

A SINGLE STAGE HIGH POWER FACTOR 3 PHASE 60V/100A POWER SUPPLY USING A LINE-SIDE INTERPHASE TRANSFORMER AND AN ISOLATED PUSH-PULL CONVERTER

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Abstract - A novel single stage, high power factor three-phase power supply which consists of a high frequency, line-side interphase transformer and a high switching frequency, isolated, DC-DC Current Sourced Push-Pull Converter is presented. Besides the high power factor it presents soft switching both in turn-on and turn-off of the power and auxiliary switches. The high power factor and low harmonic content is reached by means of the Line Interphase Transformer which is in turn switched at a high frequency switching by means of a push-pull converter. The main analytical equations, simulation and experimental results are presented.

I. INTRODUCTION

High power factor (HPF) three-phase power supplies have been usually implemented by means of multiple switched stages. The first one is almost always a pre-regulator rectifier stage with high voltage level at its output (~400V) [1,2,3,4]. In order to obtain an isolated, regulated and low level output voltage, as required by the applications, the use of a DC-DC converter as a second stage is mandatory. One known topology is made up of three groups of a single phase power factor corrector in series with an isolated DC-DC converter [5]. Although it has the advantage of using three independent converters its disadvantages are the great number of components and the characteristic single phase pulsed power flow from the utilities. Another three-phase topology is formed by using three groups of single phase power factor corrected DC-DC converter [6], with the same disadvantages as above, but with the advantage of having no front-end pre-regulator circuit. The use of a three-phase power factor corrected scheme followed by a DC-DC converter has also been studied [7,8,9,10], not always avoiding the use of a great number of components and a complex control circuitry.

Solutions for single stage there exist but they are very complicated and make use of many power switches [11,12]. A new single stage scheme is proposed in this paper with the use of the Line-Side Interphase Transformer [13], acting as a passive power factor corrector, integrated with an isolated high frequency Push-Pull DC-DC Converter.

II. THE PROPOSED CIRCUIT

Since the proposed topology is made up of two integrated parts, the description below will present, by order, the Line-Side Interphase Transformer (LIT) and the DC-DC converter.

A. The Line-Side *Interphase* Transformer

This line interphase transformer was originally used in a low frequency scheme of a high power factor, 12-pulse three-phase rectifier, intended for medium power levels (tens of kilowatts), followed by two paralleled three-phase diode bridge rectifiers (Fig. 1) [14]. And this special transformer is the main reason for the high power factor of the current driven from the utilities.

In this low frequency scheme the LIT allows, by itself, a high power factor and eliminates de low order harmonics up to the 9th. The 11th and the immediately above ones are minimized by the introduction of three input inductors (X_L) just before the LIT.

The LIT is a kind of autotransformer made up of three single phase transformers with three windings each: one primary (W_A) and two secondaries (W_B and W_C). These three transformers are interconnected according to Fig. 1. By designing it with a proper turns ratio the LIT is capable of transforming a unique balanced three-phase system into two three-phase systems, also balanced, but with a 30° phase-shift. The output voltage (V_o in Fig. 1) is then a 12-pulse DC voltage and the resulting line current driven from the mains is

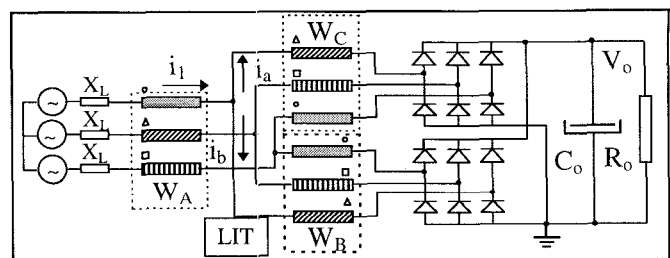


Fig. 1. Low frequency LIT-based 3 ϕ rectifier.

like that in Fig. 2(top), without the three-phase input reactors (X_L). With the inclusion of these reactors, the line current becomes that of Fig. 2(bottom).

