MULTIFUNCTIONAL, THREE-PHASE, FOUR WIRE, AC-DC BOOST CONVERTER FOR UPS APPLICATIONS

LUIZ D. S. BEZERRA[1], R. P. TORRICO-BASCOPÉ[2], AND CÍCERO M. T. CRUZ[2]

1. *IFCE – Instituto Federal de Educação Ciência e Tecnologia do Ceará, Campus Maracanáu. Instituto Federal de Educação, Ciências e Tecnologia – IFCE, Campus Maracanaú, Av. Parque Central, S/N - Distrito Industrial I, Maracanaú - CEARÁ - Brasil, CEP: 61939-140*
E-mails: 1. danielbezerra@ifce.edu.br

2. *UFC – Universidade Federal do Ceará, LCE – Laboratório de Condicionadores de Energia, Depto. de Engenharia Elétrica.*
Departamento de Engenharia Elétrica, Centro de Tecnologia, Universidade Federal do Ceará, Caixa Postal 6001 - Campus do Pici, CEP: 60.455-760 Fortaleza - CE
E-mails: 2. rene@dee.ufc.br, cicero@dee.ufc.br

Abstract— This paper presents control strategy for multifunctional, three-phase, four wire AC-DC converters. The converter is named multifunctional because it operates as a battery charger and as a load power supplier. In other words, two different loads in parallel are connected simultaneously to the converter. For this purpose some current and voltage signals are necessary to send to the control circuit. The indicated signals are, input main currents, output load currents, battery bank currents, voltage across of each battery bank, total output voltage, and input main voltages for feed-forward networks and current shape. The proposed converter control strategy is applied in non-isolated three-phase UPS systems. The relevant features of the proposed converter control strategy are, power factor correction, common neutral point between input and output to facilitate bypass circuit installation, symmetrical divided output voltage for inverters with neutral point, and battery current control with high power factor. Principle of operation of the control circuit and experimental results obtained from a small power scale prototype are presented.

Keywords— AC-DC rectifier control, three-phase AC-DC converter, three-phase battery charger, non-linear rectifier control.

Resumo— Este trabalho apresenta uma estratégia de controle para conversor a quatro fios, trifásico, com característica multifuncional. O conversor é considerado multifuncional devido à operação como carregador de baterias e fonte de energia para a carga. Em outras palavras, duas cargas em paralelo são conectadas de forma simultânea ao conversor. Para possibilitar o controle adequado, é necessário obter amostras de corrente e tensão e enviá-los ao circuito de controle. Os sinais amostrados são: correntes de entrada, corrente através das cargas, correntes através dos bancos de baterias, tensão sobre cada banco de baterias, tensão total e tensão da rede elétrica para as malhas de *feed*-forward e conseguir o formato senoidal da corrente de entrada. A estratégia proposta para o conversor é aplicada em sistemas de UPS trifásicos. Os principais aspectos da estratégia proposta são: correção do fator de potência, neutro comum entre a rede elétrica e a saída do retificador, o que facilita a instalação do circuito de *bypass*, tensões simétricas de saída para inversores com neutro e controle de corrente de carga e das baterias. São apresentados no artigo, o princípio de operação do circuito de controle e resultados experimentais obtidos desde um protótipo de pequena escala de potência.

Palavras-chave— Controle de Retificador CA-CC, Conversor trifásico CA-CC, Carregador de Baterias Trifásico, Controle não Linear de Retificadores.

INTRODUCTION

According to the Brazilian Standard NBR 15014 (2003), UPS (Uninterruptible Power Supplies) are classified in three main categories: on-line or double conversion, where the load is continuously supplied by the rectifier and inverter, thus performing a dual power conversion (AC-to-DC and DC-to-AC); line interactive, and off-line or stand-by.

In the on-line UPS, the output voltage frequency is independent of the input voltage frequency due to DC voltage bus. On the other hand, in the line interactive UPS and off-line UPS, the output voltage it has the same frequency of the input voltage. During grid mode operation, the line interactive UPS presents output voltage regulation, and the standby UPS it not has output voltage regulation. The figures below show these structures defined by the Standard. As shown the three figures, they all require a separated battery charger converter, which can be isolated or not isolated.

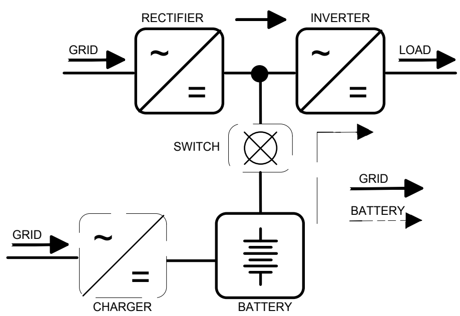

Figure 1 – Double conversion UPS system, NBR 15014 (2003).

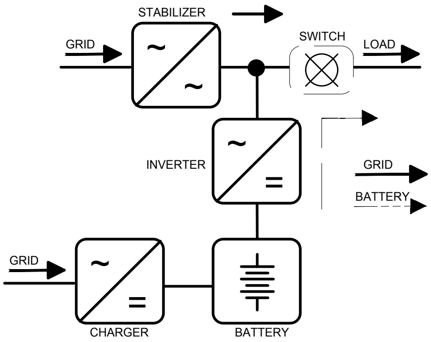

Figure 2 – Interactive UPS system as defined, NBR 15014 (2003).

