

A PFC Circuit Based on a DCM Operated BOOST Converter with Integration Control

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Abstract – In the present paper is presented a power factor correction circuit based on a DCM operated BOOST converter. The proposed circuit uses an integration control method having the main benefit that it does not need input current sensing. There are also presented some simulation results and the main merit parameters for the proposed circuit

Keywords: DCM BOOST converter, power factor circuit, integration control

I. INTRODUCTION

For a DCM operated BOOST converter in PFC applications, with constant switching frequency and duty-cycle, it is well known that the input current wave shape is imposed in an automatic way. But, despite the fact that the control circuit is a simple one, the main disadvantage is that the input current wave shape is distorted. These unwanted current distortions became smaller when the DCM BOOST converter operates with an output voltage much bigger than the input voltage. Therefore this operation mode is generally suitable for high voltage applications [4].

By operating the BOOST converter at the limit between continuous and discontinuous conduction modes (critical mode control) the current distortions can theoretical be eliminated, but this type of control needs variable switching frequency and depending of the control method at least one multiplier. In many applications a variable switching frequency on a large range is an unwanted option. Other control methods such as the one with the second order current harmonic injection requires a complex accorded adaptive control circuit and also presents practically difficulties in control [4].

On other hand it is possible to maintain the input current proportional with the mains supply voltage by using a current loop, a good example being the non-linear carrier control method. This control method needs current sensing, reason that makes her more suitable for high power applications with continuous conduction mode operation [2].

The proposed integration control method for the PFC circuit based on a DCM operated BOOST converter presents the following advantages: provides unity power factor, does not require that the output voltage to be significantly greater compared to the input one, operation at constant switching frequency, no needing of multipliers or other complex circuits, does not need the input current sensing, easy to be implemented [1].

II. PFC OPERATION WITH INTEGRATION CONTROL

Taking into consideration a PFC circuit based on a DCM BOOST converter, having the mains supply voltage $v_g = V_M \sin \omega t$ and V_o the output voltage, the duty cycle must be time-variable in order to emulate a resistive character at the input. The inductor current waveform for the DCM BOOST converter is presented in Fig.1.

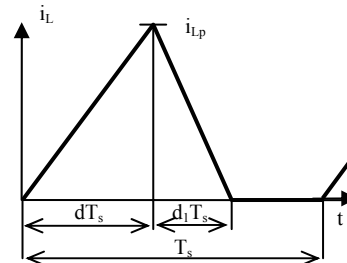


Fig.1. Inductor current waveform for a DCM BOOST converter

From Fig.1 the inductor current averaged value on a switching period, T_s , results:

$$\bar{i}_L = \frac{1}{T_s} \frac{1}{2} (d + d_1) T_s i_{Lp} = \frac{1}{2} (d + d_1) i_{Lp} \quad (1)$$

The peak value of the inductor current can be expressed in two different ways, assuming of course that the switching frequency is much greater than the main frequency, meaning that on a mains period the

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supply voltage can be considered to be a constant one. On the dT_s switching interval, when the transistor is on, the inductor current peak value is:

$$i_{Lp} = \frac{v_g}{L} dT_s \quad (2)$$

Regarding the d_1T_s switching interval, when the diode is on, leads to the following value of the same current:

$$i_{Lp} = \frac{V_o - v_g}{L} d_1T_s \quad (3)$$

From (2) and (3) results:

$$d_1 = \frac{v_g}{V_o - v_g} d \quad (4)$$

By replacing d_1 from (4) in (1) and using the i_{Lp} expression given by (2) the averaged value of the inductor current will be:

$$\bar{i}_L = \frac{1}{2Lf_s} \frac{V_o v_g}{V_o - v_g} d^2 \quad (5)$$

where $f_s = 1/T_s$ is the operation switching frequency. Because the inductor current represents in fact the input current for the PFC circuit, $i_g = i_L$, and imposing the operation condition for a power factor correction circuit, $\bar{i}_g = v_g/R_e$, where R_e is the emulated resistance, the (5) relation becomes:

$$\frac{v_g}{R_e} = \frac{1}{2Lf_s} \frac{V_o v_g}{V_o - v_g} d^2 \quad (6)$$

The last equation can be rewritten as follows:

$$V_o - v_g = \frac{V_o R_e}{2Lf_s} d^2 \quad (7)$$

Relation (7) shows that the controller can be easily implemented by using a universal trailing edge modulator. More than that, the same relation reveals that the duty-cycle does not depend on any current, meaning that the PFC circuit is not containing current transducers, this fact being another big advantage of the proposed application. In order to define the control voltage, V_m , it can be observed that the last equations right part has a large value, uncommon to a control circuit. Therefore, both members in the (7) equation can be multiplied with a sub-unitary constant factor K , small enough to provide typical values for a control circuit. Practically, this fact requires the using of some simple resistive dividers. The (7) relation will be then:

$$K(V_o - v_g) = K \frac{V_o R_e}{2Lf_s} d^2 \quad (8)$$

From this last equation the control voltage of the trailing edge modulator can be defined as:

$$V_m = K \frac{V_o R_e}{2Lf_s} \quad (9)$$

The final form of the controller equation will be then:

$$K(V_o - v_g) = V_m d^2 \Rightarrow K(V_o - v_g) = V_m \left(\frac{t}{T_s} \right)^2 \quad (10)$$

In Fig.2 is presented the circuit schematic for the PFC circuit based on the DCM BOOST converter controlled by a universal PWM trailing edge modulator with two integrators.

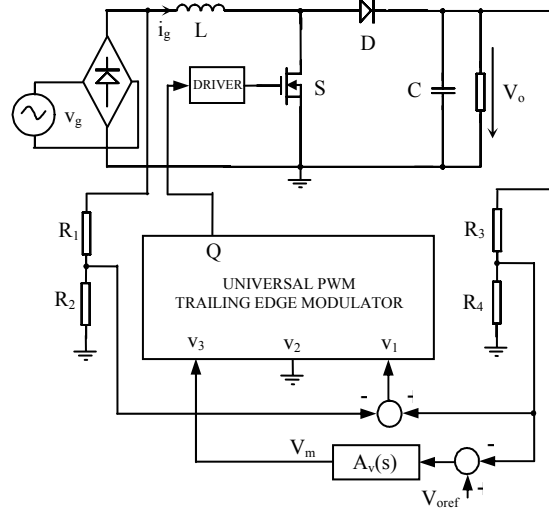


Fig.2. The PFC circuit based on the DCM BOOST converter with the universal PWM trailing edge

The universal PWM trailing edge modulator [3] with two integration steps, presented in Fig.3, implements a general type modulation equation such as:

$$v_+(t) = v_2 \frac{t}{T_s} + v_3 \left(\frac{t}{T_s} \right)^2 \quad (11)$$

In this relation, v_1 , v_2 , v_3 can be considered to have insignificant variations regarding the switching frequency, $v_+(t)$ being a polynomial function in t/T_s and representing the carrier signal for the modulator.

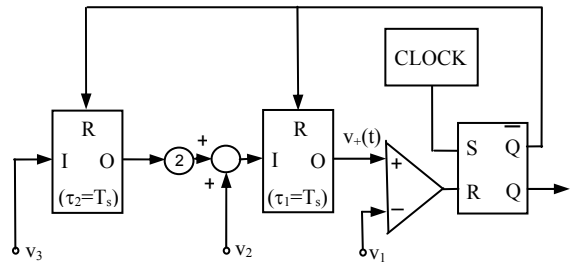


Fig.3. The universal PWM trailing edge modulator with two integration steps

From (9), the emulated resistance by the circuit is:

$$R_e = \frac{2Lf_s V_m}{K V_o} \quad (12)$$

Now, knowing the values for V_m , K , V_M , the output power, $P_o = V_M^2 / 2R_e$, and the circuit elements, the output voltage provided by the circuit will result:

$$V_o = \frac{4Lf_s P_o}{K V_M^2} V_m \quad (13)$$

If the PFC circuit supplies a resistive load, then by replacing in (13) the output power as $P_o = V_o^2 / R$ it will lead to the output voltage relation as follows:

$$V_o = K \frac{R V_M^2}{4Lf_s V_m} \quad (14)$$

III. HARDWARE IMPLEMENTATION OF THE CONTROLLER

The control circuit for the PFC circuit presented in Fig. 2 can be implemented by the schematic presented in Fig.4. It contains a clock generator for f_s , one latch, a comparator, two integration circuits which can be reset through S_1 and S_2 . By identifying the control signals with the ones from Fig.3 it can be easily observed that $v_1 = K(V_o - v_g)$, $v_2 = 0$, $v_3 = V_m$.