In this Fig. 2(bottom) the low order harmonic content (3^{rd} to 9^{th}) is eliminated and the line current waveform approaches a sinusoidal one, with low total harmonic distortion (THD): less than 6%.

In order to obtain the 12-pulse output rectified voltage the following relations should be guaranteed [14]:

$$N_a = \frac{W_B}{W_A} \Rightarrow N_a = 2.73 \quad \text{and} \quad N_b = \frac{W_C}{W_A} \Rightarrow N_b = 3.73 \quad (1)$$

where N stands for turns ratio and W stands for number of turns of the windings. And the average output DC voltage is given by:

$$V_{dc} = 1.24 \cdot V_L \quad (2)$$

where V_L is the line-to-line voltage of the electric network.

A high frequency scheme with the LIT is already known [15,16] and is shown in Fig. 3 which consists of the LIT and of a high switching frequency pulse width modulation (PWM) output stage with boost-like characteristics. In this high frequency scheme the DC-DC Boost converter is switched at a very higher frequency than that of the AC mains, and if the discontinuous current mode (DCM) for each L input inductor is guaranteed, then the LIT windings are driven at high frequency and the use of a low volume ferrite core is made possible, resulting in a global magnetic volume much less than that of the low frequency LIT rectifier in Fig. 1.

The drawback of the unregulated output voltage related to the low frequency scheme is surmounted by the duty cycle control of the output Boost converter in the high frequency scheme. The main waveforms derived by numerical simulation for a 6kW, 26kHz, 220Vca/400Vdc are presented

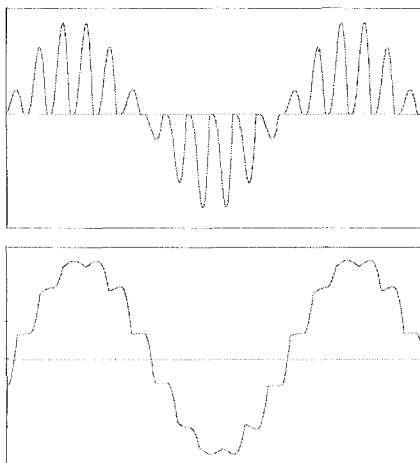


Fig. 2. Line current without filter (top); Line current with filter (bottom).

in Fig.4. As can be seen in this figure, the topology is able of working as a three-phase, high power factor converter.

B. The ZVS-PWM, Clamped Mode, Double Primary-Side Inductor Converter (DIC)

Also known as a Current-Sourced (Push-Pull) DC-DC converter it was first reported in [17], derived from the Half-Bridge converter from the duality principle. As can be seen in Fig. 5, this converter has two primary-side, input inductors acting, together with the batteries, as current sources. This topology is perfectly adapted to be connected to the two separated (positive) current sourced outputs of the LIT (Fig. 3). Due to the high switching frequency of this converter the LIT can be designed to use ferrite-type cores. Its equivalent inductance (L_{eq}) is shown to keep the following relation with the inductance of each input inductor of the three-phase power supply:

$$L = \frac{1}{3} \cdot L_{eq} \quad (3)$$

The operating principle of this converter is based upon the overlapping of the power switches: when they are both ON the input inductors are charged and when one switch goes OFF (while the other is still ON) the energy just stored in the corresponding inductor is transferred to the load via the isolating transformer and one rectifier diode. By controlling

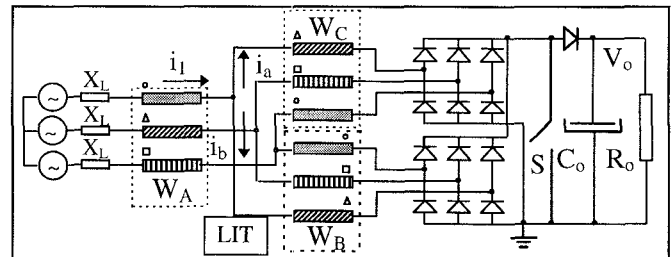


Fig. 3. High frequency LIT-based 3 ϕ rectifier.

