W is turn off and the Flyback transformer transfers energy to the load through D_2 (fig 3). That allows the energy flow in the circuit to maintain continuity, providing a path through which the inductor current can free wheel the current. This is represented by equation (5).

The mmf, during this interval is given by:

$$mmf\big|_{\Delta toff} = n_2 \cdot i_{L2}\big|_{\Delta toff} \tag{2}$$

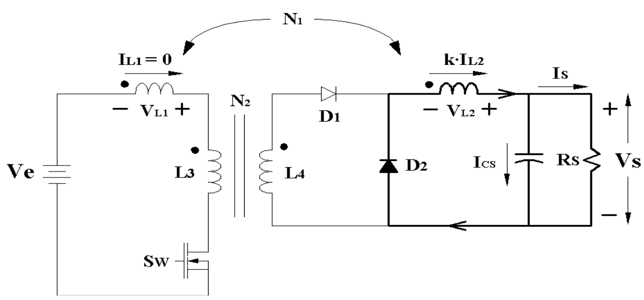

Fig. 3- Second stage of operation

1) Value of the current through L_2 inductor: In steady state the magnetic flux is invariable in one period of operation, therefore the mmf contained in the core of the Flyback transformer must stay constant, equaling (1) and (2) it is obtained:

$$i_{L2}\big|_{\Delta toff} = (1 + {N_1}/{N_2}) \cdot i_{L2}\big|_{\Delta ton} \tag{3}$$

Defining:

$$k = \left(1 + \left({N_1}/{N_2}\right)\right) \tag{4}$$

Then:

$$i_{L2}\big|_{\Delta toff} = k \cdot i_{L2}\big|_{\Delta ton} \tag{5}$$

The equation (5) shows that the current through L2, during the interval *(1-D)T* is increased in a factor k respect to the value in interval *DT*, therefore the energy transferred towards the load is increase.

2) Value of the equivalent inductance L_e: The equivalent inductance Le, behaves like a nonlinear inductance, taking a different value in each stage. Reflecting the primary circuit to the secondary of the Forward transformer (fig 4), the value of Le in function of L2, to this stage is obtained:

$$Le\big|_{\Delta ton} = k^2 \cdot L_2 \tag{6}$$

Where k has been defined to the equation (4).

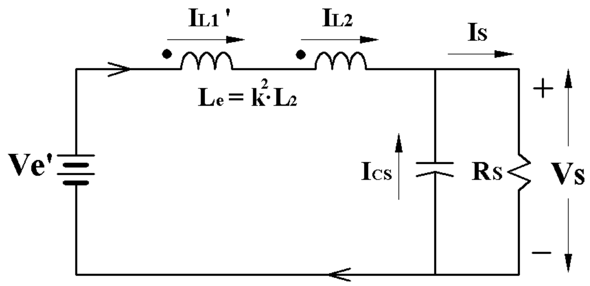

Fig. 4- Equivalent circuit to first stage.

In the second stage, figure 5, is observed that Le is identically equal to L2:

$$Le\big|_{\Delta toff} = L_2 \tag{7}$$

3) Main waveforms: The theoretical main waveforms are shown in fig 6 to 8. Figure 6, shows the currents in the windings of the Flyback transformer, There can be observed a step of current in the second stage. The current is twice the current of the previous interval when N_1 equals N_2,.

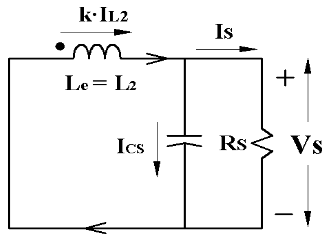

Fig. 5- Equivalent circuit to the second stage

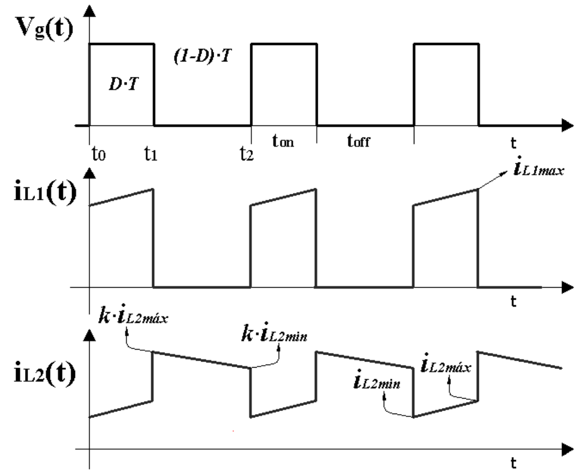

Fig. 6 – Theoretical waveforms of the currents trough the windings of the Flyback

Figure 7, shows the voltage across the windings of the Forward transformer, these voltages are related between them, by the N_2 transformation ratio. From this figure it is observed that the converter operates in an asymmetric form, which explains why the method of demagnetization of the core is necessary. The voltage across the switch, is shown in the figure 8, this is ideally zero during the conduction and will reach a value of ($Ve+V_{L1}$) in the second stage, exactly after the magnetization current is zero.