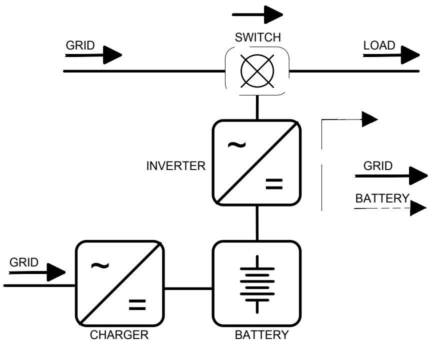

Figure 3 – Standby UPS as defined, NBR 15014 (2003).

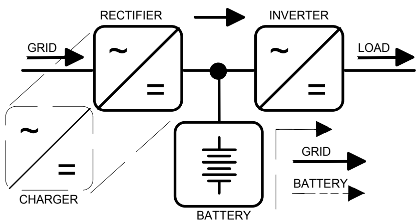

Figure 4 - Re-definition proposed to the double conversion UPS system.

This paper presents a modification of double conversion UPS shown in Figure 1. The battery charger converter is incorporated to the rectifier, so, the battery charger converter is eliminated. For this purpose the rectifier or AC-to-DC converter fulfills the functions of battery charger and load supplier. The batteries are charged with constant current, and also the voltage across the terminal is controlled. Other characteristics of the rectifier is its power factor correction, this re-definition is shown in Figure 4. The four-wire connection simplifies the bypass circuit connection because the neutral wire is common between the input, and the output.

Analysis, design, and control of a three-leg converter with split dc bus was studied by, Lo, Y. K. (2002), Jiang, S. (2011), Ghosh, R. (2008), which can be used as a four-wire front-end converter in three-phase transformerless line conditioner and UPS applications, such as realized by, Lo, Y. K. (1995), working as battery charger, whose function is incorporated in the proposed control strategy, thus describing a multifunctional converter, which poses two functionalities: as charger and as line conditioner.

II. MULTIFUNCTIONAL CONVERTER

Control techniques have been reported for three-phase ac–dc converters which was studied by, Escobar, G. (2011), Wen, J. (2006), and Batista, F. A. B. (2006). Most of them require complex transformations, PLL, and a number of voltage and current sensors. As a resulted, the associated control scheme becomes complex and its implementation requires large computational work as shows, Ghosh, R. (2008).

Addressing the above issues, the indirect current control scheme has been reported for three-wire rectifier, single-phase, and half-bridge rectifier, Ghosh, R. (2008), which do not require input voltage sensing. Various issues such as balancing the two halves of the DC bus and maintaining low neutral current were addressed by, Greul, R. (2007), Singh, B. (2004), and Ghosh, R. (2008).

The control schemes presented in Lo, Y. K. (1995), and Jiang, S., (2011), it uses a conventional sine-triangle PWM (CSPWM) scheme to generate the gating pulses for the converter switches. The three sinusoidal voltage references are compared with a common high-frequency triangular carrier. It is shown that the above PWM scheme results in a peak-to-peak neutral current ripple greater than the peak-to-peak ripple in the line currents.

A common important feature is the power factor correction and the reduced voltage stress across the active semiconductors. Such features can be achieved by using suitable topologies and control techniques, Ghosh, R. (2008).

The concept proposed in Figure 5 presents the advantage of only two required battery banks and reduced amount of power processing devices. The three-phase four wire block can be replaced by any kind of converter, even multi-level converters, with proper circuit modifications. However, in this case the battery bank is non-isolated from the load and from the main, this could be a drawback when a fault occurs in the semiconductors of the power stage, and as a result a DC voltage is applied to the load.

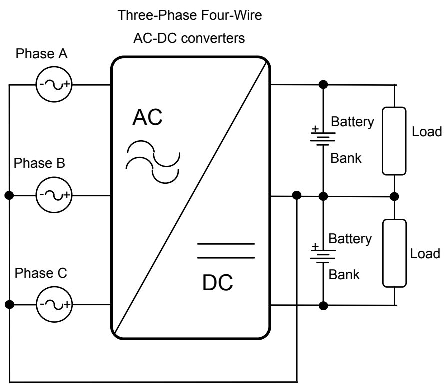

Figure 5 - Simplified block diagram of a multifunctional three-phase four-wire AC-DC converter feeding two loads simultaneously.

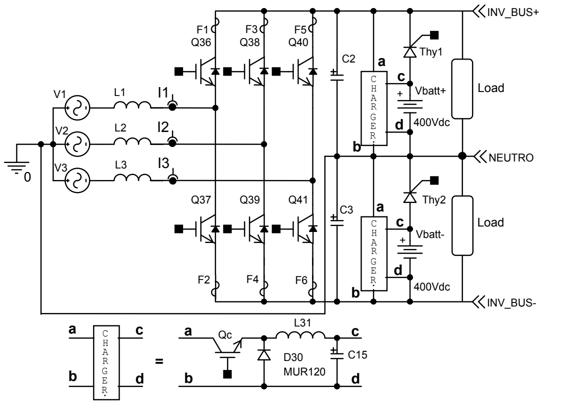

Figure 6 - Two level three-phase rectifier with four wire connection, Buck battery charger is used, presenting the main protections necessary for safe operation.

