ACTIVE POWER LINE CONDITIONING OF A THREE-PHASE LINE INTERACTIVE UPS SYSTEM WITH IMPROVED DYNAMIC RESPONSE

Sérgio Augusto Oliveira da Silva[1,2]
Department of Electrical Engineering – UTFPR [1]
Department of Computer Engineering – UNOPAR [2]
Av. Alberto Carazzai, 1640, CEP. 86.000-300 [1]
Cornélio Procópio – PR, BRAZIL
augus@utfpr.edu.br [1]; sergio.computacao@unopar.br [2]

Rodrigo A. Modesto[1]; Lúcio dos Reis Barbosa [1,2]
Department of Electrical Engineering – UEL [1]
Department of Computer Engineering – UNOPAR [2]
Rod. Celso Garcia Cid, Pr 445, Km 380 [1]
CEP. 86.051-990 Londrina – PR, BRAZIL
lbarbosa@uel.br

***Abstract*-This paper presents an improved method to generate the compensation reference currents applied to a three-phase line-interactive Uninterruptible Power Supply (UPS) system with series and parallel active power line conditioning capabilities. The reference currents are used to compensate the reactive power and to eliminate harmonic currents generated from the non-linear loads, in a three-phase, four-wire system. The control strategy is based on the synchronous reference frame (SRF) method, in which the implemented current SRF-based controller does not have the task of compensate, at fundamental frequency, the negative and zero sequence components of the load currents that exist due to the unbalance conditions of the loads or the source voltage. Thus, in standby mode of operation, the efficiency of the three-phase UPS system is increased when it is feeding unbalanced single-phase non-linear loads, because the PWM parallel converter compensates only the harmonic load currents. Three strategies, employed to generate the reference currents are discussed, such as, the SRF conventional strategy, the SRF single-phase strategy and the improved SRF single-phase strategy. Besides, the active powers that flow through the parallel PWM converter using the three presented strategies are shown and a comparative analysis of them is made to validate the predicted theoretical results.**

***Keywords* – Harmonic currents, Line-interactive, UPS system.**

I. INTRODUCTION

Reduced power factor and polluted utility voltage have been rising due to the increase of use of non-linear loads by residential, commercial and industrial customers. The problem increases when single-phase non-linear loads are connected in three-phase, four-wire systems. In this case, even perfectly balanced single-phase loads, a very large third harmonic component and its multiples can flow through the neutral wire. Besides, the neutral current amplitude can exceed the amplitude of the line currents [1]. The excessive neutral current can cause damage both in the neutral conductor and in the transformers in which the non-linear loads are connected [2]. If non-linear loads are unbalanced, the neutral current will contain both the fundamental and the harmonic components.

Active Power Filters (APF) and Uninterruptible Power Supply (UPS) systems have been used to compensate the currents drawn from the utility, allowing the improvement of the power quality [2-9]. In [6], a three-phase line-interactive UPS system has been implemented for three-phase, four-wire system, using the conventional SRF method based on balanced three-phase loads. Therefore, the source currents had to be controlled to be sinusoidal and balanced providing negative and zero sequence components compensation. In [7], for single-phase unbalanced non-linear loads, the efficiency of the UPS system has been improved using the SRF single-phase strategy, in which the negative and zero sequence components at fundamental frequency were not compensated. By software implementation, the acquired load current is phase delayed of 120^o and 240^o, producing the two other load currents. Thus, each phase of the system can be treated separately as a balanced three-phase system and only the harmonic currents are compensated. The drawback of the SRF single-phase strategy is the delay introduced in the algorithm in order to generate the new currents [7].

In this paper, an improved SRF single-phase strategy to generate the compensation reference currents of the series active power filter is presented. Therefore, apart from the increase of the three-phase UPS system efficiency, the reference currents can be generated faster.

II. OPERATION OF THE LINE-INTERACTIVE UPS TOPOLOGY

The line-interactive UPS system topology is shown in Fig. 1. Two PWM converters, coupled with a common dc-bus, are used to perform the series active filter and parallel active filter functions. The series active filter is connected in series both with the line and the load through three single-phase linking transformers. A battery bank is placed in the dc-bus and a static switch '*sw*' is incorporated to the circuit to provide a fast disconnection between the UPS system and the power supply when an occasional interruption of the incoming power occurs.

