"ISOLATED FLYBACK-CURRENT-FED PUSH-PULL CONVERTER FOR POWER FACTOR CORRECTION"

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Abstract - This paper presents a single-stage high-power factor isolated power supply based on the classical Flyback-Current-Fed Push-Pull Converter.

The proposed converter operates as a buck one at a duty-cycle below 50% and as a boost one at duty-cycle above this range. Therefore, when properly driven, this converter is suitable for high power factor applications, with many advantages when compared with the boost-isolated current-fed converter, including inrush current control and less voltage stress over the power semiconductors.

Theoretical analysis, design methodology, design example, control strategy, and experimental results are presented is paper.

I. INTRODUCTION

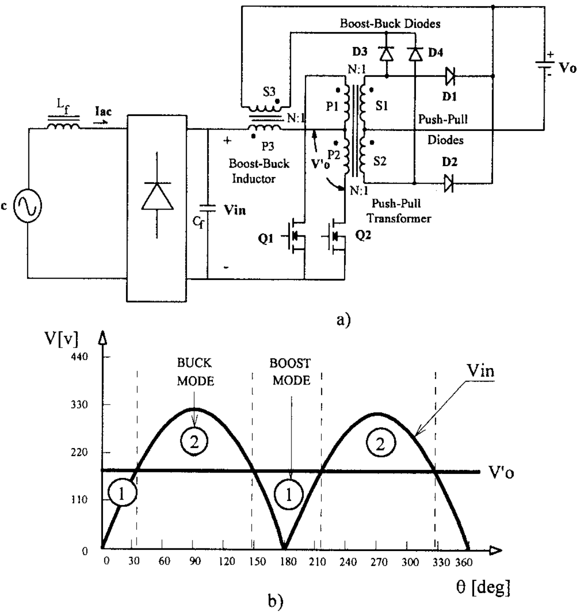
For distributed power systems with 48 V intermediate DC bus, AC-DC converters featuring unity power factor and isolation are often required.

The utilization of an Isolated Boost Converter was proposed in reference [1] and [2]. Three drawbacks of this scheme have been related: high voltage stress of the power switches; start-up problem caused by the inrush current; and no overload protection by switches turn-off.

These problems can be are avoided when a **Flyback Current-Fed Push-Pull Converter** [3] operating with **0** to **100%** duty cycle is employed, instead of the Isolated Boost Converter.

II. TOPOLOGY AND PRINCIPLE OF OPERATION

The diagram of the proposed topology is shown in Fig. 1a. The circuit is composed of a single phase AC input, passive input filter, full wave rectifier, Boost-Buck inductor, Push-Pull transformer, two main switches, two push-Pull diodes, two Boost-Buck diodes, output filter, and load.



a)

b)

Fig. 1 - a) Basic Circuit of the Converter, b) Two different Operating Modes

The converter works in two different operating modes during a half period of the AC line, as one can observe from Fig. 1b. Initially, when the input rectified voltage is lower than the output voltage referred to the primary (V'_o), the converter operates in the Boost Mode. Later, when that voltage becomes greater than V'_0, the converter operates in the Buck Mode.

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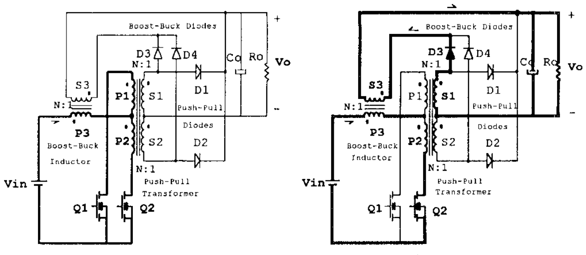
The converter presents the followings features:

- There is galvanic isolation between the input supply and the load.
- Power factor correction is achieved whit a single power processing stage.
- It operates at constant frequency.
- Both cores (Push-Pull transformer and Boos-Buck inductor) have the same transformer ratio.
- Since the converter operates in continuous mode, it is able to process high power levels.

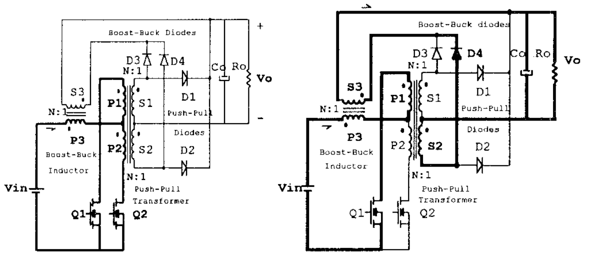
The Principle of operation of the proposed converter is based on analyses concerning DC-DC converter [1, 3] and power factor correction [2, 4]. Each operating mode is analyzed independently from another. Besides that, some simplifications were introduced in the models, but they do not greatly affect converter's behavior.

