DIRECT WATER HEATER POWER CONTROL FOR REDUCED HARMONICS AND FLICKER CONTENT WITH OPTIMIZED HALF-CYCLE POWER CONTROL

Wilson Komatsu[#], Cláudio José de Oliveira Júnior*, Paulo Sérgio Valle Carvalho*
[#]Escola Politécnica da Universidade de São Paulo *DEPD – Lorenzetti S/A
[#]Av. Prof. Luciano Gualberto, trav. 3, no. 158, sala A2-05 – 05508-900 São Paulo SP BRAZIL
wilsonk@usp.br

***Abstract* - This paper presents an optimized Half-Cycle Power Control for Direct Water Heater with reduced harmonic content and flicker control. The method is presented, as well as results of computer simulations and experimental results.**

***Keywords* - Cycle-by-cycle power control, direct water heater, flicker, half-cycle power control, harmonics and power quality, integral-cycle power control.**

I. INTRODUCTION

Electronic power control of a Direct Water Heater (DWH) [1], in usually made by variation of the rms voltage applied to the resistive load. The more widespread used electronic power control for this application nowadays is the phase angle power control (PAPC) type [2], which changes the rms voltage content applied to load by shaping the sine current waveform through a semiconductor switch (e.g., a triac), between the voltage source and the controlled load. It is widely known that this type of power control produces highly distorted currents and its associated high harmonic content. Among the problems produced by harmonic distortion, one can mention [3][4][5]:

1. Reduction of transformers lifetime and motor operation malfunction;
2. Reduction of transformers lifetime and motor operation malfunction;
3. Increased loss in conductors;
4. Electromagnetic interference in communication networks;
5. Erroneous breaker operation;
6. Excessive current in neutral conductors;
7. Power factor worsening due to harmonic rms current.

Besides, this type of control causes problems of voltage notching in the public supply network waveform [14].

This paper proposes an Optimized Half-Cycle Power Control [a] (OHCPC) to minimize such problems, as well as flicker problems associated with PAPC and cycle-by-cycle power control (CBCPC), also known as integral-cycle power control.

II. CONVENTIONAL CYCLE-BY-CYCLE CONTROL

The conventional CBCPC [6] is a better alternative, compared to PAPC, in DHW applications.

For "m" cycles applied to load during the time "T_1", and being "M" the number of cycles during the total time "T", the total power P_1 applied to the load is given by (1), being P the total power if $m=M$ (see figure 1).

$$P_1 = P \cdot \frac{m}{M} \tag{1}$$

The ratio "m/M" given by (1) depends on the available controller precision.

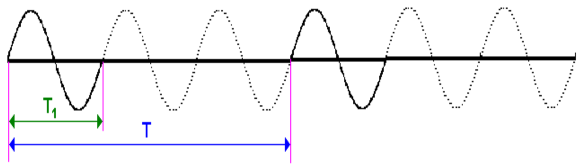

Fig. 1: Cycle-by-cycle (integral-cycle) power control.

The CBCPC removes harmonic distortion (for harmonic orders above the fundamental) and does not alter the power factor (compared to phase angle control), but some factors must be taken into consideration [7][8]:

1. Water temperature variation: In DWH, the power variation between on and off cycles can cause uncomfortable variation in output water temperature because there is little time of contact between the water and the heater element; if the rate of water flow is larger, the problem worsens;
2. DC current imbalance: One needs to ensure conduction for equal numbers of whole positive and negative half-cycles to avoid dc imbalances that can induce power-line distortion;
3. Flicker effect: The CBCPC, being a periodic sequence of on and off states, produces a sub-harmonic current. Depending on this sub-harmonic amplitude and frequency, light intensity oscillation in the lamps can be produced (*flicker effect*).

III. THE FLICKER EFFECT

Flicker [4][5][9][10][11][12][13] can be defined as the slow and repetitive variation of the rms value of voltage, typically at the 1 to 30 variations per second, being a negative factor as it induces an impression of unsteadiness on visual sensation, which is induced by a light stimulus whose luminance or spectral distribution fluctuates with time. It causes electrical and health problems, being the health problems usually more relevant.

Flicker (scintillation) curves, like the one shown in figure 2, are empiric (produced from controlled practical experiences) and is usually given for rectangular voltage fluctuations in the frequency dominium. Above the curves, the probability of discomfort is larger, and under it is very

[a] Protected in Brazil by INPI process number PI-0103054-0 [15]

small. As it is dependant on the time constant of the lamp, it is a function of the lamp power.