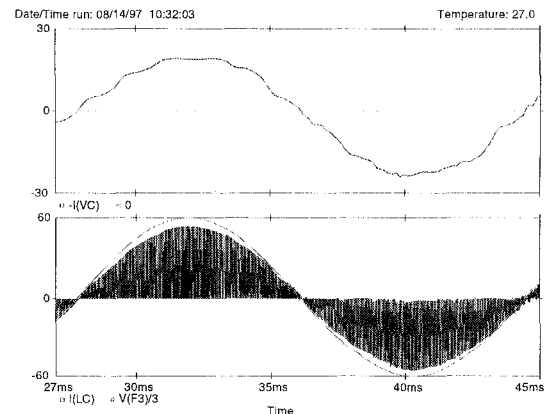


Fig. 4. Simulation results for the high frequency LIT-based scheme.

the duty cycle of the switches, in the pulse width modulation circuit, the power flow is regulated.

The most important analytical results, besides the equation (3) above and disregarding the leakage inductance, are the following:

- static gain (or voltage ratio) in CCM:

$$q = \frac{V_o'}{V_{in}} = \frac{1}{1-D} \quad (4)$$

- static gain (or voltage ratio) in DCM:

$$q = \frac{V_o'}{V_{in}} = \frac{1}{2} \left[1 + \sqrt{1 + \frac{4 \cdot D^2}{L_{eq} \cdot f}} \right] \quad (5)$$

$$\sqrt{1 + \frac{R_o \cdot (n/2)^2}{L_{eq} \cdot f}}$$

where $V_o' = \frac{n}{2} V_o$, is the half of the output voltage referred to

the primary, L_{eq} is the equivalent input inductance, f is the switching frequency, R_o is the load resistor and D is the duty ratio (defined as the simultaneous ON time of the power switches, S_1 and S_2).

The theoretical high frequency waveforms of the DIC converter, in DCM, are shown in Fig. 6 as simulation results. In this figure one can see the duty cycle "D" which is defined (for the sake of comparison with the basic Boost) as the simultaneous ON-time of the power switches over half the switching period. "I_L" stands for the line current, which is also the current through any input inductor. The auxiliary drive signals are shown in lower amplitude and are complementary to the correspondent main drive signal.

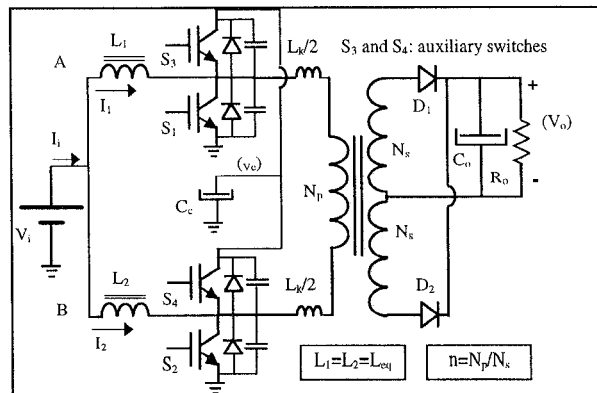


Fig. 5 - Current-sourced push-pull converter.

The current-sourced converter is operated in DCM so that the LIT makes use of the high switching frequency of the converter and the line current results with high power factor. In continuous conduction mode the LIT does not make use of the high frequency and should be designed under the low line frequency resulting in much bigger size. Only in this case the high power factor would be guaranteed.

Due to the presence of an inevitable leakage inductance (L_k) in the primary of the output transformer, the use of the so called *active clamping* [18] is recommended with very good results, having as a consequence (with the use of switching capacitors in parallel with the switches) the soft switching of the power and auxiliary switches. The clamping circuit consists of the clamping capacitor (C_c) and the auxiliary switches (S_3 and S_4), and the switching capacitors (C_{1-4}) cause the soft switching to happen with the help of the leakage inductor's current.