1 - BOOST MODE

In this operating mode, the main switches work with a duty cycle between 0.5 and 1.0. During each switching period, the converter presents four stages of operation. They are illustrated in Fig. 2, while the main waveforms can be seen in Fig. 3.



1^{st} Stage 2^{nd} Stage



3^{rd} Stage 4^{th} Stage

Fig. 2 - Stages of Operation Boost Mode.

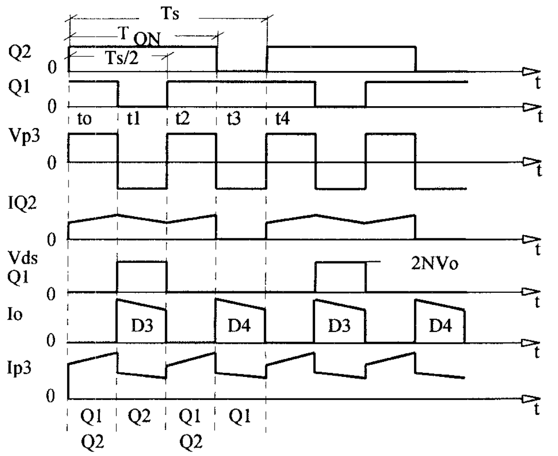


Fig. 3 - Main Voltage and Current Waveforms observed in the Boost Mode of Operation

1^{st} Stage(t_0 , t_1) - At instant $t = t_0$, when Q2 turned on, Q1 is yet in conduction state. Since the magnetic fluxes of each winding of the Push-Pull transformer are in opposite directions, this transformer is short-circuited. As a result, V_{in} is applied across Boost-Buck inductor. In brief, this is an energy storage stage.

2^{nd} Stage (t_1 , t_2) - At $t = t_1$, switch Q1 is turned off, while Q2 remains in conduction state. During this stage, both Boost-Buck inductor and V_{in} transfer energy to the load through D3. D1, D2 and D4 remain in the off state. The voltage applied across the Boost-Buck inductor changes its polarity, and the current through this element decreases. In steady state, Boost-Buck inductor delivers to the load all the energy it stored during the previous stage.

3^{rd} Stage (t_2 , t_3) - At $t = t_2$, switch Q1 is turned on. Since Q2 is still on, Push-Pull transformer is Short-circuited. The voltage across Boost-Buck inductor is equal to V_{in}, allowing a linear increase of the current through it. This stage is similar to the first one.

4^{th} Stage (t_3 , t_4) - At instant $t = t_3$, switch Q2 is turn off. Q1 remains in conduction state. In this stage, Boost-Buck inductor and Push-Pull transformer transfer energy to the load via D4. This stage is similar to the second one.

It can be observed that, in this operating mode, Push-Pull transformer diodes are never put into conduction. All the energy is transferred through Boost-Buck diodes.

The characteristic of the converter in this mode is similar to the characteristic of the conventional Boost converter in continuous conduction mode (CCM). The static gain of the converter in this operating mode is given below:

$$G = \frac{V_o'}{V_{in}} = \frac{D}{1-D} \qquad (1)$$

$$D = \frac{T_{ON}}{T_s} \qquad (2)$$

Where:

D : duty cycle in Boost Mode

T_{ON} : conduction time of the switch,

Ts : commutation period,

$V'_o = NV_o$: output voltage referred to the primary side of the transformer,

V_{in} : input voltage.

2 - BUCK MODE

In each switching period the converter presents four stages of operation. These stages are described below and the equivalent circuits are illustrated in Fig. 4. The main waveforms can be seen in Fig. 5. In this operating mode, switches work with duty cycle in the range $0 \le D \le 0.5$.

1^{st} Stage (t_o, t_1) -At instant $t = t_0$, the switch Q1 is turned on and the conduction begins. The switch Q2 is off. During this stage the Boost-Buck inductor stores energy and also limits the inrush current. Energy is transferred to the load through P1, S2 and D2, while D1, D3 and D4 remain reverdely biased.