The second concept shown in Figure 6 presents a two-level bidirectional rectifier working as AC-to-DC stage. However, the efficiency is compromised in the battery powered mode, due to two semiconductors in series with the batteries. In this concept were adopted two-isolated battery chargers. The main advantage of the first concept is its simple connection, and battery banks protection.

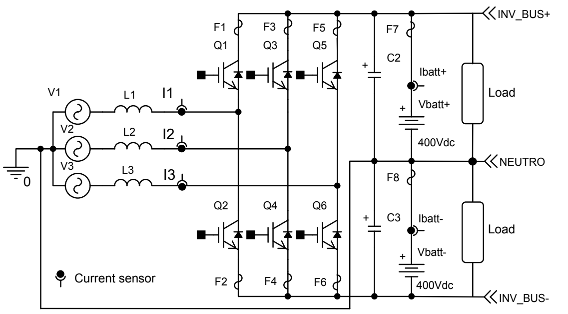

Figure 7 - Proposed multifunction two-level three-phase rectifier with four-wire connection that feeds directly batteries and loads, presenting the main protections necessary for safe operation.

The Figure 6 shows a classic structure of three-phase rectifier with batteries connected indirectly to the DC bus through a thyristors. In Figure 7, is shown the proposed configuration in which the batteries are directly connected to the DC bus. This structure differs from conventional structure because the batteries are directly connected to DC bus, without the need for auxiliary thyristors in series with the batteries.

Thus, comparing both topologies it could be concluded that the first block diagram shown in Figure 5 corresponds to Figure 7. The same presents more advantages than the second one.

III. CONTROL STRATEGY

Once the batteries are configured as shown in Figure 7, it is mandatory the use of additional protections for IGBT modules to avoid improper operation during false triggering of the switches.

A classical approach proposed for controlling the three-phase rectifier suggested by, Jiang, S., (2011), is shown in Figure 8, in which the control loops are: $C_I(s)$ current controller per phase, ($V_{BUS\text{-}sum}$) total bus voltage loop sample, $C_V(s)$ voltage loop controller, ($V_{BUSdiff}$) differential voltage loop controller, and $C_D(s)$ unbalance voltage loop controller. This strategy usually employs PI or PID controllers, whose characteristic is the reduced computational effort and whose tuning is already well established in technical literature.

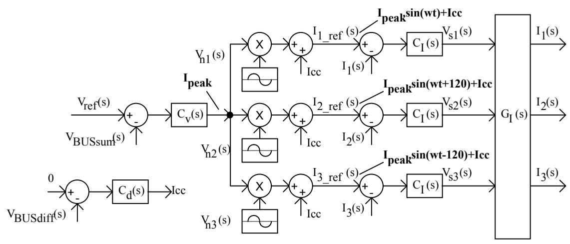

Figure 8 - Classical control methods of high power factor control for three-phase rectifiers.

The four wire controlled rectifier allows the simplification of bypass operation and unbalanced loads connected to the DC bus. Also there's a possibility for connection of three phase inverters with neutral point. Thus it is necessary to control the DC bus voltage (unbalance) for different loads condition.

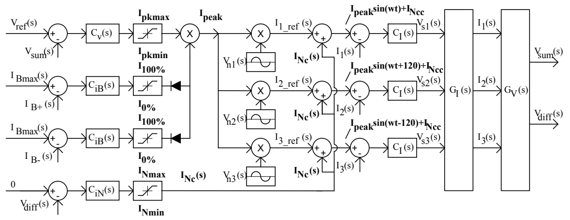

Figure 9 - Proposed control block diagram of the three-phase, four-wire rectifier. The control loop monitors the input current, the current through the battery and the voltage on each battery.

Thus, a modification to the classic strategy is shown in Figure 9, which meshes auxiliary circuits employing non-linear change the peak value of the output reference voltage loop are proposed. This modification allows the change of the peak value of the current flowing through the main by modifying the power that is delivered to the battery and the load.

IV. MATHEMATICAL MODELS

Figure 10 shows the main waveforms for some switching periods of the single phase two level converter. These waveforms are allowed once the mains voltage has an operating frequency much lower than the switching $\omega_{grid} << \omega_s$

A) Single-Phase Time Domain Analysis

For time domain analysis is considered, the ideal switches, ideal capacitors, and is analyzed for continuous conduction mode (CCM), since the current through the inductor is non zero during the switching period.

The nomenclature used for analysis of the rectifier shown in Figure 10.

V^+, Vbatt+, V^-, Vbatt-, INV_BUS+, INV_BUS-, voltage from batteries and buses;

$I_{1,2,3}$, IBatt+, IBatt- phase and batteries currents;

$v_{x0}(t)$ instantaneous voltage between the central switch terminal and neutral;

$V_{x0}(t)$ average voltage for each switching period;

D(t), D'(t), average duty cycle and its complement;

Ia, Ip, Ic: average currents through active, passive, and common terminal, respectively.