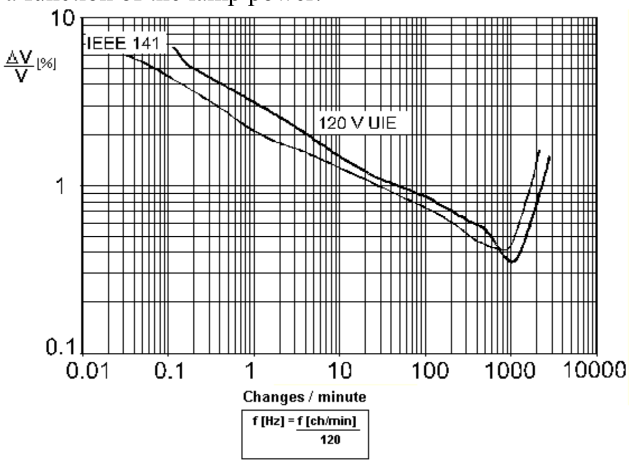

Fig. 2: Example of a typical flicker curve [12][13].

A. The Human eye

The persistence of the vision is the most important part under the point of view of the flicker effect. It consists on the retina property of keeping for some time (about 100 ms) the image of any object. An incandescent lamp turns on and off at each 8,33 ms in 60 Hz (120 scintillations per second) so one does not perceive this oscillation. If this variation period is increased to a time period greater than 100 ms (less than 10 scintillations per second), one easily perceives the luminosity variation. As the iris is adjusted according to the variation of luminosity, it is greatly affected by low frequency scintillation.

IV. OPTIMIZED HALF-CYCLE POWER CONTROL

A solution to minimize flicker effect is to apply an optimized half-cycle power control (OHCPC) [7][15]. For instance, given a total period *T* of 3 AC cycles (1/20 seconds at 60 Hz), the commutation must be done providing more than 30 changes for second, and keeping the DC level to zero. Such control configuration generate current waveforms as given in figures 3 and 4.

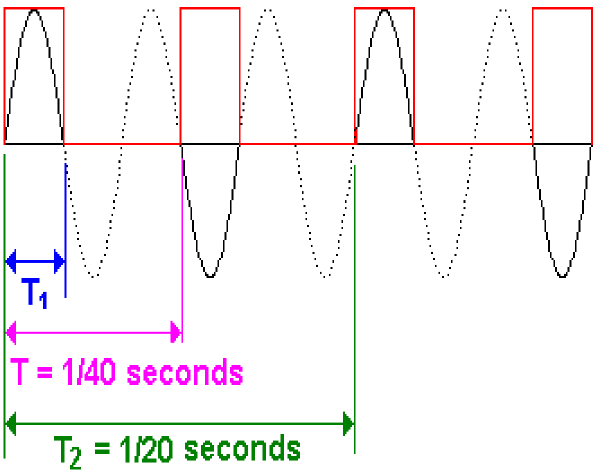

Fig. 3: Current waveform (not in scale) for OHCPC, providing 1/3 of total available electric power. 60 Hz mains frequency.

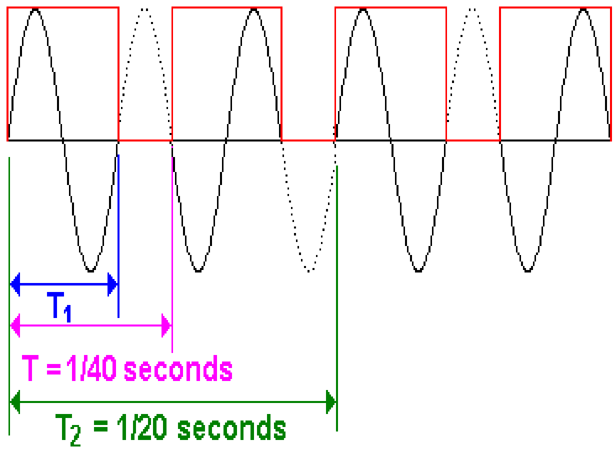

Fig. 4: Current waveform (not in scale) for OHCPC, providing 2/3 of total available electric power. 60 Hz mains frequency.