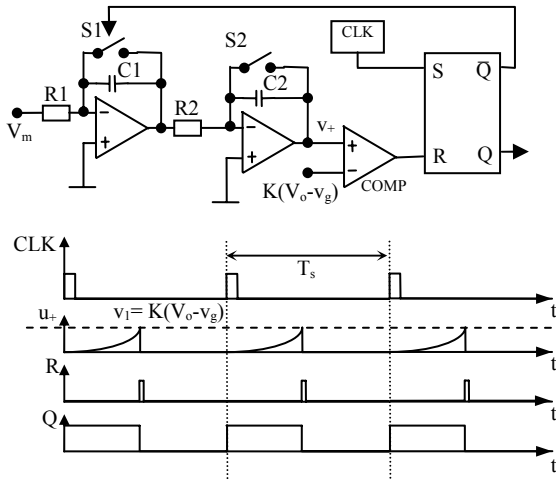


Fig.4. The integration control circuit schematic and his corresponding waveforms

On each clock signal, $Q=1$ and the transistor S is on. In the same time S_1 , S_2 are in off state meaning that the integration circuits are performing the integration function. Assuming that the control voltage has a constant value, at the second integrator exit the resulting voltage will be given by:

$$v_+ = \frac{V_m}{2R_1C_1R_2C_2} t^2, 0 \leq t \leq T_s \quad (15)$$

When v_+ equals v_l the latch will be reseted, the transistor S will be in off state, S_1 and S_2 will be on permitting for C_1 , C_2 to be discharged in order to obtain $v_+ = 0$, meaning that the control circuit is ready for another switching period. Because $v_l = v_+$ and taking into consideration (10) and (15), the integration control equation for the modulator circuit will be then:

$$K(V_o - v_g) = V_m \frac{T_s^2}{2R_1C_1R_2C_2} \left(\frac{t}{T_s} \right)^2 \quad (16)$$

From (7) and (16) the emulated resistance results:

$$R_e = \frac{V_m}{V_o} \frac{2Lf_s}{K} \frac{T_s^2}{2R_1C_1R_2C_2} \quad (17)$$

Considering the circuit operation at unity power factor ($V_M^2 / (2R_e) = V_o^2 / R$) and replacing R_e from (17) it will result the output voltage value:

$$V_o = \frac{V_M^2 R}{2V_m} \frac{K}{2Lf_s} \frac{2R_1C_1R_2C_2}{T_s^2} \quad (18)$$

In the last equation the load resistance can be replaced as $R = V_o^2 / P_o$, meaning that (18) will finally become:

$$V_o = \frac{2V_m P_o}{V_M^2} \frac{2Lf_s}{K} \frac{T_s^2}{2R_1C_1R_2C_2} \quad (19)$$

The inductor L value results from the condition of unconditioned operation in DCM mode for BOOST converters [2], ($R = V_o^2 / P_o$, $M_{min} = V_o / V_M$), as follows:

$$L < \frac{V_o^2}{4f_s P_o M_{min}^2} \left(1 - \frac{1}{M_{min}} \right) \quad (20)$$

Finally, the value for the control voltage of the modulator circuit, assuming the operation at unity power factor, results from (19):

$$V_m = \frac{1}{2} K \frac{V_o V_M^2}{P_o L} f_s \tau_1 \tau_2 \quad (21)$$

where $\tau_1 = R_1C_1$, $\tau_2 = R_2C_2$. The value of the dividing ratio between V_o and v_g , K , must be chosen in order to obtain a value for the control voltage V_m normally between 0 and 15 volts. Having V_m it is easily to find the value of the product between τ_1 and τ_2 . Practically the R_1C_1 , R_2C_2 values (usually $\tau_1 = \tau_2$) can be find by imposing that the exit values of the integration circuits are to remain in the range of their supplying voltages.

IV. SIMULATION RESULTS

In order to verify the correct behavior of the proposed PFC circuit, a simulation was performed in the CASPOC medium (Simulation Research).