2^{nd} Stage (t_1, t_2) - In $t = t_1$, Q1 is turned off. In this way, during this stage both main switches are in the off state. There is an energy transfer from Boost-Buck inductor to the load through D3 and D4. D1 and D2 remain off. The transformer is demagnetized during this stage.

3^{rd} Stage (t_2, t_3) - At $t=t_2$, the switch Q2 is turned on. Q1 remains off. In this stage the Boost-Buck inductor stores energy again, while energy is transferred to the load through Push-Pull transformer. The operation resembles the first stage.

4^{th} Stage (t_3, t_4) - At instant $t = t_3$, the switch Q2 is turned off, while the switch Q1 remains off. During this stage the inductor transfers energy to the load, and the transformer is demagnetized. This stage is similar to the second one, and it finishes at the instant $t = t_4$.

The proposed converter operates in continuous conduction mode (CCM) in a way similar to the classical Buck converter in continuous conduction mode (CCM).

The static gain of converter in this mode is given as follows:

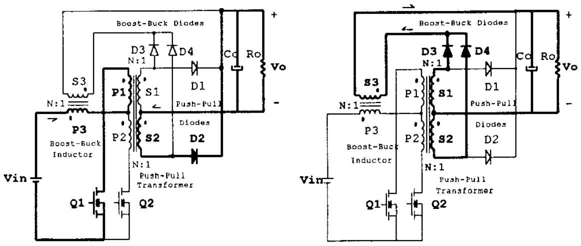
$$G = \frac{V'_o}{V_{in}} = 2 \cdot D \qquad (3)$$

Where:

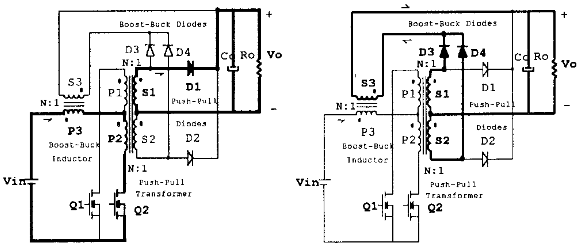
D : duty cycle in Buck Mode;

V'_o : output voltage referred to the primary side of the transformer;

V_{in} : input voltage.



1^{st} *Stage* 2^{nd} *Stage*



3^{rd} *Stage* 4^{th} *Stage*

Fig. 4 - Stages of Operation of Buck Mode

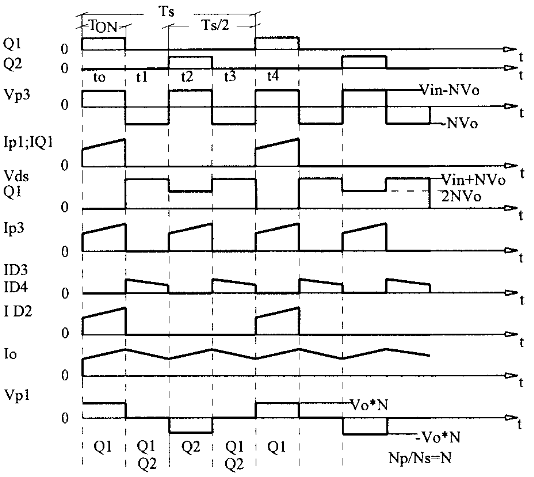


Fig. 5 - Main Voltage and Current Waveforms of the Converter in Buck Mode

3 - BOOST-BUCK MODE TRANSITION

In the transition point, which occurs at 0.5 duty cycle, the converter operates in both modes at same time. Consequently, equation (1) and (3) lead to the same value of static gain.

Since converter's performance in the transition point is not problematical, this structure can be used where the input voltage range is wide.

In Fig. 6.a one can observe the static gain in both operating modes. The variation of the duty cycle a function of the angle $\theta = \omega.t$ is described by equations (4) and (5), and shown graphically in Fig. 6b, for half line cycle.