Some OHCPC features, at 60 Hz mains frequency, are:

1. Minimization and elimination of harmonics over 60 Hz;
2. Flicker goes to 40 changes (scintillations) per second (4.800 changes/minute), above the human eye comfort limit, according to the flicker curve (figure 2);
3. Four temperature steps are possible with one heating element: null current (zero power), 1/3 of total power (figure 3 case), 2/3 of total power (figure 4 case) and the full waveform (full power);
4. On/off periods are reduced compared to CBCPC, which is suitable for DWH applications, as water temperature variation is minimized, thus improving user comfort.

The typical load for the application of this control type is one-phase fed, therefore maintaining power feeding compatibility with conventional DWHs. Three-phase loads were not studied, but there are no technical reasons forbidding such implementation.

A. Power steps increase with more than one heater element

Implementation of more than one independently controlled heating element (HE) allows more power steps, and if these HEs have different power rating, the power gradation can be smoother. For instance, by using two HEs with a power ratio of two (power *P* for HE1 and *2P* for HE2), one can obtain 10 power steps: Element HE1 can deliver four power steps: zero, *P/3*, *2P/3* and *P* (refer to waveforms of fig. 2, 3). HE2 will have zero, *2P/3*, *4P/3* and *2P* steps. This association can provide 10 power steps, as seen in Table I.

TABLE I
Available Power Steps associating two HEs, with total powers *P* and *2P*.

HE1 Step	HE1 power	HE2 Step	HE2 power	Total Step Number	Total Power
1	0	1	0	1	0
2	P/3	1	0	2	P/3
3	2P/3	1	0	3	2P/3
4	P	1	0	4	P
3	2P/3	2	2P/3	5	4P/3
4	P	2	2P/3	6	5P/3
3	2P/3	3	4P/3	7	2P
4	P	3	4P/3	8	7P/3
3	2P/3	4	2P	9	8P/3
4	P	4	2P	10	3P

Table I shows that with one HE there are four possible power steps. The increase of HEs allows for more power steps (equations 2 and 3):

$$Ns = \frac{PT}{(mp/3)} + 1 \quad \rightarrow \quad Ns = \frac{3 \cdot PT}{mp} + 1 \qquad (2)$$

$$Ns = \left[\left(2^{Ne} - 1\right) \cdot 3\right] + 1 \qquad (3)$$

Where:

Ns → number of steps;
PT → total power of all HEs [W];
mp → power of the smallest HE [W];
Ne → number of HEs;

Formulas (2) and (3) are valid only if all HEs powers are integer multiples of the smallest power (mp) HE. For instance:

- in a DWH with two HEs, $PT=3mp$;
- in a DWH with three HEs, one can have $P_{HE1}=mp=1.5kW$, $P_{HE2}=3kW$ and $P_{HE3}=6kW$, resulting in $PT=7mp$.

Following the above requirement, Table 2 summarizes the relationship between power steps and number of heater elements.

TABLE II
Number of power steps x number of heating elements.

Number of heating elements [Ne]	Number of steps [Ns]
1	4
2	10
3	22
4	46
5	94
6	190
7	382
8	766

A microcontroller allows the practical implementation of the OHCPC rules. In a balance between performance, cost and ease of implementation, Ne=2 is usually applied.

V. IMPLEMENTATION

A. Hardware block diagram

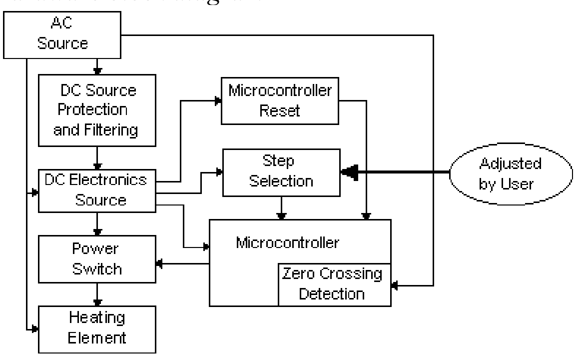

Fig. 5: Hardware block diagram.

The implemented hardware is presented in a block diagram form in fig. 5. AC Source (mains) feeds the system. The DC Source Protection and Filtering block protects the DC Electronic Source, which provides reduced DC voltage for the control system. The Microcontroller Reset resets the Microcontroller in the case of some abrupt AC variation voltage. The Step Selection block is a potentiometer commanded by the user and informs the desired heating level. The Microcontroller sends trigger order to the Power Switch block, which is composed by electronic switch(es) (triacs), connected to the HE(s). Zero Crossing indicator detects the AC voltage zero crossing instant, and is located inside the Microcontroller.