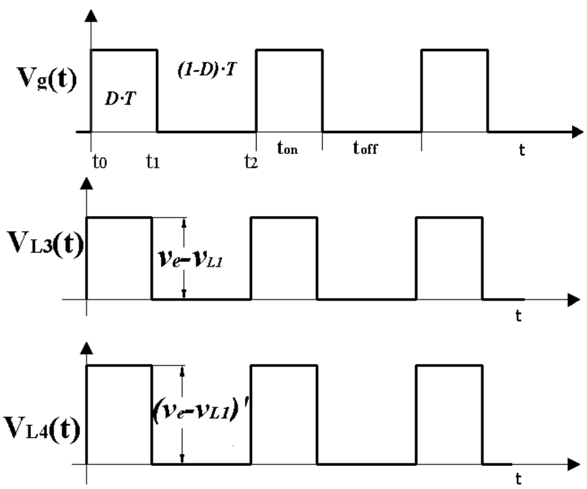

Fig. 7- Theoretical waveform of the voltages across the windings of the Forward transformer

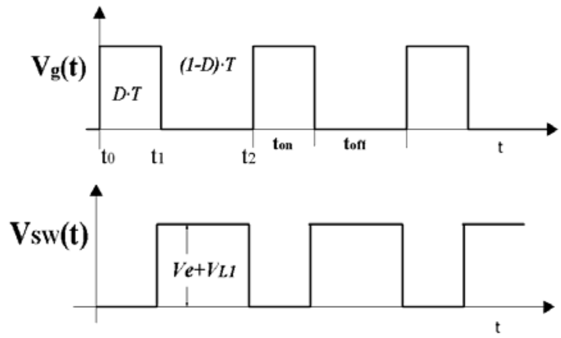

Fig. 8 – Theoretical waveform of the voltage across the switch

IV. STATIC GAIN IN CCM

It is known that in steady state, within one period of commutation the net flux in the inductor is constant, therefore:

$$V_{L2}\Big|_{\Delta ton}\cdot D\cdot T = V_{L2}\Big|_{\Delta toff}\cdot(1-D)\cdot T \qquad (8)$$

Solving this equation for the values of voltage in V_{L2} to each stage, the following equation it is obtained:

$$G(D,k,N2)=\frac{V_S}{V_e}=\frac{D}{N_2\left(D+(1-D)\cdot k\right)} \qquad (9)$$

Equation (9) shows that the static gain of the converter depends on the k factor, which depends of both transformer turn ratios (equation 4), and the duty ratio of the converter. In the particular case of equal transformer turn ratio between the Flyback and Forward transformer (k = 2) the equation (9) is reduced to:

$$\frac{V_S}{V_e}=\frac{D}{N_2\left(2-D\right)} \qquad (10)$$

This last equation has been plotted as function of D using N_2 as parameter, the curve obtained is shown in figure 9, for values of N_2 greater than unity and in figure 10, for values smaller than unity.

V. OUTPUT CURRENT RIPPLE

As it has been already stated, the current ripple in L_2, takes two values . The output ripple is given by:

$$\Delta i_{L2}\Big|_{\Delta ton} = i_{L2\max} - i_{L2\min} = \Delta i_{L2} \qquad (11)$$

And the current ripple in *(1-D)T* is given by:

$$\Delta i_{L2}\Big|_{\Delta toff} = k\cdot\Delta i_{L2} \qquad (12)$$

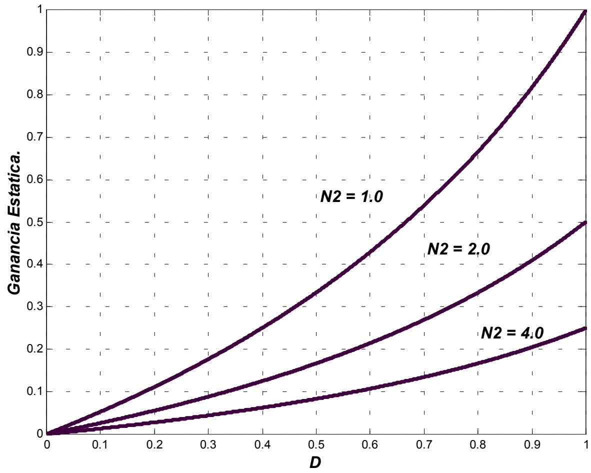

Fig. 9 - Static gain in CCM for N2 ≥ 1

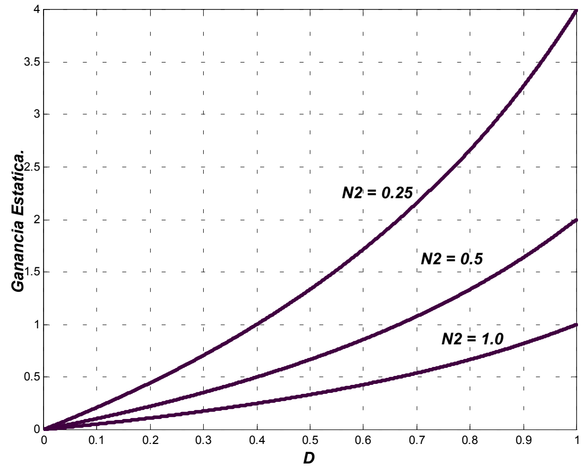

Fig. 10 - Static gain in CCM for N2 ≤ 1

In addition

$$\Delta i_{L2}\big|_{\Delta ton} = \frac{\left(V_{L1}' - V_{L2}\right)}{Le\big|_{\Delta ton}} \cdot D \cdot T \tag{13}$$

And on the other hand:

$$\Delta i_{L2}\big|_{\Delta toff} = \frac{\left(V_{L2}\right)}{Le\big|_{\Delta toff}} \cdot (1-D) \cdot T \tag{14}$$

Replacing (11) and using the equations (12) and (13), it is possible to obtain an expression for the current ripple in the output inductor, the expression is given by:

$$\left(\overline{\Delta i_{L2}}\right) = \frac{D \cdot (1-D)}{k\left(D + (1-D) \cdot k\right)} \tag{15}$$

Moreover:

$$\left(\overline{\Delta i_{L2}}\right) = \frac{L_2 \cdot f_C \cdot \Delta i_{L2} \cdot N_2}{Ve} \tag{16}$$

Figure 11, shows three different curves where the ratio between N_1 and N_2 has been varied, having in the superior curve, $N_1 = (0.5) \cdot N_2$; the central curve is the normalized output current ripple to $N_1 = N_2$, and finally the inferior curve shows the case $N_2 = (0.5) \cdot N_1$.

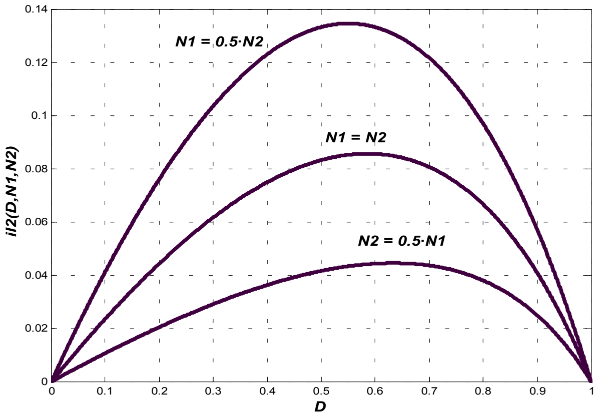

Fig. 11 - Normalized current output ripple

VI. EXPERIMENTAL RESULTS

A laboratory prototype, operating in CCM, has been designed and implemented. Its specifications are as follows:

TABLE I
Design Specifications

Parameters	Description
P_S = 250 [W]	Output power at full load
V_S = 60 [V]	Output voltage
V_E = 48 [V]	Input voltage
I_S = 4.2 [A]	Average output current at full load
D= 0.21	Nominal duty cycle
f_c = 50[KHz]	Switching frequency
ΔI_S = 10% de I_S	Output current ripple

The turns ratio N_2 is calculated by using equation (9), for D = 0.21 and k = 2.25. Taking saturation voltage across the switches equal to 1 [V], we obtain $N_2 = 0.081$.
The turns ratio N_1 is calculated by using equation (4), for N_2 before calculated, so $N_1 = 0.101$. The primary and secondary Flyback transformer inductances L_1 and L_2, are calculated using equations (15), (16) and the turns ratio N_1.The values obtained are $L_1 = 10$ [μH] and $L_2 = 938$[μH]

The power and control diagrams are shows in figure 12 and the parameters of the prototype are given in Tables II and III, for the power stage and the control circuits, respectively.