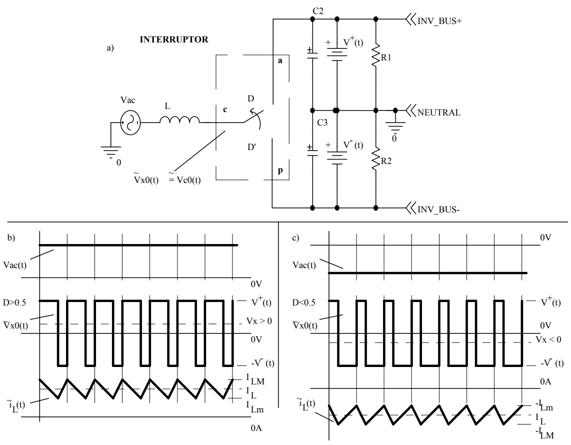

Figure 10 - Two level converter, a) ideal switch model, b) and c) main waveforms to grid voltages Vac>0 and Vac<0.

The average voltage in a switching period is expressed in (1). This equation correspond to the average value of switch model depends on each bus voltage, duty cycle, and its complement, in continuous conduction mode of the converter. Such averaged switch model looks like a controlled voltage source, as shown in Figure 11.

$$V_{x0}(t)=\langle v_{x0}(t)\rangle_{Ts}= \frac{1}{T_s}\int_t^{t+T_s} v_{x0}(\tau)d\tau = D(t)\cdot V^+ - D'(t)\cdot V^- \quad (1)$$

B) Single-Phase Static Model

A simplified model for feature extraction of the transfer functions of the converter can be analyzed as proposed in Mohan, N. (1995), Rashid, M. H. (2001), Barbi, I. (2012), Erickson, R. W. (2000), Borgonovo, D. (2005), Batista, F. A. B. (2006). Such analysis yields the instantaneous averaged value of electrical model for a single phase converter is shown in Figure 11.

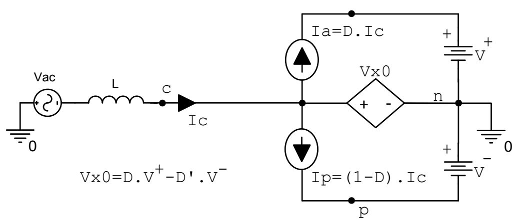

Figure 11 - Simplified single-phase model for operation in continuous conduction mode of the two-level converter.

Using the derived switch model in Figure 11, the currents through the active terminal (Ia) and passive terminal (Ip) ports necessarily depend on the current flowing through the common terminal (Ic), and whose value is equal to that flowing through the L inductor and given by (2).

$$i_L(t)=\frac{1}{L}\int_t^{t+T_s}\left[V_{ac}(\tau)-V_{x0}(\tau)\right]d\tau + i_L(0) \quad (2)$$

The active (Ia) and passive (Ip) terminal currents may be partially divided to the load and the battery, so that a current controller can imposes a controlled charging of the batteries, also providing the regulation of the DC bus voltage with proper methodology.

C) Three-Phase Static Model

The Figure 12 shows the complete model of the three-phase rectifier, considering the instantaneous averaged values as PWM switch model, with batteries modeled as DC voltage sources and the load being omitted, Lin, B. R. (2004). The static single phase model can be extended to three-phase model and is presented by (3) and (4), in which each averaged PWM switch is shown as controlled voltage sources and its value is represented as the difference between the positive bus voltage multiplied by the corresponding phase duty cycle and negative bus voltage multiplied by complementary phase duty cycle. In steady state, the variation of the current term given by (4), shall be null, otherwise the current through the inductor tends to grow indefinitely. The current controller imposes small variations in the phase duty cycle, resulting in successive increments of the integral term, thus enabling the proper shaping of current through the phase.

$$Vx_{r,s,t,0}(t)=\langle Vx_{r,s,t,0}(t)\rangle_{Ts}= = D_{r,s,t}(t)\cdot V^+ - D_{r,s,t}'(t)\cdot V^- \quad (3)$$

$$i_{Lr,s,t}(t)=\frac{1}{L}\int_t^{t+T_s}\left[V_{r,s,t}(\tau)-Vx_{r,s,t0}(\tau)\right]d\tau + i_{Lr,s,t}(0) \quad (4)$$

$$P_{IN}(t)=\frac{3}{2}V_P\cdot I_P+0 \therefore P_{out}=V_{sum}(t)\cdot I_o(t)=\eta\cdot P_{IN}(t) \quad (5)$$

$$P_{IN}(t)=I_P(t)\cdot\frac{3}{2}V_P \therefore \quad (6)$$

$$I_o(t)=\eta\cdot I_P(t)\cdot\frac{3}{2}\frac{V_P}{V_{sum}}=I_b(t)+I_{load}(t) \quad (7)$$

The current through the batteries are the result of the sum of the average current available from each rectifier stage minus the current delivered to the load. Considering the balance of energy absorbed from the grid and delivered to the load and battery, it is shown that output current - $I_O(t)$ - (5) is obtained from the relation between the time-variant peak main current ($I_P(t)$ - value that is adjusted by loop voltage controller), main peak voltage (V_P (t) - variant due to the grid itself), with the sum of bus voltages (V_{SUM} (t)) and the total current delivered to the load and the batteries ($I_O(t)$), Borgonovo, D. (2005), Batista, F. A. B. (2006).