B. Microcontroller pinout assignment description

The applied microcontroller is Microchip PIC12C508A [16], with the pinout assignment description shown in fig. 6:

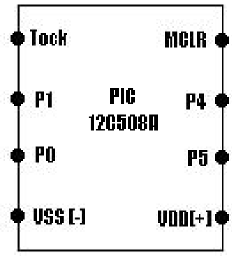

Fig. 6: Microchip PIC12C508A pinout.

VSS(-) and *VDD(+)* feed the IC; Tock receives attenuated AC signal for voltage zero crossing detection; *P1* and *P0* are input gates, used to determine the number of steps *Ns* (equations (2), (3)) according to the received signal; MCLR resets the microcontroller if an abrupt AC voltage variation occurs; *P4* and *P5* are output gates that send trigger signals to the power switches (triacs).

C. Software Flowchart

Implemented software flowchart is illustrated in fig. 7.

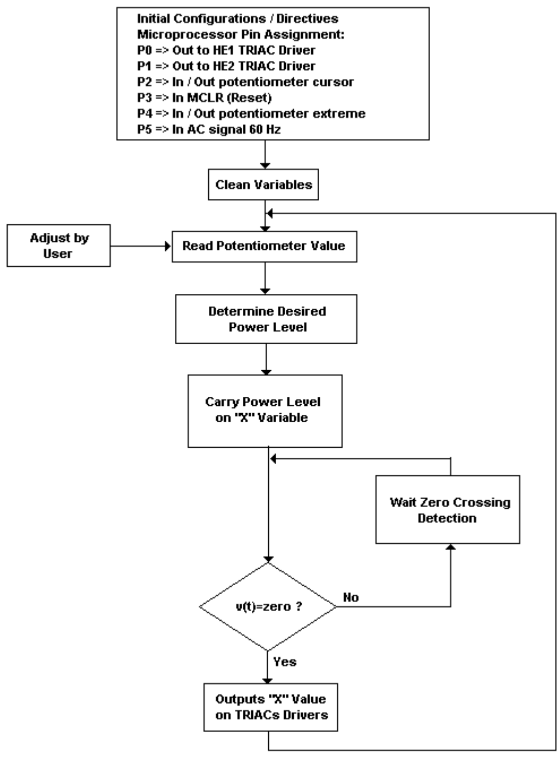

Fig. 7: Implemented software flowchart for two heating elements HE1 and HE2.

"*X*" variable in Fig. 9 indicates if the power switches (triacs) connected to HE 1 and HE2 are to fired at the zero voltage crossing, according to the computed power level, following the strategy given in Table I.

D. Hardware connection diagram

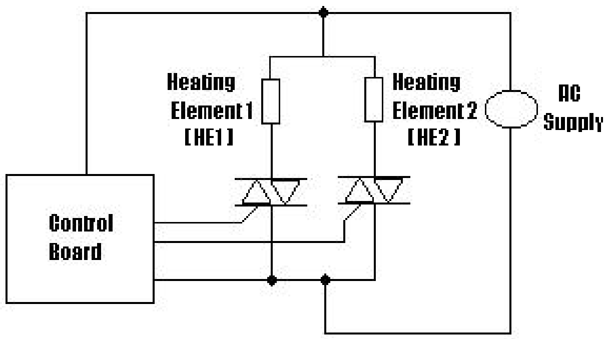

Fig. 8: Hardware connection diagram with two HEs (*Ne=2*).

Figure 8 shows a typical hardware connection diagram with two HEs (*Ne=2*).

VI. SIMULATION AND EXPERIMENTAL RESULTS

Computer simulations of AC current spectra using Matlab (shown in figs. 9 and 11) and experimental results (shown in figures 10 and 12), both using hardware connection of figure 8 (two HEs), were performed in order to validate the proposed solution. OHCPC control laws corresponding to figures 3 and 4 (1/3 and 2/3 of total available power) were applied.