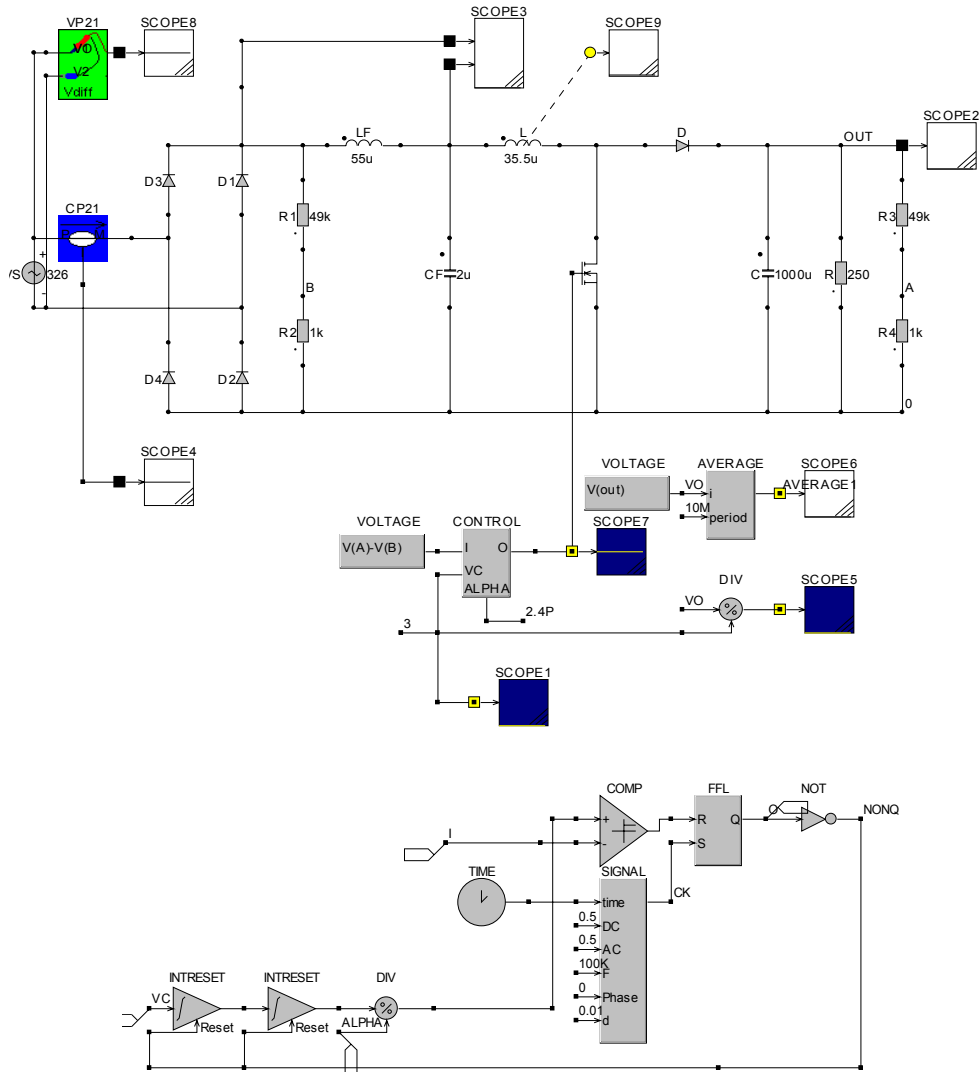


Fig.5. Simulation circuit in CASPOC for the DCM BOOST PFC circuit with integration control and the architecture of the integration control circuit (CONTROL.lib)

The peak mains voltage is $326V$ at $50Hz$ frequency, the value of the L inductor is $35.5\mu H$, the output power $P_o=1.44kW$ and output voltage $V_o=600V$ are corresponding to a resistive load $R=250\Omega$. The circuit used for simulation, containing a RF input filter and the library block architecture of the integration control circuit are presented in Fig.5.

The waveforms corresponding to the input current, absorbed from the mains supply by the PFC circuit, together with the mains supply voltage, are presented in Fig.6. It can be easily observe that the input current shape is sinusoidal and also it is in phase with the mains input voltage.

The converter inductor current waveform and also a detailed section of the same current, showing the DCM operation mode, are presented in Fig.7.

The spectral analysis of the input current (in the presence of a RF input filter) performed in MATLAB, presented in Fig.8, reveal very good values for the merit parameters as it can be seen from Table1 (only harmonics until the 20th order were considered) and Tabel2 (all the harmonics were considered).