C. The Proposed Topology

The proposed topology consists of three input inductors, the LIT and the ZVS-PWM, clamped mode DC-DC

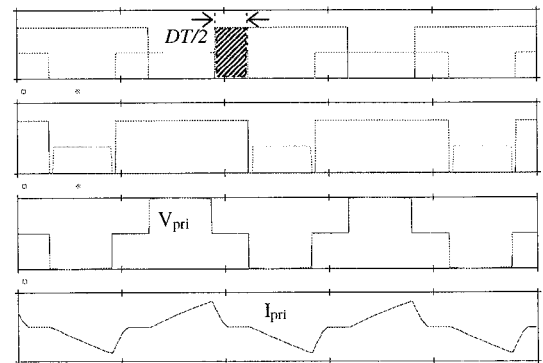


Fig. 6. Main high frequency waveforms.

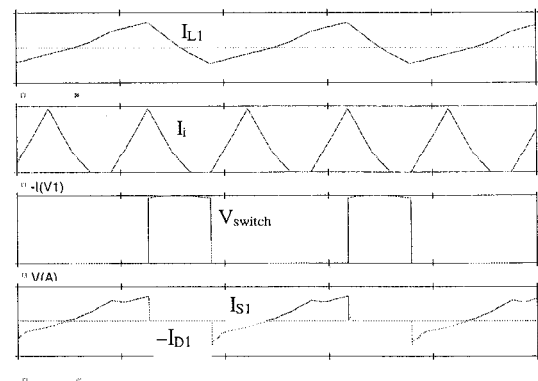


Fig. 7. Main high frequency waveforms.

converter, according to Fig. 8. The design is made in such a way that the three input inductors are put in discontinuous conduction mode. When both power devices are simultaneously ON those inductors are short circuited and their current follow the applied phase voltage. When either switch is turned OFF the energy stored in the inductors is transferred to the load via the LIT, together with its diode bridges, the clamping circuit, the output transformer and one output rectifier. The duty cycle (D) of the DIC converter is the power flow control variable.

Due to the discontinuous operation of the converter, the resulting line current will be proportional to the phase voltage during the simultaneous ON-time of the power switches. The line current waveform will then tend to be close to a sinusoidal one, and in phase with the phase voltage.

III. SIMULATION RESULTS

Based upon the analytical equations and the design considerations above, the proposed power supply was designed and simulated, with the following specifications: rated output of 6kW (60V/100A), line voltage of 220V/60Hz (line-to-line), switching frequency of 26kHz. The main parameters are: $L=12\mu\text{H}$, $D=0,16$, $L_k=75\mu\text{H}$, $R_o=0,6\Omega$, $V_o=60\text{V}$. Some main waveforms are shown in figures 9 and 10.

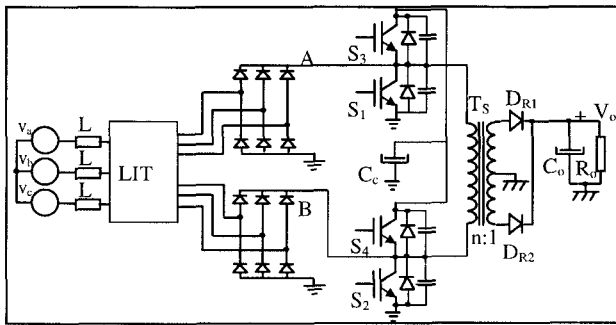


Fig. 8. High frequency, High power factor, 3φ power supply.