Also are added a RCD snubber circuit composed of Dsw, Csw and Rsw to prevent overvoltages across the switch, caused by the circuit layout parasitic inductance.

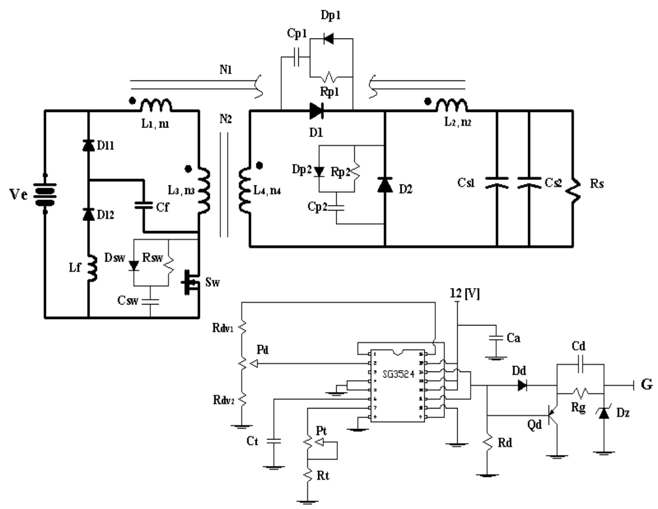

Fig. 12 - Power and control diagrams

TABLE II
Power Stage Components

S_W	IRFP250
D_2, D_1,	MUR840
Dp_1, Dp_2	MUR4100E
D_{11}, D_{12}, Dsw	FR307
Cs_1, Cs_2	470[μF], 200[V]
Cf	330[μF], 200[V]
Csw,	470[nF],
Cp_1, Cp_2	220[nF],
Rp_1, Rp_2	47 Kohm, 5 W
Rsw	1 Kohm, 5 W
Flyback Transformers EE-55	n_1 =5 turns, 67 wires, AWG30 n_2 = 48 turns, 24 wires, AWG30 gap : 0.6 mm
Forward Transformers EE-55	n_3 = 6 turns, 67 wires, AWG30 n_4 = 74 turns, 6 wires, AWG30
Lf EE-20	70 turns, AWG30 250 uH

TABLE II
Control Circuits Components

IC	SG3524
Qd	BC177
Dd	MUR120
Dz	1N4740
Ct	0.005 uF
Ca	1 uF
Cd	50 nF
Pt, Pd	5 Kohm
Rt	1.5 K, 1/8 W
Rd	390 ohm, 1/8 W
Rg	5 ohm, 1/8 W
Rdv_1	13 Kohm, 1/8 W
Rdv_2	4.7 Kohm, 1/8 W

Fig. 13 and 14 depict the primary and secondary current through the flyback transformer which it is approximately at rated load power. On secondary current can be observed a step of current when the transistor is turn-off, this confirms that output inductance L_2 behaves nonlinear, also k factor for this case is equal 2.25.

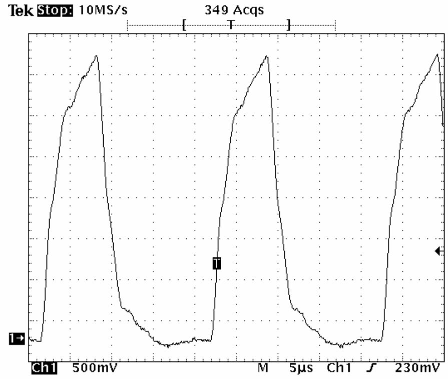

Fig. 13 – Primary Flyback Transformer current 5[A/div]

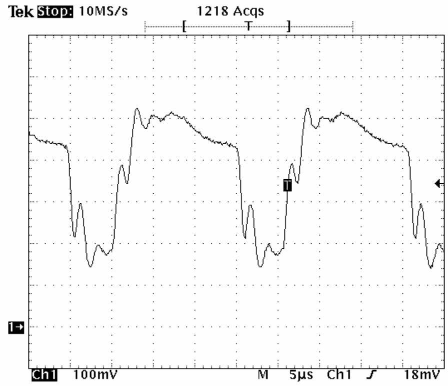

Fig. 14 – Secondary Flyback Transformer current 1[A/div]

The following figures shown primary Flyback (fig.15) and primary Forward (fig.16) windings voltages, where, in both cases, can be noted negative voltages indicated that resets the transformer cores.