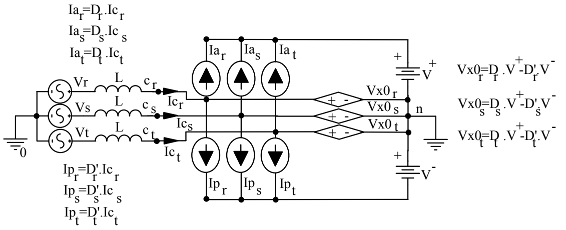

Figure 12 - Three-phase simplified model for continuous conduction mode considering the complete model of the rectifier.

A change is proposed to the classic power factor correction controller (Figure 9), so that current flowing through the load and battery is controlled by changing the peak current flowing from the main with the appropriate format, ensuring a proper current quality, high power factor and low total harmonic distortion THD_i.

The proposed controller employs the following loops:

• Current loop for phases 1, 2 and 3, ensuring the sinusoidal current format flowing through power main;

• Differential voltage loop to ensure the balance of bus voltages V^+ and V^-;

• Total voltage loop to ensure proper regulation of voltages V^+ and V^-;

• Current loop through the battery connected to the positive and negative DC bus, enabling limitation of the charging current.

This methodology can also be extended to single-phase systems and can be used in DQ reference frame based rectifiers.

D) Single Phase Dynamic Model

By analyzing the large signal model shown in Figure 11, main transfer functions for control and stability analysis of the converter are extracted (8)-(16).

$$\begin{aligned} Z_{in} &= \frac{\hat{v}_{ac}}{\hat{i}_c} = sL + \left(1-2D_{static}\right)\cdot\left(r_{se} \parallel Z_o\right) \\ &= sL + \left(D'_{static} - D_{static}\right)\cdot\left[r_{se} \parallel \left(R_o \parallel \frac{1}{sC_o}\right)\right] \\ &= sL + \left(D'_{static} - D_{static}\right)\cdot\frac{R_o}{1+\frac{R_o}{r_{se}} + s\cdot C_o\cdot R_o} \end{aligned} \qquad (8)$$

The value of r_{se} is the equivalent series resistance of the battery in parallel with the capacitor equivalent series resistance.

$$\begin{aligned} G_{iLd} &= \frac{\hat{i}_L}{\hat{d}} = -\frac{R_o}{r_{se}+R_o}\frac{V_o^+ + V_o^-}{sL+\left(1-2D_{estático}\right)\cdot\left(r_{se} \parallel R_o\right)} \\ &= -\frac{R_o}{L\left(r_{se}+R_o\right)}\frac{V_o^+ + V_o^-}{s+\left(D'_{estático} - D_{estático}\right)\cdot\frac{r_{se}\cdot R_o}{L\left(r_{se}+R_o\right)}} \end{aligned} \qquad (9)$$

The transfer function relating the current through the inductor and duty cycle is presented in (9). Such expression is necessary for the proper design of current controller loop.

$$G_{v_o^+\_i_L}\Big|_{\substack{v_o^-=0\\ d=0}} = \frac{v_o^+}{i_L} = \frac{sL}{D_{estático}} + R_o\frac{D_{estático}}{1+sR_o\cdot C_o} \qquad (10)$$

$$G_{Vo^-\_i_L}\Big|_{\substack{v_o^+=0\\ d=0}} = \frac{v_o^-}{i_L} = -\frac{sL}{D'_{estático}} - R_o\frac{D'_{estático}+1}{1+sR_o\cdot C_o} \qquad (11)$$

In (10) the transfer function relating the output voltage and current through the inductor, essential function to calculate and project the bus voltage loop controller.

E) Model for Multifunctional Three-Phase Four Wire Converter

For analysis of the dynamic model, the output power stage is shown in Figure 13, which has capacitors, batteries, and loads, connected respectively to the positive and negative DC bus of the rectifier power stage.

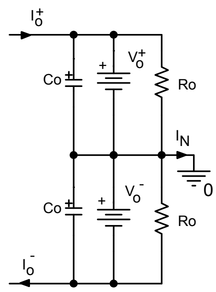

Figure 13 - Schematic diagram of voltages and currents at the load and battery, considering the unbalanced voltages V_0^+ e V_0^-.