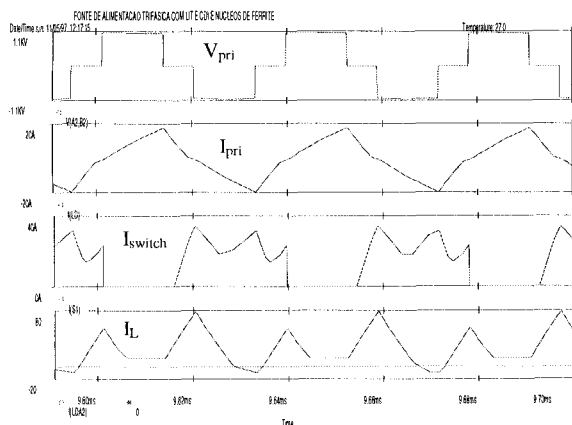


Fig. 9. High frequency simulation results: (from the top) V_{pri} , I_{pri} , I_{switch} , I_L .

IV. EXPERIMENTAL RESULTS

The experimental results provided below correspond to a prototype not yet implemented for the rated power, due to some problems in the availability of the specified diodes for the diode bridges in the output of the LIT, and also due to some practical problems (unbalanced line voltages, lack of a good AC voltage variator, construction of the LIT and so one). Up to the moment this paper is concluded, just a 1kW prototype could work. But it worked properly and confirmed the main expectations derived from the theoretical analysis and simulations.

The laboratory assembly implemented the circuit of Fig. 8 where the main drive signals have been generated by a 3527 IC-based circuit and the auxiliary drive signals have been obtained by the simple inversion of the main ones. The part number of the IGBTs used have been the SK 75 123 D (75A/1200V with integrated body diode) with their correspondent drives (SKHI 23). The switching frequency was varied between 23kHz and 26kHz, being fixed, eventually, at 23kHz. The line voltage was fixed at 120V and the output reached 51V at 20A with duty ratio of 16%.

The main waveforms, presenting a high power factor, although in a light load, are shown in figures 11 to 14.

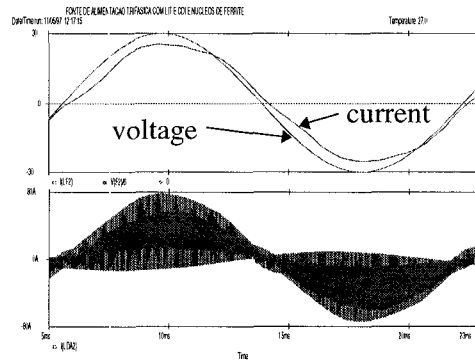


Fig. 10. Low frequency: input inductor current (bottom); Line current and phase voltage (divided by 6) with high power factor (top).

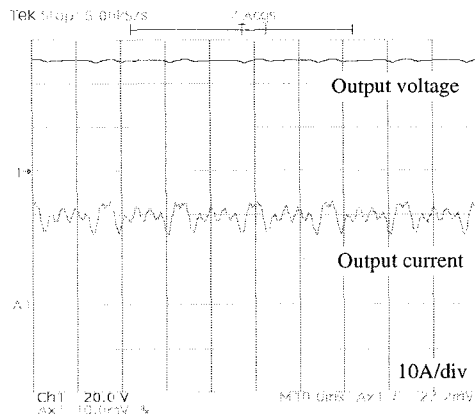


Fig. 11. Output voltage and current for 1kW.

These preliminary results can already show that the proposed LIT-based, high frequency, 3 ϕ power supply works in the manner it has been conceived and can constitute a suited solution for a single stage, high power factor power supply. The resulting power factor, even for this light load, points to a better result for higher load and with global improvements in the prototype.

The clamping circuit worked properly and clamped the voltage within the expected level (see Fig. 15) although an expression for this clamping voltage is still under research.

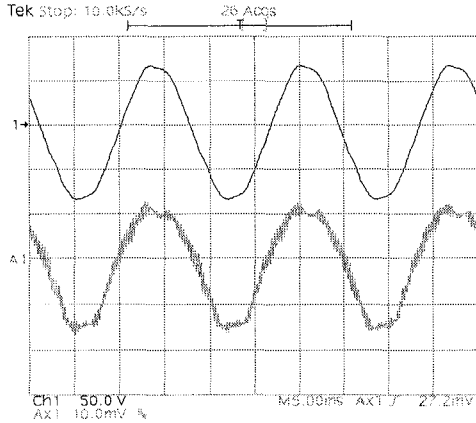


Fig. 12. Phase voltage (top) and switched inductor current (in the High Resolution of the oscilloscope).

