Sensorless Cancelation of the Low-Frequency Harmonics in DICM-PFC Boost Converters

M.O. Buss **D.S. Schramm**
Universidade Federal de Santa Maria
Departamento de Eletrônica e Computação - CT
e-mail: dss@nafa.ufsm.br

Abstract: This paper shows a new technique to cancel the low frequency harmonics (3ª , 5ª , 7ª ...) of the input current in Boost converters which operate in the discontinuous current mode with no need of current sensor in the Boost inductor. The proposed control scheme eliminates the necessity of any type of current sensors with no loss of performance or overcurrent risks. These features are obtained by controlling the switch on-time. Input voltage fluctuations are also considered whose normally cause some harmonic current reappearing with the use of the proposed technique. An improved new technique is then introduced to reach the research goal. Practical results and simulations prove the efficiency of the new technique presented in this paper.

I. INTRODUCTION

In an unity power factor operation, the line current must flow in phase with the source voltage and must contain only the fundamental component in order to suppress harmonic currents. The requirements about the harmonic components of the input current imposed by the present IEC 1000-3-2 has forced the use of different solutions rather than the classical rectifying stage followed by a bulk capacitor. PFC Boost converters operating in Discontinuous-Inductor-Current-Mode is popular from low to medium power levels, although this operation mode shows input current distortion [1] due to variable dead time between current pulses. In [2], a technique was published to eliminate the line-frequency harmonics by using a modulation in the power switch on-time. This modulation was achieved by using a clock transition of a fixed frequency signal to initiate the conduction and an adequate inductor peak current reference to obtain the turn-off signal. This peak current reference modulates the inductor peak current envelope producing a null theoretical harmonic content in the low frequency spectrum. This reference is calculated according with the particular parameters of a given converter. This method requires the use of one current sensor in each interleaved module when this technique is used. In this paper a technique to cancel the low frequency harmonics which has no need of current sensors is presented. The paper's objective is reached using a look-up table to 'memorize' the current references using an indirect method. Each reference is normalized for each Vo/Vp ratio, where Vo is the output voltage and Vp is the input voltage amplitude. This method is possible due to the normalized peak current references be dependent only of the ratio Vo/Vp. It is independent of any other kind of converter parameter like output power, switching frequency, etc ... The power stage implemented in this paper where the proposed harmonic cancellation technique were applied is shown in Fig. 1. The block diagram of the full circuitry is shown in Fig. 2.

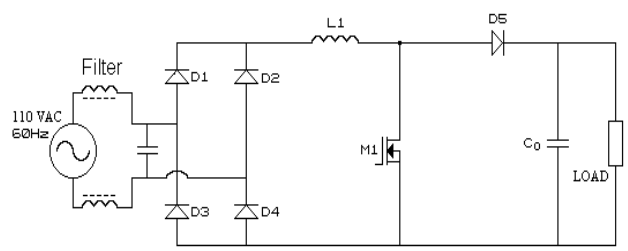

Fig. 1- Implemented power stage.

II. AVERAGE INPUT CURRENT ANALYSIS OF THE CONVENTIONAL DICM BOOST CONVERTER

For a fixed frequency operation the input current waveform of the conventional Boost converter is analyzed considering it as triangular pulses along the semi-period. To simplify the analysis some considerations are assumed:

a) the input voltage is constant over one switching period and its value is taken at the middle of the switching period;

b) the power switch on-time is constant within a half-line cycle, as used in conventional Boost converters;