Consider the decomposition of the currents I_o^+ and I_o^-, as described in the expressions (12)-(14). Applying the corresponding Laplace transform, it is possible to obtain the transfer function that relates those currents and voltages (15)-(16).

$$I_o^+(t) = I_o^-(t) + I_N(t) \qquad (12)$$

$$\begin{cases} I_o^+(t) = I_{Co}^+(t) + I_{Ro}^+(t) = C\dfrac{dV_o^+(t)}{dt} + \dfrac{V_o^+(t)}{R_O} & (13) \\ I_o^-(t) = I_{Co}^-(t) + I_{Ro}^-(t) = C\dfrac{dV_o^-(t)}{dt} + \dfrac{V_o^-(t)}{R_O} & (14) \end{cases}$$

$$\frac{V_{diff}(s)}{I_N(s)} = \frac{R_O}{1+sCR_O} \qquad (15)$$

$$\frac{V_{sum}(s)}{I_P(s)} = \eta\cdot 3\frac{V_P}{V_{sum}}\cdot\frac{R_O}{1+s\cdot R_O\cdot C} \qquad (16)$$

Thus, it is possible to obtain expressions for the dynamic differential voltages, and the total voltage of the bus, which assist in the design of controllers (15)-(16).

V. SIMULATION RESULTS

The system incorporating the methodology proposed in this paper is simulated in PSIM environment, shown in Figure 14. Grid-currents, battery voltages and currents, can be seen in Figure 15, during a 1,5 seconds charging process. Detailed view of those can be seen in Figure 16.

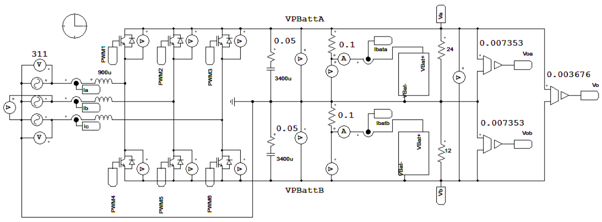

Figure 14 - Employed simulation circuit of two level three-phase rectifier with output power of 30kW.

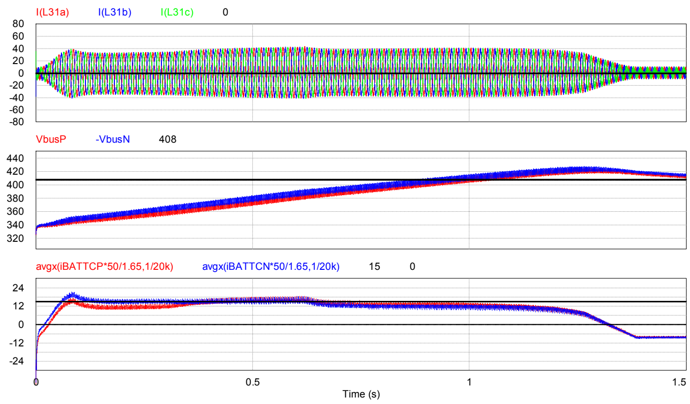

Figure 15 - Simulation results for an output power of 30kW, showing the charging process (current through both battery banks), the upper graph shows the current per each phase of the rectifier.

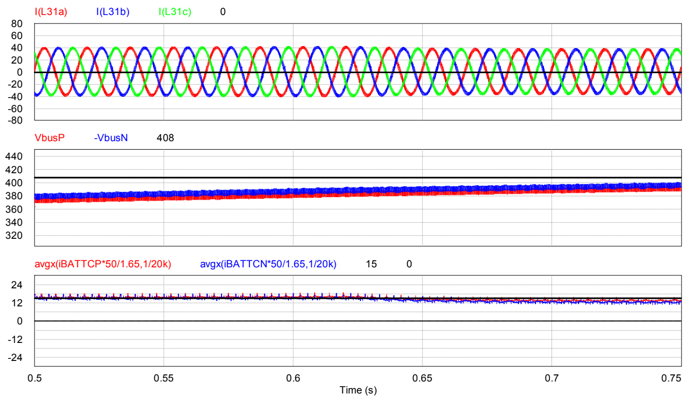

Figure 16 - Detailed simulation results of 30kW output power, showing the charging process, the upper graph shows the current per each phase of the rectifier, the middle shows the battery voltage, and the lower graph shows the averaged charging battery currents.

VI. EXPERIMENTAL RESULTS

Experimental results of the proposed control technique are presented. The prototype was designed for small-scale power (150W) employed for validation of the technique. All data were obtained from a DSO-2014A-X oscilloscope with current probe FLUKE 80i-110S. The files were obtained in CSV format, and converted to images via MATHCAD © for viewing. The Figure 17 exhibits the three-phase voltages and one phase current, it shows an improved current quality, reduced harmonic content and high power factor (PF> 0.98), at nominal converter power, balanced loads and charged batteries. Table I shows the data of the small-power-scale experimental prototype employed to validate the proposed technique. The total power output of small-scale prototype is 150W with 12V batteries, 7Ah, and totaling two buses of +/-24Vdc.