The series active power filter acts as a sinusoidal current source. It has high impedance, which is enough to isolate the line from the load related to the harmonic currents. An SRF-based controller is used to control the series active power filter making the line currents (i_{sa}, i_{sb}, and i_{sc}) sinusoidal with low THD.

The parallel active power filter acts as a sinusoidal voltage source with constant rms output voltages (v_{fa}, v_{fb}, and v_{fc}) and low THD. It has low impedance, which is enough to absorb the harmonic currents of the load.

Both the output UPS voltages and the line currents are individually controlled to be in phase with the line voltages (v_{sa}, v_{sb}, and v_{sc}). Both the parallel and the series filter use three independent controllers acting on half-bridge inverters. In this line-interactive UPS system, an effective power factor correction is carried out.

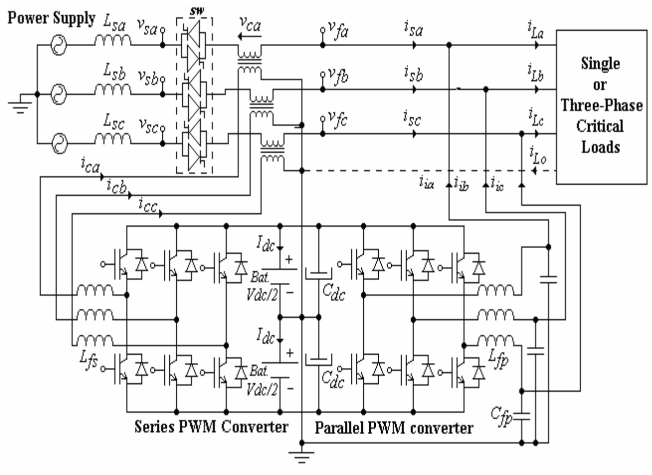


Fig. 1. Line-interactive UPS topology.

III. ALGORITHMS TO GENERATE THE REFERENCE CURRENTS OF THE UPS (STANDBY MODE)

A. Conventional SRF-Based Controller for Current Compensation (Conventional SRF Strategy).

An SRF-based controller is used to provide and to control the sinusoidal compensating reference currents (i^*_{ca}, i^*_{cb}, and i^*_{cc}) for the series PWM converter shown in Fig. 1. The block diagram of the control scheme for current compensation is shown in Fig. 2.

The three-phase load currents i_{La}, i_{Lb}, and i_{Lc} are measured and transformed into a two-phase stationary reference frame $(dq)^s$ quantities (id^s, iq^s) based on the transformation (1). After that, these quantities are transformed from a two-phase stationary reference frame $(dq)^s$ into a two-phase synchronous rotating $(dq)^e$ reference frame, based on the transformation (2), where $\theta = \omega t$, is the angular position of the reference frame. The coordinates of unit vector, $sin\theta$ and $cos\theta$, are obtained from a PLL system. The currents at the fundamental frequency ω (id^e and iq^e) are now dc quantities and all the harmonics, transformed into non-dc quantities, can be filtered using a low pass filter (LPF) as shown in Fig. 2. Thus, id^e_{dc} and iq^e_{dc} represents the active and reactive fundamental components of the load current in *dq* axis, respectively.

$$\begin{bmatrix} id^s \\ iq^s \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} id^e \\ iq^e \end{bmatrix} = \begin{bmatrix} cos\ \theta & sin\ \theta \\ -sin\ \theta & cos\ \theta \end{bmatrix} \begin{bmatrix} id^s \\ iq^s \end{bmatrix} \quad (2)$$

Now, only the dc component current of the synchronous rotating reference frame id^e_{dc} must be transformed into the stationary reference frame $(dq)^s$ to obtain the fundamental reference currents (i^*_{ca}, i^*_{cb}, i^*_{cc}). Therefore, the reactive and harmonic components of the load currents are eliminated. As the currents i^*_{ca}, i^*_{cb} and i^*_{cc} are balanced, the compensation of the negative and zero sequence components has been performed.