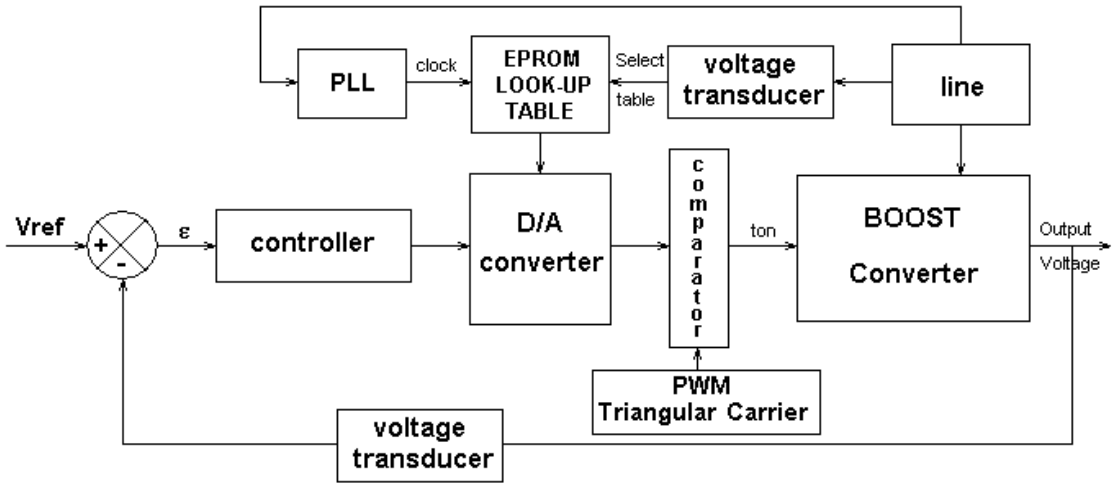

Fig. 2 – Block diagram of the full circuitry.

c) the switching frequency is much higher than the line frequency. Hence, the average input current is formulated as follows:

$$t_{on} = D.T_s \tag{1}$$

$$t_{off} = t_{on}.\frac{V_p.\left|sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right)\right|}{V_o - V_p.\left|sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right)\right|} \tag{2}$$

$$I_{avg} = \frac{1}{L}.\frac{V_p.sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right)t_{on}.(t_{on} + t_{off})}{2.T_{pwm}} \tag{3}$$

where D is the duty cycle, T_s is the switching period, θ_i is the initial angle of the θ_{pwm} period, and θ_{pwm} is the angle of the switching period $(\theta_{pwm}=2.\pi.f.T_s)$. Using (1), (2) and (3), gives:

$$I_{avg} = \frac{D^2.T_s.V_o}{2.L}.\frac{sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right)}{a - \left|sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right)\right|} \tag{4}$$

where '*a*' is the ratio between the output voltage and the input voltage amplitude *(a=Vo/Vp)*.

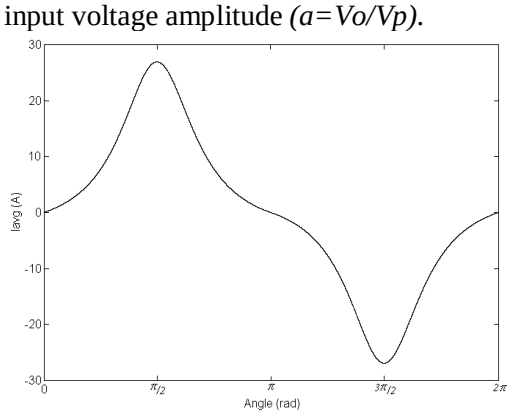

Fig. 3 - Average input current waveform with line harmonic distortion.

The average input current waveform shown in Fig. 3 was obtained using (4) with the following values: $D=0.15$; $T_s=100\ \mu s$; $P_{out}=1400\ W$; $L=78\mu H$; $f=60\ Hz$; $V_p=110.\sqrt{2}\ V$; $w=2\pi 60\ rad/s$; $a=1.2$.

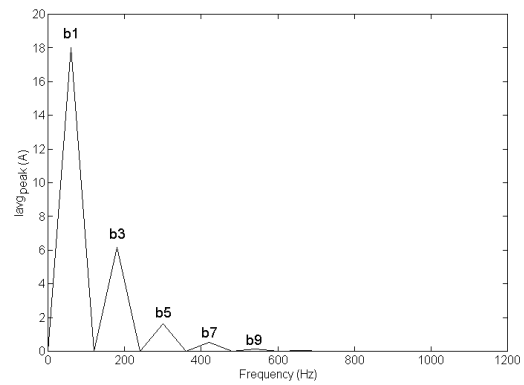

Fig. 4 - FFT analysis of the average input current waveform shown in Fig. 3.

Table 1 shows the percentage ratios between the line-frequency harmonic components and the fundamental component for some '*a*' ratios. As seen is this table, the low-frequency harmonic components are greater when the '*a*' parameter becomes closer to 1.