Boost Mode:

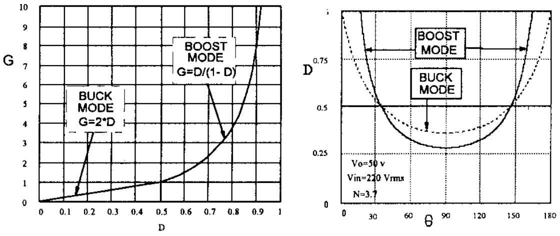
$$D(\theta) = \frac{V_0'}{V_P \cdot SIN(\theta) + V_0'} \tag{4}$$

Buck Mode

$$D(\theta) = \frac{V_0'}{2 \cdot V_P \cdot SIN(\theta)} \tag{5}$$

Where:

V_P : peak of AC line voltage



a) *b)*

Fig. 6 a) External Characteristic of the Converter, b) Duty Cycle as a Function of Angle $\theta = wt$

III. MODULATION TECHNIQUE

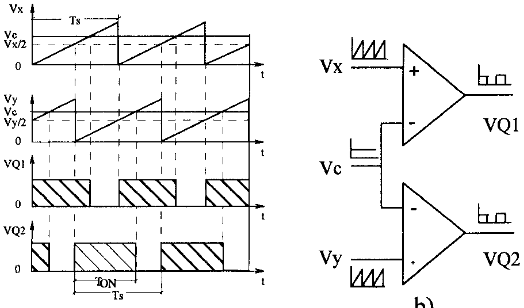
The modulation for the converter is obtained from two sawtooth functions with constant frequency F_s, phase shifted one from another by 180^0. These signals are the inputs to two different comparators. The other inputs are the same control voltage V_C. So PWM pulses are obtained at the output. Details can be seen in Fig. 7.

When control voltage V_C is lower or equal to the middle of the peak value of V_X and V_Y, the converter operates in the Buck Mode. Therefore, the main switches work in **Non-Overlapping** Mode. Equation (6) gives the range of V_C in which Buck Mode occurs.

$$0 \leq V_C \leq \frac{V_X}{2} \quad \text{Buck Mode} \tag{6}$$

When the control voltage V_C is greater or equal to $V_X/2$, the converter operates in the Boost Mode, in the main switches work in the **Overlapping** Mode. V_C varies in the following interval:

$$\frac{V_X}{2} \leq V_C \leq V_X \quad \text{Boost Mode} \tag{7}$$



a) b)

Fig. 7 a) PWM Modulation Technique PWM, b) PWM Modulator

IV. CONTROL STRATEGY

The converter operates alternately like a Buck and like a Boost one, in the continuous conduction mode with constant switching frequency. The control technique applied to the circuit is Average Current Mode Control [4], using the Boost-Buck inductor current as control parameter.

In order to give to the input current the necessary frequency, shape and synchronism with the input voltage. It is employed the UNITRODE UC3854 controller [4]. In this application, this component is not used as controller itself, but it only generates the reference current I_{ref}, through an internal multiplier/divider. It is implemented a current composition loop, using an operational amplifier, internal to the UC3854, and also an input voltage Feedforward loop.

The input current is sampled through a shunt resistor and compared with I_{ref}. The error signal, V_C, is then sent to the PWM comparator, where the conduction orders for the main switches are generated.

In order to define the current compensation loop, it is used the small signal transfer function of the power stage, based on the variation of the current through the inductor in relation to changes in the duty cycle. Such current oscillates at the double of the switching frequency. With this procedure, the transfer functions of the classical Boost and Buck topologies become:

Boost converter,

$$\frac{i_L(s)}{d(s)} = \frac{V_0}{L \cdot s} \tag{8}$$

Buck converter,

$$\frac{i_L(s)}{d(s)} = \frac{V_{in}}{L \cdot s} \tag{9}$$

Where $L = L_{P3}$ is the inductance of the Boost-Buck inductor.

From the above equations, one can observe that the Boost mode's transfer function is independent on the input voltage. The same does not occur in relation to the Buck Mode.

The appropriate transfer function, applicable for both operating modes, is that of the classical Boost converter, given by the following expression:

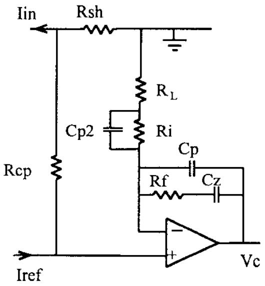
$$\frac{i_L(s)}{d(s)} = \frac{R_{SH} \cdot V_o'}{V_X \cdot L_{P3} \cdot s} \tag{10}$$

Where R_{SH} is the shunt resistance.