The inverse transformation matrix from a two-phase synchronous reference frame to two-phase stationary reference frame is given by (3). The matrix that provides the linear transformation from a two-phase system to three-phase stationary reference frame system is given by (4).

$$\begin{bmatrix} id^s_f \\ iq^s_f \end{bmatrix} = \begin{bmatrix} \cos\theta & -sin\ \theta \\ sin\ \theta & \cos\theta \end{bmatrix} \begin{bmatrix} id^e_{dc} \\ 0 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} id^s_f \\ iq^s_f \end{bmatrix} \quad (4)$$

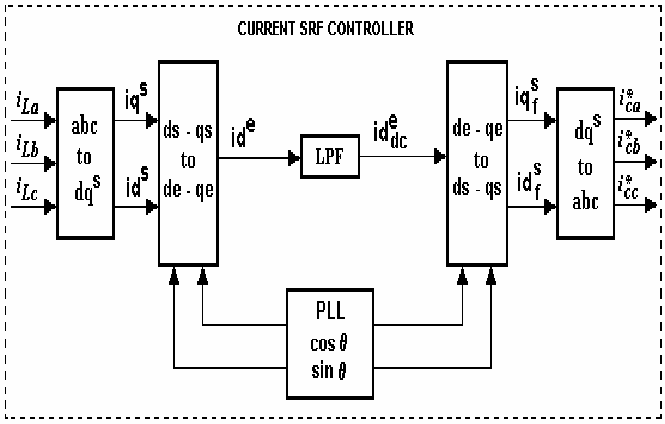


Fig. 2. Block Diagram of the Current SRF-Based Controller.

B. SRF-Based Controller Applied to Unbalanced Loads (SRF Single-Phase Strategy)

The previous presented SRF method generates balanced reference currents because it is based on balanced three-phase loads. Thus, additional power rate is handled through the converters to perform the current compensation of negative and zero sequence components, decreasing the efficiency of the series and parallel converters.

Applying the SRF single-phase strategy, in which each phase is treated separately, it is possible to get three-phase load currents by the acquisition of only one of them (i_{La}, i_{Lb}, or i_{Lc}), as shown in Fig. 3. By software implementation, the acquired load current is phase delayed of 120° and 240°, producing the two other fictitious balanced load currents. Thus, the conventional SRF method can be used.

As expected, the phase delay introduced by the algorithm produces an increase in the transient time, and the dynamic response of the system becomes slower than the dynamic response that is obtained in the conventional method [7].

Based on SRF method applied to a single-phase strategy shown in Fig. 3, the new reference currents can be achieved using (5). Now, the series reference currents i^*_{ca}, i^*_{cb}, and i^*_{cc} are sinusoidal, though unbalanced, because the compensation of the negative and zero sequence components has not been performed.

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1/2 & \sqrt{3}/2 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} id^s_{fa} \\ iq^s_{fa} \\ id^s_{fb} \\ iq^s_{fb} \\ id^s_{fc} \\ iq^s_{fc} \end{bmatrix} \quad (5)$$

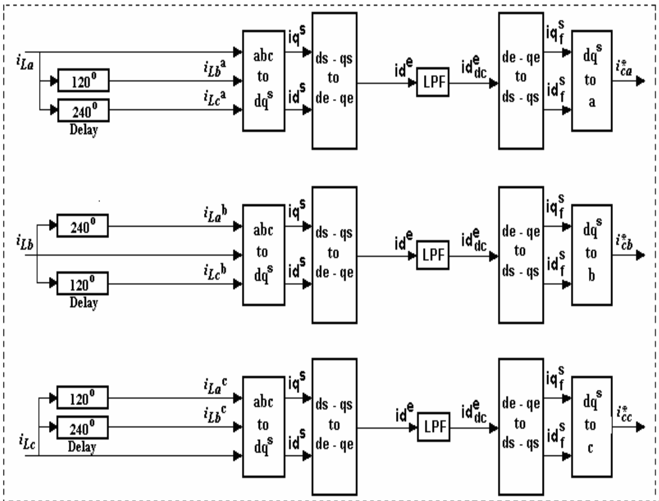


Fig. 3. SRF Single-Phase Strategy (SFS).