Table 1 - Percentage ratios between the line-frequency harmonic components and the fundamental component.

a	**3rd**	**5th**	**7th**	**9th**
1.05	56.6 %	29.8 %	15.9 %	8.49 %
1.2	34.3 %	9.14 %	2.87 %	0.71 %
1.4	23.6 %	3.34 %	0.82 %	0.03 %
1.6	18.2 %	1.43 %	0.45 %	0.05 %
1.8	14.8 %	0.57 %	0.31 %	0.09 %
2.0	12.6 %	0.13 %	0.26 %	0.09 %

Notice that these percentage values are dependent only of the '*a*' parameter, being independent of any other converter parameter such as power, switching frequency, etc... That is, if there is a Boost converter operating at the discontinuous inductor current mode,

these values are always valid. This is proved in [2] by the Fourier Analysis of the input current in the Boost converters operating at discontinuous inductor current mode.

III. CONTROL MODE FOR THE PROPOSED LINE-FREQUENCY HARMONIC CANCELLATION TECHNIQUE

As seen in Fig. 3 and 4 and in Table I, the harmonic content of the Boost converter operating in the discontinuous mode can be a lot significant as the '*a*' ratio gets closer to the unit. In [1], it is shown a relation between the low frequency harmonic content and the '*a*' ratio where the solution to reduce these harmonic components is to increase the Vo/Vp ratio. However, to eliminate the input current harmonics in Boost converters which operate with any possible Vo/Vp ratio, the switch on-time must be modulated within the half line cycle in order to produce a sinusoidal average input current. This requires a non-sinusoidal inductor peak current envelope and it is reached through a different switch on-time modulation. The conventional PWM must be then modified. The average input current must follow the equation below,

$$I_{avg} = K_a.sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right) \qquad (5)$$

Using (2), (3) e (5) gives,

$$K_a.sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right) = \frac{1}{L}.\frac{V_p.sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right).t_{on}.(t_{on} + t_{off})}{2.T_s} \qquad (6)$$

and so,

$$t_{on} = \sqrt{\frac{2.K_a.L.T_s.\left(a - \left|sin\left(\theta_i + \frac{\theta_{pwm}}{2}\right)\right|\right)}{V_o}} \qquad (7)$$

In this manner, a table was created for all possible values of t_{on} along the semi-period, making θ_i to vary from 0º up to 180º. Also, new tables must be created if different '*a*' ratios are to be used in the same Boost converter, hence, making it an adjustable converter. In Fig. 5 we can see some t_{on} modulation curves for a total low frequency harmonic cancellation of different '*a*' ratios. Fig. 6 shows the FFT analysis of the input current obtained with this corrected t_{on}.

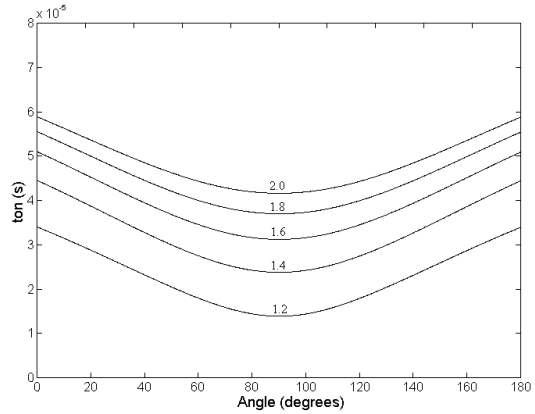

Fig. 5 – Switch on-time at different time instants for total line-harmonic cancellation.

IV. CONTROL SCHEME

In this paper, the output power is controlled using the switch on-time as the control variable, and keeping of course, the t_{on} modulation constant. Another fact to be considered is the input voltage fluctuations. These fluctuations produce a dynamic variation in the ratio Vo/Vp making the previously calculated t_{on} erroneous as the input voltage changes. This error results in harmonic reappearing. To eliminate this problem a real-time correction of the '*a*' parameter in (7) must be used. This is obtained by creating t_{on} tables not only for the various '*a*' parameters to be used within the converter but also making tables for these same '*a*' values considering the V_p fluctuations (tables for '*a*'± Δ%), where Δ% is the input voltage fluctuations given in percentage ratio. The choice of Δ is based on how significant is the Δ% fluctuation for a given '*a*' parameter in the harmonic reappearing. Fig. 7 shows the harmonic reappearing when the voltage V_p fluctuates from V_p – 20 % up to V_p + 20%, and so, no on-line correction of the look-up tables is made. The chosen '*a*' parameter is 1.2.