In order to assure a stable operation, it was elected a ***proportional-integral-derivative (PID)*** compensator, whose dynamic characteristics are suitable for this application. The transfer function is given below.

$$C(s) = K \cdot \frac{(s+Z_1)\cdot(s+Z_2)}{s\cdot(s+P_1)\cdot(s+P_2)} \tag{11}$$

The cross-over frequency (F_C) of the current loop is assumed to be 1/6 of the voltage across the Boost-Buck inductor (F_{LP3}, which equals $2F_s$). Poles and zeroes of the compensator were placed in the following way: Z_1 at half of the cross-over frequency; Z_2 and P_1 at half of F_{LP3}; P_2 at F_{LP3}; and a pole at the origin. In Fig. 8, it is as shown the diagram of the compensator and the expressions for the poles and zeros.



$$K = \frac{1}{C_P \cdot R_i}; \quad R_{cp} = R_i + R_L$$

$$Z_1 = \frac{1}{C_z \cdot R_f}; \quad Z_2 = \frac{1}{R_L \cdot C_{P2}}$$

$$P_1 = \frac{C_z + C_p}{R_f \cdot C_z \cdot C_p}; \quad P_2 = \frac{R_i + R_l}{R_i \cdot R_L \cdot C_{p2}}$$

Fig. 8 - PID Compensator

V. SIMPLIFIED DESIGN OF THE MAIN PARAMETER

The ratio between primary and secondary windings of the Boost-Buck inductor and of the Push-Pull transformer are assumed to be equal, and are called transformer ratio N.

Since the commutation is hard, the transformer ratio is elected in order to allow an operation with minimum conduction losses. The methodology employed to define N is described below.

First of all, it must be said that the main switches are MOSFETs, whose on-state resistances are function of the breakdown voltage, as follows:

$$R_{ds} = K \cdot V_{br}^{2.5} \tag{12}$$

V_{br} is obtained from the critical voltage in the Buck-Mode.

$$V_{br} = V_p + N \cdot V_o \tag{13}$$

Conduction losses in the MOSFET switch are:

$$P_{con} = R_{ds} \cdot I_{eff}^2 \tag{14}$$

Where I_{eff} stands for the efficient current through a switch as function of N.

Replacing equations (12) and (13) in (14), one obtains the function P_{con}, which, divided by constant K, produces the curves of Fig. 9. The output power is taken as parameter to plot these curves. The efficient input voltage and the output voltage are taken as constant. It is clear that, for different values of the output power, the minimum losses always occur at the same value of N. Therefore, this value is considered the best, regarding conduction losses.

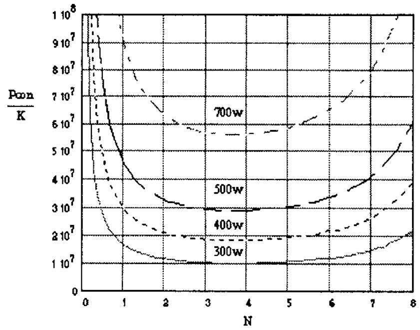


Fig. 9 - Curves of Conduction Losses as Functions of N

Once the transformer ratio is known, the other parameters can be determined.

The value of L_{P3}, the Boost-Buck inductance, is determined form the linear variation of its current during one switching interval. This analysis must be done for a half line period. The normalized current variation is given by equations (15) and (16).

Buck Mode

$$\Delta\bar{I}_{LP3} = \frac{2 \cdot \Delta I_{LP3} \cdot L_{P3} \cdot F_S}{N \cdot V_0} = 1 - \frac{N \cdot V_0}{V_P \cdot SIN(\theta)} \tag{15}$$

Boost Mode

$$\Delta\bar{I}_{LP3} = \frac{2 \cdot \Delta I_{LP3} \cdot L_{P3} \cdot F_S}{V_P} = \frac{N \cdot V_0 \cdot SIN(\theta) - V_P \cdot SIN(\theta)^2}{V_P \cdot SIN(\theta) + N \cdot V_0} \tag{16}$$

Fig. 10 illustrates the normalized current variation as a function of θ. Its maximum occurs at θ = 90°, when the converter operates in the Buck Mode. L_{P3} can be designed, talking ΔI_{LP3} as 20% of the peak input current.

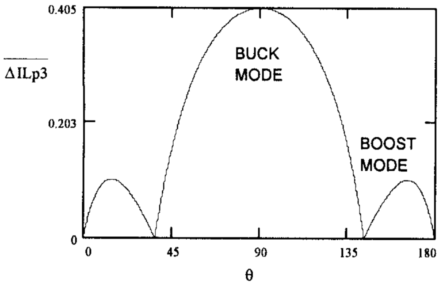


Fig. 10 - Normalized Current Variation During a Half Line Period.