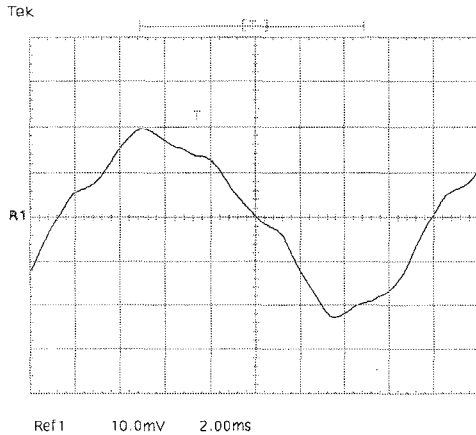


Fig. 13. Line input current (HF filtered): THD=18% and power factor=0.977 (light load).

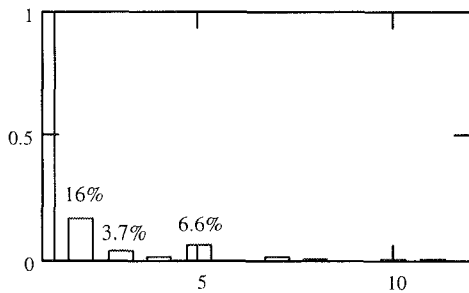


Fig. 14. Fourier analysis of the filtered line current for light load.

The diodes of the rectifying bridges in the output of the LIT should be fast and rated for high voltage, since one of the features of the proposed converter is that it stresses the LIT and its diode bridges with high voltage levels (~1kV). The saturation of the windings of the LIT is then likely to happen if a proper design is not well accomplished. The ZVS of all the switches took place accordingly, what is a very desired feature since the DCM stresses these switches with high peak current levels.

V. CONCLUSIONS

A new scheme of a single stage, high power factor, isolated, three-phase power supply with output of 60V/100A has been presented which makes use of a special kind of autotransformer, named line interphase transformer (LIT). The isolation is achieved by means of a current-sourced DC-DC converter switched at a high frequency, with just two power switches. This high frequency allows the interphase transformer to use ferrite cores, hence its volume results smaller than if it were operated under the low line frequency.

The use of the active clamping, with the addition of two more auxiliary IGBTs and a clamping capacitor, is mandatory to effectively clamp the overvoltage that arises from the leakage inductance during the turn off of either power switch. The use of small commutation capacitors in parallel with each IGBT causes the converter to operate under zero voltage switching, improving the whole efficiency. Simulation and experimentation verified the analytical results. The topology seems to be very robust because it uses just two power devices and a passive power factor corrector circuit, which is accomplished by the LIT. Due to these features, such an architecture seems to be well fitted for telecommunications loads.

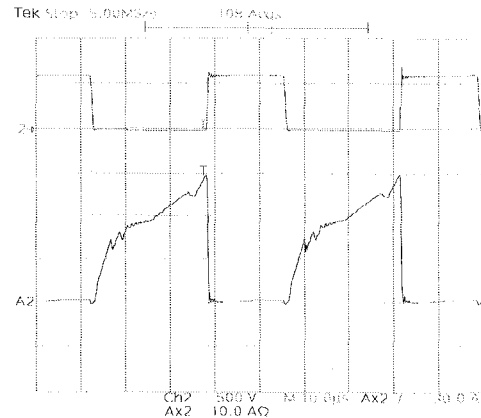


Fig. 15. Voltage across and current through the main switch.