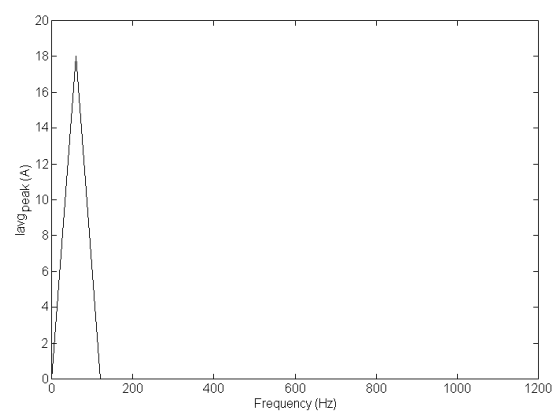

Fig. 6 - FFT of the average input current using the new t_{on} modulation.

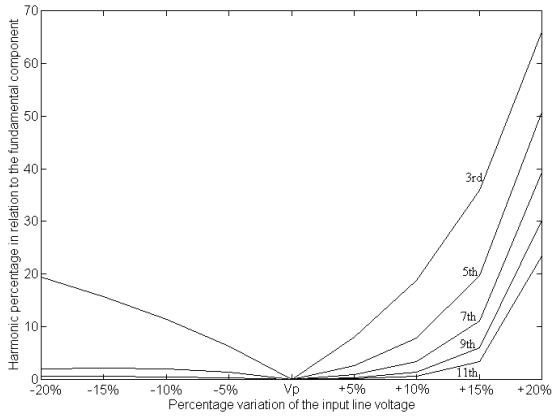

Fig. 7 – Harmonic cancellation error for various harmonic components using an 'a' equal to 1.2.

It is clearly seen that the 3rd harmonic reappearing gets significant with only $V_p \pm 2\%$, that means, a table for this fluctuation must be obtained when $V_o/V_p = 1.2$. As a consequence, we must have new tables for $V_p \pm 4\%$, $V_p \pm 6\%$, $V_p \pm 8\%$, $V_p \pm 10\%$, $V_p \pm 12\%$ and $V_p \pm 14\%$. Fluctuations greater than ± 14% were not considered in this study. This quantitative consideration of a significant 3rd harmonic reappearing is based on international standards, like the IEC 1000-3-2. In this work only values between 1% and 2% are accepted as the maximum 3rd harmonic reappearing. After bypassing this pre-established limit, the table must be changed recurringly, if necessary, to another one more adequate taking into account the existing fluctuation. These limits for some '*a*' values are as follows,

Table 2 – Limits for the 3rd harmonic reappearing (percentage value in relation to the fundamental).

'a' parameter	**1.2**	**1.4**	**1.6**	**1.8**	**2.0**
3rd harm./fund	1.43%	1.33%	1.25%	1.19%	1.15%

With this values it is possible to calculate the value of Δ% for each '*a*' ratio,

Table 3 – Relation between the 'a' parameters, the Δ% fluctuation in 'V_p' and the number of tables.

***a*=1.2**	A new table for each ± 2% of V_p fluctuation
***a*=1.4**	A new table for each ± 4% of V_p fluctuation
***a*=1.6**	A new table for each ± 6% of V_p fluctuation
***a*=1.8**	A new table for each ± 8% of V_p fluctuation
***a*=2.0**	A new table for each ± 10% of V_p fluctuation

We conclude from now on that the total number of necessary tables to cover a considerable range of fluctuation values of V_p is for some '*a*' ratios,

Table 4 – Relation between the 'a' parameter and the necessary number of t_{on} tables

'a'	**No. Tables**	**Range of fluctuation covered**
***a*=1.2**	15 tables	V_p ± 15%
***a*=1.4**	7 tables	V_p ± 14%
***a*-1.6**	7 tables	V_p ± 18%
***a*=1.8**	5 tables	V_p ± 16%
***a*=2.0**	3 tables	Vp ± 20%

V. PRACTICAL RESULTS

The experimental results of the conventional PWM Boost converter and the Boost converter operating with the proposed technique are shown as follows. The waveforms of the input current in both operation modes were recorded using a digital real-time oscilloscope. The frequency spectrum of the input current was obtained from MATLAB® software. They show the validity of the harmonic canceling technique. The '*a*' ratio adopted is 1.2. The switching frequency used was 10 kHz. The necessary tables for the on-time modulation were stored in an EPROM look-up table, where a voltage transducer connected to the mains helps to select the table to be used. A PLL synchronized with line voltage is used to select dynamically the data of a given EPROM look-up table for every angle of the 60 Hz line voltage. The output voltage control is the same of the conventional Boost converter and the controller modulates the analog voltage of a D/A converter to control the output power. A comparator produces a pulse sequence with a constant frequency (PWM) with a variable t_{on} which controls the output power as well as to cancel the input current harmonics. Fig. 8 shows the Boost inductor current waveform of the conventional Boost converter, while Fig. 9 shows the filtered line current in this operation mode. Fig. 10 shows the Fast Fourier Analysis of the converter's line current without the application of the proposed technique.