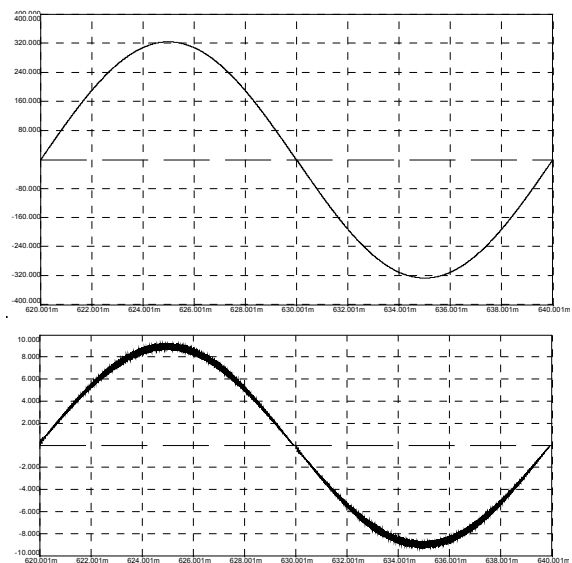


Fig.6. The mains supply voltage (up) and the input current of the PFC circuit (down)

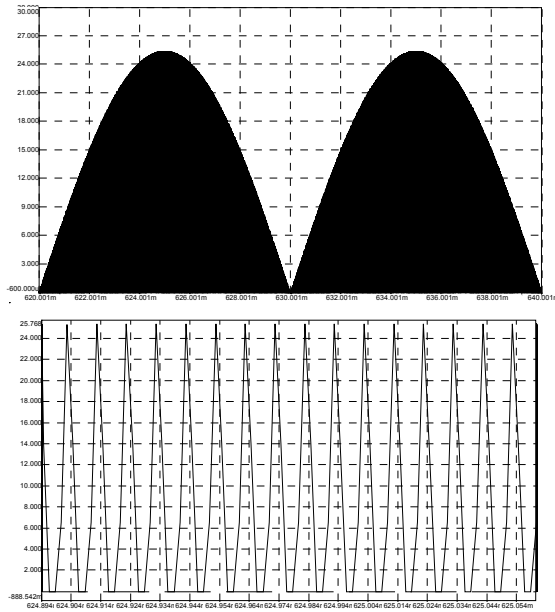


Fig.7. The inductor current, i_L , (up) and a detailed part revealing the DCM operation mode (down)

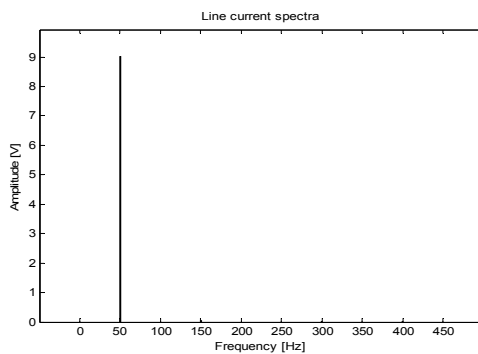


Fig.8. Spectral analysis of the PFC circuit input current in the presence of a RF input filter

Table 1

THD_{tr} [%]	Kd_{tr}	$\Phi 1$ [deg]	$K\phi$	PF_{tr}
0.3353	1.0000	2.7033	0.9989	0.9989

Table 2

THD_{tot} [%]	Kd_{tot}	$\Phi 1$ [deg]	$K\phi$	PF_{tot}
2.6035	0.9997	2.7033	0.9989	0.9985

The resulted merit parameters which are presented in the tables above are: total harmonic distortion factor THD , distortion factor K_d , the angle between the input current fundamental and the supply voltage ϕ_1 , displacement factor K_ϕ and the power factor PF

V. CONCLUSIONS

The classical approaches of the PFC circuits based on DCM operated BOOST converters are presenting a series of main disadvantages due to the necessity of

eliminating the current distortions, such as: an output voltage value much larger than the input one, variable switching frequency and at least one multiplier in critical mode control or complex control circuits, the necessity of current sensing in non-linear carrier control method.

The proposed integration control method for a DCM BOOST PFC circuit presents a series of major advantages: provides unity power factor, does not require that the output voltage to be significantly greater compared to the input one, operation at constant switching frequency, no needing of multipliers or other complex circuits, does not need the input current sensing. The integration control circuit, based on the universal PWM trailing edge modulator, is easy to be implemented in a simple manner with two integration circuits, a comparator and a latch.

As the simulation results are showing, very good values of the main merit parameters can be obtained.

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