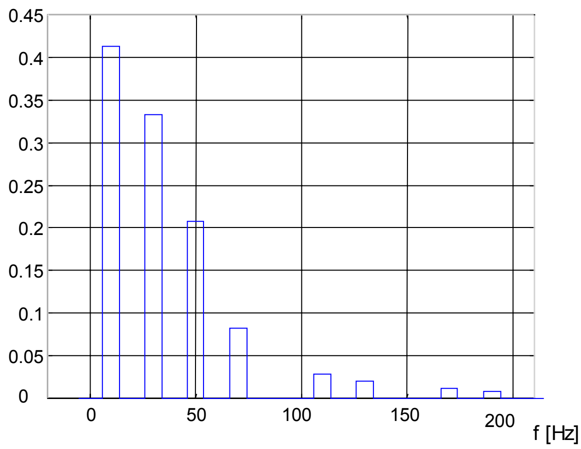

Fig. 9: Simulated AC current spectrum for 1/3 of available power. The "fundamental" (first) harmonic in this spectrum is 20 Hz (a third of fundamental). The "third" harmonic is, in this case, the mains frequency of 60 Hz.

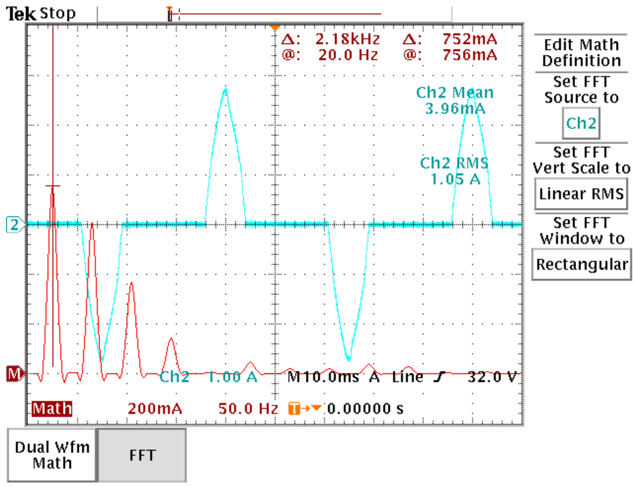

Fig. 10: Measured current spectrum and current waveform for 1/3 of available power.

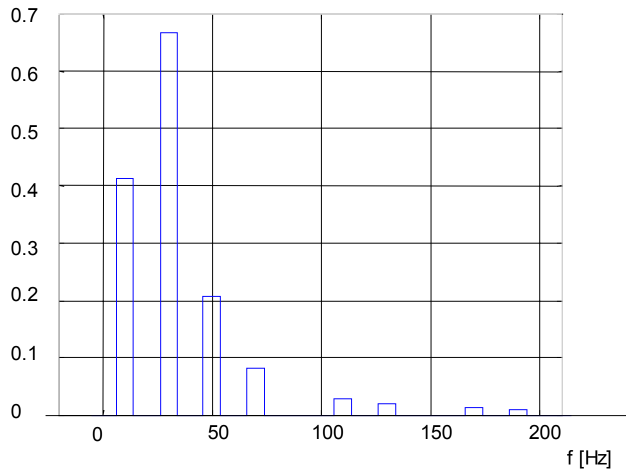

Fig. 11: Simulated AC current spectrum for 2/3 of available power. The "fundamental" (first) harmonic in this spectrum is 20 Hz (a third of fundamental). The "third" harmonic is, in this case, the mains frequency of 60 Hz.

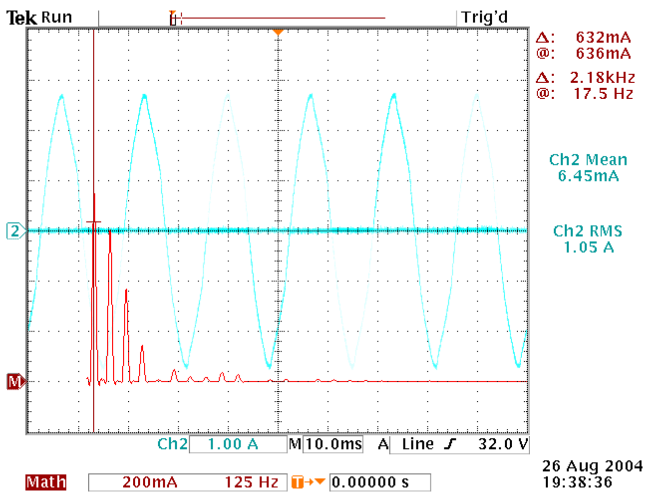

Fig. 12: Measured current spectrum and current waveform for 2/3 of available power.

Figures 10 and 12 show measured current waveforms generated by the OHCPC. Voltage drop at AC mains due to these currents are in phase, because HEs are resistive loads.