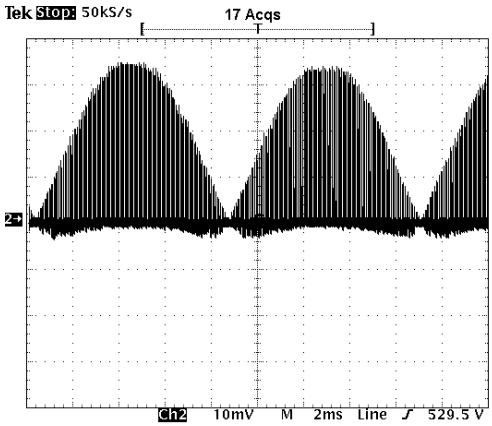

Fig. 8 – Boost inductor current waveform of the conventional Boost converter.

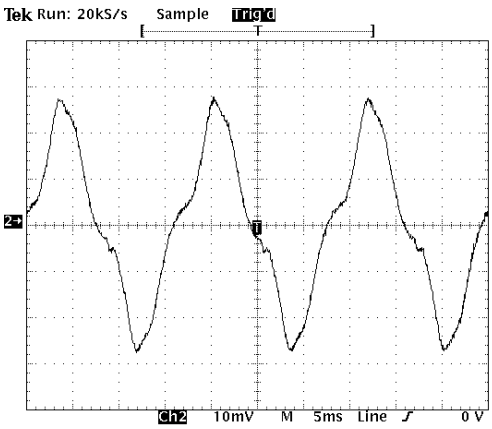

Fig. 9 – Filtered line current in the conventional Boost converter.

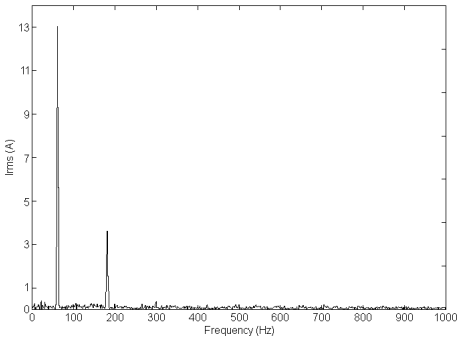

Fig. 10 – FFT of the line current without correction

Fig. 11 shows the Boost inductor current waveform of the Boost converter using the proposed technique, while Fig. 12 shows the filtered line current. Fig. 13 shows the Fast Fourier Analysis of the converter's line current with the application of the proposed technique. As seen in these figures, the low frequency harmonics are eliminated.

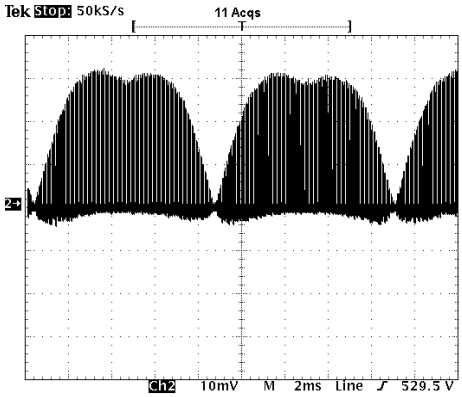

Fig. 11 – Boost inductor current waveform of the Boost converter using the proposed technique.

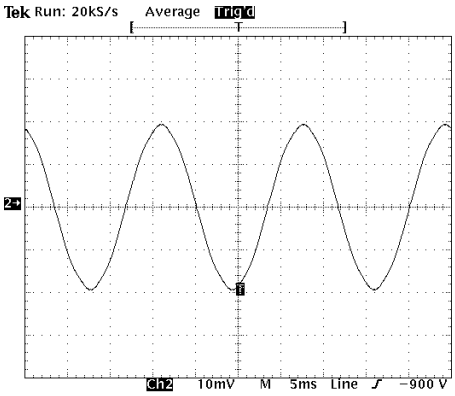

Fig. 12 – Filtered line current in the Boost converter using the proposed technique.