VI. EXPERIMENTAL RESULTS

Aiming to verify the principle of operation as well as the control strategy and the modulation technique, a 600W-50kHz prototype was implemented. Its complete scheme can be seen in Fig. 11.

The values of the parameters and devices employed in the prototype are specified bellow:

- $N = 3.7$
- $V_{in} = 220\ V_{CA}$ $V_0 = 50\ V$
- $V_X = V_Y = 5V$ shifted by 180^0.
- $R_{SH} = 0.25\ \Omega$
- Q_1, Q_2,- APT8075
- D_1, D_2, D_3, D_4 -MUR 850
- - Dr_1, Dr_2, Dr_3, Dr_4 -MR 506
- Boost-Buck Inductor
  $L_{P3} = 870\mu H$ $N_p = 60$ turns (6x24AWG)
  $N_s = 16$ turns (10x24 AWG) core E65/26
- Push-Pull Transformer
  core E55 $N_p = 22$ turns, (3x22AWG)
  $N_s = 6$ turns (6x22AWG)
- $L_f = 3.65\mu H$ 145 turns (17 AWG) core E55
- $C_f = 1\mu F$ polypropylene
- $C_0 = 15mF$ electrolytic
- $R_{gs} = 6k\Omega/40W$; $C_{gs} = 11\mu F/\ 700V$
- $D_{g1}=D_{g2}=D_{g3}=D_{g4}$ MR854
- $R_{g1}=R_{g2}= 58k\Omega/2W$; $R_{g3}=R_{g4}= 120k\Omega/2W$
- $C_{g1}=C_{g2}= 6.8nF/400V$; $C_{g3}=C_{g4}= 1.8nF/400V$

Input voltage and current are shown in Fig. 12, 13. Since the input voltage (line voltage) is itself distorted, the current is also distorted. Voltage total harmonic distortion (THD) is 3.32%, and current THD is 3.49%. Converter's power factor is 0.999.

The voltage across filter capacitor and the current through Boost-Buck inductor are shown in Fig. 13 One can observe from the acquisition the transition between Boost and Buck Operating Modes.

Clamping voltage across the main switches are shown in Fig. 14.

The control voltage V_C and the sawtooth waves V_x and V_y are shown in figs. 15a and 15b.