Standard IEC-61000-3-3:1994+A1:2001 [10] define at item 3.5 voltage fluctuation as "*series of changes of r.m.s. voltage evaluated as a single value for each successive half-period between zero-crossings of the source voltage*", meaning that one has to "measure" (calculate) the rms value of voltage in each semi-cycle. As the rms value of a positive semi-cycle is the same as its negative counterpart [2], current waveforms of figs. 10 and 12 have fundamental frequencies of 40 Hz (4,800 changes/minute), for flicker measurement effects.

Note 3 of item 4.2.3.2 of the same Standard (IEC-61000-3-3:1994+A1:2001 [10]) informs that no graphical extrapolation can be made on Standard curves in order to avoid unacceptable errors (original text: "*Note 3: Extrapolation outside the range of the figures may lead to unacceptable errors*". It means that, as Fig. 2 curves extend up to 3,000 changes/minute, and the OHCPC has 4,800 changes/minute, which is above the established upper limit of the curves, one can conclude that the OHCPC is in accordance of the limits established by Standard IEC-61000-3-3:1994+A1:2001 [10][12]. Also, studies demonstrate that the threshold of human irritability is around 30 Hz (3.600 changes / minute) [5].

VII. FINAL REMARKS

This paper proposes a power control, based on a modified cycle-by-cycle method, for direct water heaters, which minimizes current harmonics and flicker, usually associated with conventional power control schemes. The method is suitable to direct water heaters, as it minimizes water temperature variations, improving user comfort. Computer simulations and experimental results validate the proposed method.

ACKNOWLEDGEMENT

The authors thank Lorenzetti S.A. for supporting this work.

REFERENCES

[1] Inmetro. Projeto de Norma de Chuveiros Elétricos - Requisitos de desempenho e segurança de aparelhos eletrodomésticos fixos de aquecimento instantâneo de água; Inmetro; Revisão 04; 2001. <in Portuguese>

[2] Rashid, M.H. "Power Electronics: Circuits, Devices and Applications". Prentice Hall, 2nd Edition, 1993.

[3] Procobre. Qualidade de Energia - Harmônicas; Procobre - Instituto Brasileiro do Cobre. <pamphlet>

[4] Arrilaga, J.; Bradley, A.; Bodger, P.S. "Power System Harmonics". John Wiley & Sons, 1989.

[5] Deckmann, S.M. "IT-012: Avaliação da Qualidade de Energia Elétrica". Unicamp, 2002. <class notes>.

[6] Bird, B.M.; King, K.G.; Pedder, D.A.G. "An Introduction to Power Electronics", John Wiley & Sons, 2nd Edition, 1993.

[7] Lorenzetti. Estudos sobre Redução de Harmônicas. <internal report>.

[8] Lorenzetti. Ensaios de Laboratório: Curvas de Pressão x Vazão, Temperatura x Vazão. <internal report>.

[9] IEC-61000-3-2. Edition 2.1; 2001.

[10] IEC-61000-3-3. Edition 1.1; 2002.

[11] IEC-61000-3-4. Première édition; 1998.

[12] IEC-61000-3-5. Première édition, 1998.

[13] Halpin, S.M.; Bergeron, R.; Blooming, T.M.; Burch, R.F.; Conrad, L.E.; Key, T.S. "Voltage and lamp flicker issues: should the IEEE adopt the IEC approach?" IEEE Trans. On Power Delivery, v.18, n.3, July 2003, p.1088-1097.

[14] Jesus, N.C.; Castoldi, F.T.; Nonenmacher, CF.B.; Santos, T.F.; Oliveira, H.R.P.M.; Papaléo, G. "Análise da Influência de Cargas Não-Lineares: Avaliação dos Efeitos e Limites de Cortes de Tensão (Voltage Notching). In: Seminário Brasileiro sobre Qualidade da Energia Elétrica - SBQEE, 5. Sergipe, Aug. 2003. <in Portuguese>

[15] Lorenzetti, C.L. Circuito Eliminador de Harmônicas e Flicker em Aquecedores Elétricos de Passagem. Int. CI H02J-3/01 H05B-1/02 G05B-9/02 BR n. PI0103054-0. July, 2001. Revista da Propriedade Industrial: Seção I. Rio de Janeiro, n.1699, July 2003. <in Portuguese>

[16] PIC – 12C5XX – Series User´s Manual – Microchip – 2002