TABLE I - Experimental components for small-scale prototype

Power Rectifier main components			
Item	**Number**	**Kind / Value**	**Observations**
$L_{r,s,t}$	900uH	Input inductances	-
$S_{1,2,3,4,5,6}$	IGBTs + Drivers	600V / 10A	IRAMS10UP60B
$C_{1,2}$	6 x 2200uF / 100V for each bus	Epcos	-
$B_{1,2}$	Lead Acid 12V, 7Ah	2x 12V battery for each bus	-
$R_{1,2}$	2.6 Ohm/75W, by Load	Load	Total output power is 150W
$T_{1,2,3}$	Input transformers	$220V_{RMS}/12V_{RMS}$	48W each, $4A_{RMS}$

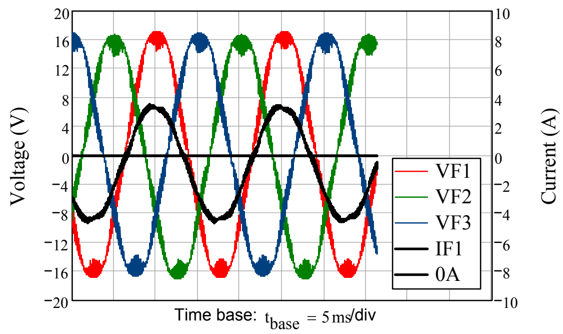

Figure 17 – Input voltages of the phases 1, 2, 3, and current through phase 1. The waveforms correspond to full power, balanced loads, and charged batteries.

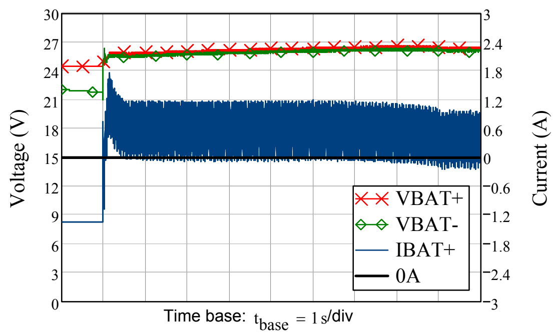

Figure 18 - DC bus voltages under load with battery average current limited at 0.7 A. During the floating voltage condition there's a reduction on the averaged battery current.

The result of the entire charging process (constant-current and constant-voltage) is shown in Figure 18. The averaged battery current drops after 8 seconds, as the controller changes to the constant-voltage (CV) charging mode. Before the CV charging mode, the averaged battery current remains at aprox. 0.7A, performing a constant-current charging mode.

VII. CONCLUSION

This paper proposes a control technique of two-level three-phase rectifier, which is easily extensible to other three-phase rectifier topologies, aiming the charger stage removal and incorporate its functionality on the control loops. This proposal also ensures the basic operations of the three-phase rectifier:

- High power factor, even during charging of the batteries;
- Charge the battery in case of full load and no load connected on the bus, even with minimum and maximum mains voltage condition;
- Method of charging batteries by limiting the averaged current flowing through them;
- Process of bus voltage equalization through the use of unbalanced loop controls;
- Process of total bus voltage stabilization through the use of proper loop control;
- Limitation of the absorbed main power, by limiting the current drawn from the grid, in order to protect the power semiconductor;

A small-power-scale prototype was built to verify the proposed control methodology. The author belive this strategy can be incorporated in medium and large scale UPS systems, as it is simple and cheaper than traditional configurations.

VIII. ACKNOWLEDGEMENT

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VIII. REFERENCES

Amin, M. M., Mohammed, O. A., 2011, "A three-phase high frequency semi-controlled battery charging power converter for plug-in hybrid electric vehicles". In Energy Conversion Congress and Exposition, ECCE´11, 2641-2648.

Alahuhtala, J., Tuusa, H., 2006, "Four-wire unidirectional three-phase/level/switch (VIENNA) rectifier". In IEEE 32nd Annual Conference on Industrial Electronics, IECON´06, pp. 2420–2425.

Barbi, I., 2012, "Eletrônica de potência". 7ª edição, Florianópolis-SC, Editora do Autor.

Batista, F. A. B., Barbi, I., 2007, "Space vector modulation applied to three-phase three-switch two-level unidirectional PWM rectifier". In IEEE Transactions on Power Electronics, Vol. 22, No. 6, pp. 2245-2252.

Batista, F. A. B., 2006, "Modulação Vetorial Aplicada a Retificadores Trifásicos PWM Unidirecionais". Tese de Doutorado, Universidade Federal de Santa Catarina.

Bekiarov, S. B., and Emadi, A., 2002, "Uninterruptible power supplies: classification, operation, dynamics, and control". In Proc. IEEE APEC´02, Dallas, TX, pp. 597–604.

Borgonovo, D., 2005, "Análise Modelagem e Controle de Retificadores PWM Trifásicos". Tese de Doutorado, Universidade Federal de Santa Catarina.

Branco, C. G. C., Torrico-Bascopé, R. P., Cruz, C. M. T., Lima, F. K. de A., 2013, "Proposal of three-phase high frequency transformer isolation UPS topologies for distributed generation applications". In IEEE Transactions on Industrial Electronics, vol. 60, No4, pp 1520-1531.

Chen, M., Rincón-Mora, G. A., 2006, "Accurate electrical battery model capable of predicting runtime and I–V performance". In IEEE Transactions on Energy Conversion, Vol. 21, No. 2, pp. 504-511.

Dai, M., Marwali, M. N., Jung, J. W., Keyhani, A., 2005, "A PWM rectifier control technique for three-phase double conversion ups under unbalanced load". In Proc. IEEE Applied Power Electronics Conf. Expo. APEC´05, pp. 548–552.

Dalessandro, L., Round, S. D., Kolar, J. W., 2008, "Center-point voltage balancing of hysteresis current controlled three-level PWM rectifiers". In IEEE Transactions on Power Electronics, Vol. 23, No. 5, pp. 2477-2488.