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REFERENCES

- [1] A. R. Prasad, P. D. Ziogas and S. Manias. "An Active Power Factor Correction Technique For Three Phase Diode Rectifiers," in *Conference Record IEEE PESC*. 1989. pp. 58-65.
- [2] E. Ismail and R. W. Erickson. "A Single Transistor Three Phase Resonant Switch for High Quality Rectification," in *Conference Record IEEE PESC*. 1992. pp. 1341-1351.
- [3] J. Pffor and L. Hobson. "A Novel Power Factor Corrected Single Ended Resonant Converter with Three Phase Supply," in *Conference Record IEEE PESC*. 1992. pp. 1369-1375.
- [4] E. L. M. Mehl and Ivo Barbi. "An Improved High Power Factor and Low Cost Three-Phase Rectifier," in *Conference Record IEEE APEC*. 1995. pp. 835-84.
- [5] D. Gauger et al. "A Three phase Off Line Switching Power Supply with Unity Power Factor and Low TIF," in *INTELEC Rec*. 1986. pp. 115-121.
- [6] Elias S. de Andrade. "High Power Factor, Three Phase, Series Resonant, Isolated Battery Charger with Resonant Capacitor Voltage Clamping," M. Sc. dissertation (in Portuguese), Institute of Power Electronics (INEP), Federal University of Santa Catarina (UFSC), Brazil. November, 1994.
- [7] E. L. M. Mehl, Ivo Barbi. "An Improved High Power Factor and Low Cost Three-Phase Rectifier," *Proceedings of APEC*. 1995. pp. 835 - 841.
- [8] A. R. Prasad, et al. "An Active Power Factor Correction Technique for Three-Phase Diode Rectifiers." *Proceedings of PESC*. 1989. pp. 58 - 66. in *Transactions on Power Electronics*. vol. 6, n° 1, January 1991. pp. 83 - 92.
- [9] E. Ismail, R. W. Erickson. "A Single Transistor Three Phase Resonant Switch for High Quality Rectification," *Proceedings of PESC*. 1992. pp. 1341 - 1351.
- [10] J. Pffor, L. Hobson. "A Novel Power Factor Corrected Single Ended Resonant Converter with Three Phase Supply". *Proceedings of PESC*. 1992. pp. 1369 - 1375.
- [11] V. Vlatkovic, D. Borjevic, X. Zhuang and F. Lee. "Analysis and Design of a Zero-Voltage Switched, Three-Phase PWM Rectifier with Power Factor Correction," in *Conf. Record IEEE PESC*. 1992. pp. 1352-1360.
- [12] P. Prestifilippo, R. Sibilia, G. Baggione and G. Caramazza. "Switched-Mode Three-Phase 200A/48V Rectifier with Input Unit Power Factor," in *Proc. of INTELEC*. 1996. pp. 543-547.
- [13] M. Depenbrock; ABB AG (1988). "Leistungseinspeisung mit Saugdrossel." (Power Supply with a Special Filtering Transformer.) Patentanmeldung p.38 26 524.9 vom 4/08/88 beim Deutschen Patentamt.
- [14] Clemens Niermann. "New Rectifier circuits with Low Mains Pollution and Additional Low Cost Inverter for Energy Recovery," in *Proceedings of EPE'1989*, pp. 1131 - 1136.
- [15] Carlos A. Muñoz B. and Ivo Barbi. "A New High Power Factor Three-Phase Diode Rectifier," in *Proceedings of IECON*. 1995. pp. 451-456.
- [16] Wilson C. P. de Aragão Filho and Ivo Barbi. "Design Oriented Analysis of The High Power Factor Three-Phase Rectifier with Line Interphase Transformer in Discontinuous Current Mode," in *Proc. of COBEP* (Brazilian Power Electronics Conference), Belo Horizonte - MG, Brazil. unpublished.
- [17] Peter J. Wolfs. "A Current-Sourced DC-DC Converter Derived via the Duality Principle from the Half-Bridge Converter," *IEEE Transactions on Industrial Electronics*. vol. 40, no 1, February 1993.
- [18] Cláudio M. C. Duarte and Ivo Barbi. "A Family of ZVS-PWM Active Clamping DC-to-DC Converters: Synthesis, Analysis and Experimentation," *Proceedings of INTELEC*. 1995. pp. 502-509.