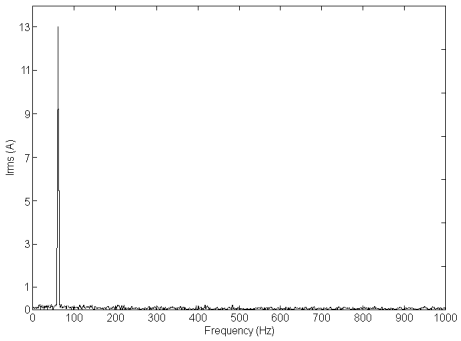

Fig.13 – FFT of the line current with correction.

VI. CONCLUSION

The Boost converter operating in discontinuous input current mode (DICM) has been widely accepted by industry for power factor correction in low and medium power applications. Zero Current Switching (ZCS) in the switch turn-on instant is another advantage in DICM Boost converters, which reduces switching losses.

In conventional Boost converters two control modes have been used: a fixed frequency with a fixed duty cycle where the turn-on switch time is constant (usually in DICM) and by using the input inductor

peak current compared with a sinusoidal reference (usually in continuous current mode - CCM).

This work presents a new and improved technique to cancel the line harmonics (low frequency) in Boost converters which operate in the discontinuous mode without the use of any current sensor. Simulation and practical results have shown the technique validity and also, theoretical results have shown a simple and effective technique to completely cancel the line harmonics taking into account that the V_o/V_p ratio can be fixed at any possible value. The new t_{on} modulation produces also a new modulation in the inductor current discharge time allowing the low frequency harmonics of the input current to be cancelled. So far line harmonic reduction has been tried by choosing an adequate V_o/V_p ratio. The proposed method in this paper cancels all line-frequency harmonics for any V_o/V_p ratio. The input current distortion due to the dead time between current pulses is eliminated with the technique proposed here, i.e., the new modulation of the inductor discharging time produces a sinusoidal average input current, free of line-frequency harmonics.

REFERENCES

[1] Kwang-Hwa Lu and Yung-Lin Lin, "Current Waveform Distortion in Power Factor Correction Circuits Employing Discontinuous-Mode Boost Converters", Proceedings of PESC'89, pp. 825-829.

[2] D.S. Schramm, M.O. Buss, "Mathematical Analysis of a New Harmonic Cancellation Technique of the Input Line Current in DICM Boost Converters", Proceedings of PESC'98, pp. 1337-1343.

[3] D. Weng and S. Yuvarajan, "AC-DC Converter Using Second Harmonic-Injected PWM", Proceedings of PESC'95, pp. 1001-1006.

[4] C. Zhou, R.B. Ridley and F.C. Lee, "Design and Analysis of a Hysteretic Boost Power Factor Correction Circuit", Proceedings of PESC'90, pp. 800-807.

[5] C.H. Chan, M.H. Pong "Input Current Analysis of Interleaved Boost Converters Operating in Discontinuous-Inductor-Current-Mode", Proceedings of PESC'97, pp. 392-398.

[6] J.J. Spangler and A. K. Behera, "A Comparison Between Hysteretic and Fixed Frequency Boost Converters Used For Power Factor Correction", Proceedings of PESC'93, pp. 281-285.

[7] Jing Wang, William G. Dunford and Konrad Mauch, "A Fixed Frequency, Fixed Duty Cycle Boost Converter with Ripple Free Input Inductor Current for Unity Power Factor Operation", Proceedings of PESC'96, pp. 1177-1183.

[8] C. Zhou and M.M. Jovanovi'c, "Design Trade-Offs in Continuous Current-Mode Controlled Boost Power-Factor-Correction Circuits", 1992 VPEC, pp. 15-26.

[9] J. S. Subjak, Jr and J. S. McQuilkin, "Harmonics-Causes, Effects, Measurement, and Analysis: An Update", IEEE Transactions on Industry Applications, Vol. 26, No. 6, 1990, pp. 1034-1042.

[10] D. J. Tooth, S.J. Finney, J.N. McNeill, B.W. Williams, "Soft Switching and Interleaving For Sinusoidal Input Current AC to DC Step Down Converters", PESC'96, pp. 183-187.