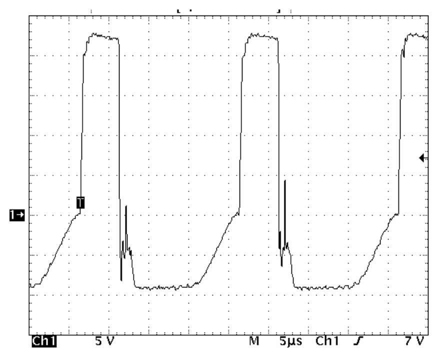

Fig. 15 – Primary Forward Transformer Voltage 5[V/div]

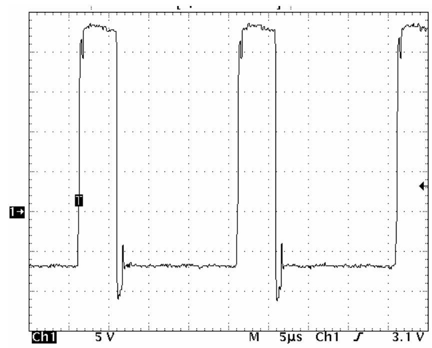

Fig. 16 – Primary Flyback Transformer Voltage [5V/div]

Fig. 17 illustrates experimental drain-source voltage, revealing voltage spikes across the transistor, this obviously increases losses of the converter, due to condition unfavorable for the converter switching transistor with turn-off loss.

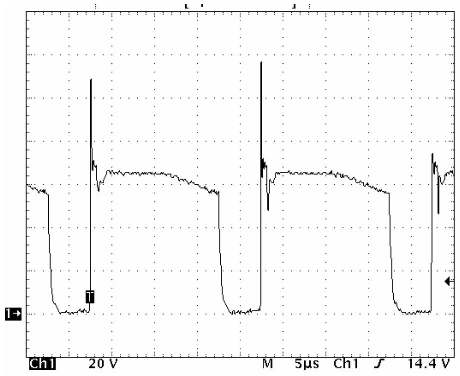

Fig. 17 – Switch Voltage [20V/div]

Fig. 18 shows the experimental output characteristic of the converter where can be observed the discontinuous and continuous regions. The efficiency obtained with full load was 0.75; this efficiency can be improved, making an optimization of clamping and snubber circuits, as well as the circuit lay out.

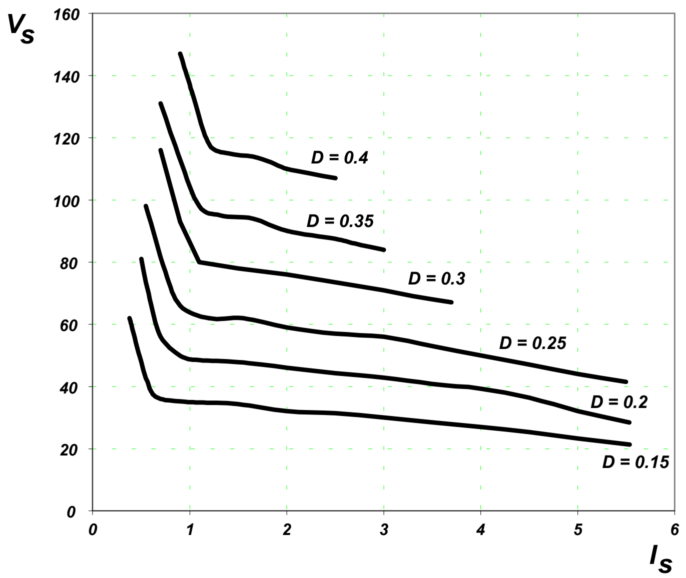

Fig. 18 – Experimentally Output Characteristic in continuous conduction mode

VII. CONCLUSION

- A complete analysis and design of a new Flyback-Forward Converter has been presented, derived from the Flyback-Push pull Converter.
- This converter integrates the features of both the Flyback and the Forward converters.
- Since factor k depends on the both turn ratios N_1 and N_2, a great versatility in the design is obtained. It is evident that k factor defines the final characteristics of the converter.

On the other hand, the following disadvantages are found:

- Switch voltage stresses increase when compared with Forward converter.
- Turn-off switching conditions are unfavorable because the switch turns off under maximum current, and maximum voltage conditions.
- Also was observed that the converter is very sensible to transformer leakage and circuit stray inductances due to the series connection of the primary transformers, because the LC snubber do not provide total protection against these parasitic inductances. Therefore requires an optimum snubber design.

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