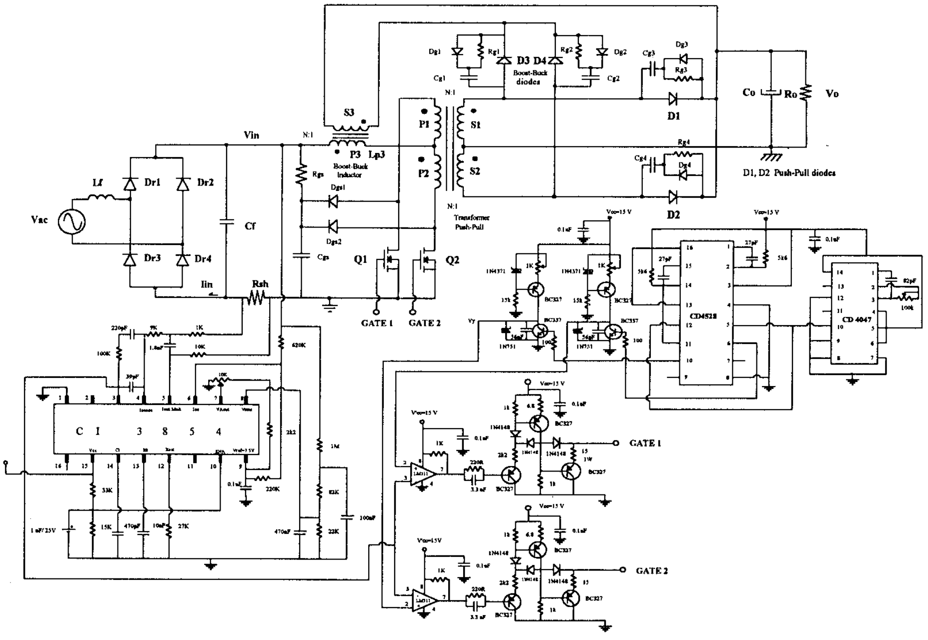


Fig. 11 - Complete Scheme of the Implemented Prototype

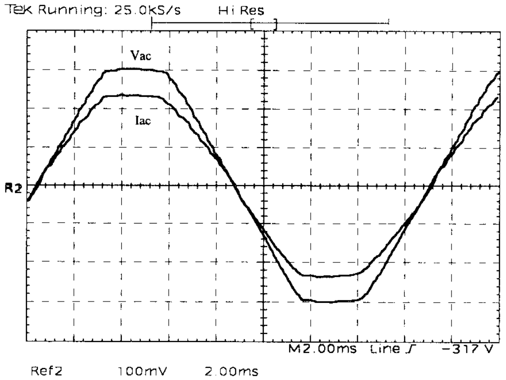


Fig. 12 - Input Voltage and Input Current scales: 100 V/div; 2A/div; 2ms/div

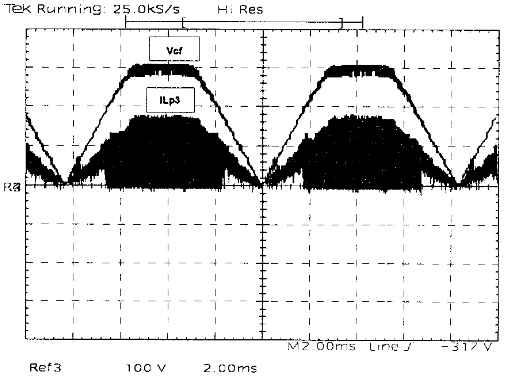


Fig. 13 - Voltage on Filter Capacitor and Current through L_{P3}.
Scales: 100V/div; 2A/div; 2ms/div

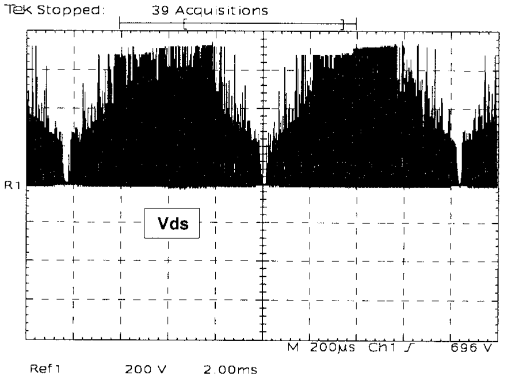
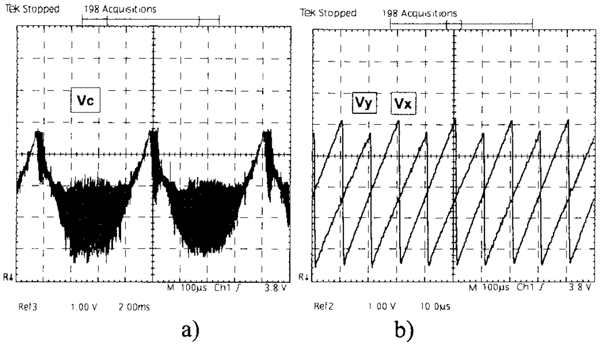


Fig. 14 - Clamping Voltage Across the Main Switches scales: 200V/div; time: 2ms/div



a) b)

Fig. 15 - a) Control Voltage V_C;
b) Sawtooth V_X, and V_Y Shifted by 180^0.

VII. CONCLUSION

From the study reported in this paper, we draw the conclusions as follows, concerning the utilization of Flyback Current-Fed Push-Pull converter:

a) the inrush current is limited, since for D < 50% it operates as a buck converter

b) for the same reason, simple is turning off the switches, protection against overload is achieved

c) it subjects the power semiconductors to less voltage stress when compared to the Isolated Boost Converter

d) active power factor correction in continuous current mode is achieved by using average current control technique, usually employed with the classical boost converter.

REFERENCES

[1] **T. S. Latos; D. J. Bosack.** "A High Efficiency 3kW Switchmode Battery Charger". PESC'82, p-p 341-349.

[2] **E. X Yang; Y. M. Jiang; G. C. Hua; F. C. Lee.** "Isolated Boost Circuit For Power Factor Correction. Proceedings of the Tenth Annual VPEC Power Electronics Seminar, 1992. p-p 97-104.

[3] **R. Redl and N. Sokal.** "Push-Pull Current-Fed, Multiple Output DC/DC Power Converter with only one Inductor and With 0 to 100% Switch Duty Ratio". IEEE Proceedings 1980.

[4] **Philip C. Todd.** "UC3854 Controlled Power Correction Circuit Design". Unitrode, Application Note, U-134 p-p 9-362 - 9-381, 1994.