Erickson, R. W., Maksimovic, D., 2000, "Fundamentals of Power Electronics". Second Edition, Kluwer Academic Publishers, New York.

Escobar, G., Martinez-Rodriguez, P. R., Valdez, A. A., Sosa, J. M., 2011, "A direct power control for three-phase rectifier based on positive sequence detection". In 37th Annual Conference on IEEE Industrial Electronics Society, pp. 1018-1023.

Ghosh, R., Narayanan, G., 2008, "Control of three-phase, four-wire PWM rectifier". In IEEE Transactions on Power Electronics, Vol. 23, No. 1, pp. 96-106.

Greul, R., Round, S. D., Kolar, J. W., 2007, "Analysis and control of a three-phase, unity power factor Y – rectifier". In IEEE Transactions on Power Electronics, Vol. 22, No 5, pp. 1900-1911.

Jiang, S., Li, Y., Lu, X., Ge, B., Peng, F. Z., 2011, "Practical control implementation for 100 kVA three-phase four-wire on-line voltage regulator". In IEEE 26th Applied Power Electronics Conference and Exposition, APEC´11, pp. 749–756.

Kim, E. H., Kwon, J. M., Kwon, B. H., 2009, "Transformerless three-phase on-line UPS with high performance". Power Electronics, IET, pp. 103–112.

Lee, W., Han, B. M., Cha, H., 2011, "Battery ripple current reduction in a three-phase interleaved

dc-dc converter for 5kW battery charger”. In IEEE Energy Conversion Congress and Exposition, ECCE´11, pp. 3535 – 3540.
Lin, B. R., Lee, Y. C., 2004, “Analysis and implementation of a three-phase four-wire switching mode rectifier based on a switch-clamped scheme”. In IEE Proc.-Electr. Power Appl., Vol. 151, No. 3, pp. 268-275.
Lo, Y. K., Song, T. H., Chiu, H. J., 2002, “Analysis and elimination of voltage unbalance between the split capacitors in half-bridge boost rectifiers”. In IEEE Transactions on Industrial Electronics, Vol. 49, No. 5, pp. 1175–1177.
Lo, Y. K., Chen, C. L., 1995, “Three-phase four wire voltage controlled AC line conditioner with unity input power factor and minimized output voltage harmonics”. In Proc. Inst. Elect. Eng.—Electr. Power Appl., vol. 142, No 1, pp. 43–49.
Moon, J. S., Lee, J. H., Ha, I. Y., Lee, T. K., Won, C. Y., 2011, “An efficient battery charging algorithm based on state-of-charge estimation for electric vehicle”. In Intern. Conf. on Electrical Machines and Systems, ICEMS´11, pp. 1-6.
Mohan, N., Undeland, T. M., Robbins, W. P., 1995, “Power Electronics: converters, applications, and design”. John Wiley & Sons, 2nd Edition, New York, USA.
Pellegrino, G., Armando, E., Guglielmi, P., 2010, “An integral battery charger with power factor correction for electric scooter”. In IEEE Transactions on Power Electronics, Vol. 25, No3, pp. 751-759.
Rashid, M. H., 2001, “Power Electronics Handbook”. Academic Press, California.
Racine M. S., Parham, J. D., and Rashid, M. H., 2005, “An overview of uninterruptible power supplies”. In Proc. 37th Annual North Amer. Power Symposium, pp. 159–164.
Singh, B., Singh, B. N., Chandra, A., Al-Haddad, K., Pandey, A., Kothari, D. P., 2004, “A review of three-phase improved power quality AC–DC converters”, In IEEE Transactions on Industrial Electronics, Vol. 51, No. 3, pp. 641-660.
Torrico-Bascopé, R. P., Torrico-Bascopé, G. V., Moura, R. D., Branco, C. G. C., Bezerra, L. D. S., Oliveira Jr. D. de S., 2008, “High Frequency isolation UPS System for low power applications”. In IEEE Applied Power Electronics Conference and Exposition, APEC´08, pp 1296-1302.
Vázquez, N., Rodriguez, H., Hernández, C., Rodríguez, E., and Arau, J., 2009, “Three-phase rectifier with active current injection and high efficiency”. In IEEE Transactions on Industrial Electronics, Vol. 56, No. 1, pp.110-119
Wen, J., Smedley, K., 2006, “Control of three-phase power factor corrected rectifier in balanced and unbalanced systems”. In IEEE 41st Industry Applications Society Conference, IAS´06, pp. 562-568.
Technical Standard NBR 15014 – DEC. 2003 “Conversor a Semicondutor – Sistema de Alimentação de potência ininterrupta, com saída em corrente alternada (Nobreak) – Terminologia”, ABNT – Associação Brasileira de Normas Técnicas.
Technical Standard IEEE Std 1184, september-2006. “IEEE Guide for batteries for uninterruptible power supply systems”. IEEE, New York, NY.
Technical Standard IEEE Std 485, 2010, IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stationary Applications, IEEE Standards Coordinating Committee on Stationary Batteries, Approved 8 November 2010.