C. Improved SRF-Based Controller Applied to Unbalanced Loads (Improved SRF Single-Phase Strategy).

To improve the steady state and dynamic response of the UPS system, a new algorithm is proposed. Now, applying the improved SRF single-phase strategy, in which each load current of the three-phase system is treated separately, it is possible to get the two-phase stationary reference frame *(dq)*^{s} quantities (id^s, iq^s) by the acquisition of only one of them (i_{La}, i_{Lb}, or i_{Lc}), as shown in Fig. 4. By software implementation, the acquired load current in treated as "d^s" coordinate of the two-phase stationary reference frame *(dq)*^{s}. After that, it is phase delayed of 90°, producing the fictitious "q^s" coordinate [10]. Therefore, a new two-phase system can be studied in *(dq)*^{s} coordinates. Based on SRF method applied to an improved single-phase strategy shown in Fig. 4, the new reference currents are achieved directly from the synchronous rotating *(dq)*^{e} reference frame as given by (6).

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 & 0 \\ 0 & \cos\theta & 0 \\ 0 & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} id^e_{dc_a} \\ id^e_{dc_b} \\ id^e_{dc_c} \end{bmatrix} \quad (6)$$

As noticed, the phase delay introduced by the algorithm produces a decrease both in the transient time and in the dynamic response when it is compared with the SRF single-phase strategy shown in Fig. 3.

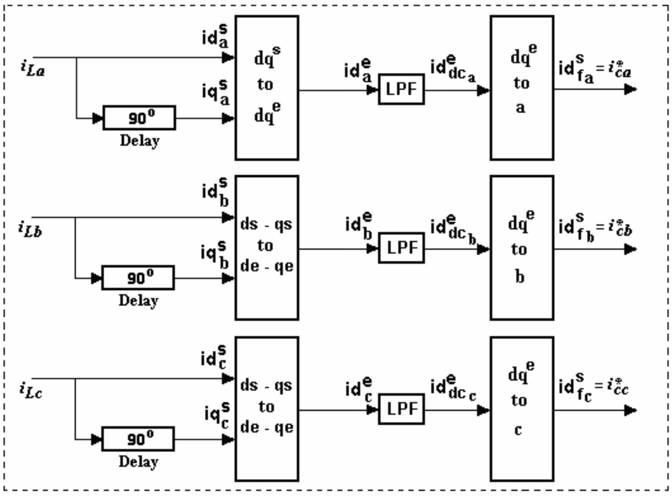


Fig. 4. Improved SRF Single-Phase Strategy (ISFS).

IV. SIMULATION RESULTS

The line-interactive UPS system, operating at 20 kHz switching frequency, has been verified by simulation, working as a series-parallel active power line filter. The UPS system feeds non-linear loads represented by three unbalanced single-phase diode bridge rectifier as shown in Fig. 5. The transition modes from the backup to standby mode (40 and 110ms) and from the standby to backup mode (80ms) are shown in Fig. 6. The phase "a" output voltage (v_{fa}), the compensated input current (i_{sa}) and the phase "a" parallel inverter current (i_{ia}) are shown in Fig. 6 (a), (b) and (c), respectively. As noticed, the parallel inverter provides compensated harmonic currents to the load when the UPS system is operating in the standby mode (40 – 80ms and 110 – 140ms) and in backup mode (0 - 40ms and 80 - 110ms) it provides the total current to feed the loads. Seamless transitions are obtained both from the backup to standby mode and vice-versa.

Fundamental unbalanced voltages of ±15% and harmonic contents have been included in the input voltages as shown in Fig. 7 (a). Up to 40ms, the active series and parallel filters are turned off. The active compensation begins after 40ms when the output voltages v_{fa}, v_{fb}, and v_{fc} become balanced and sinusoidal. The source currents i_{sa}, i_{sb}, and i_{sc} become sinusoidal, though unbalanced, following the references i^*_{ca}, i^*_{cb}, and i^*_{cc}, as shown in Fig. 7 (b). Fig. 8 shows the output signal of the Low-Pass-Filter id^e_{dc} of the algorithm shown in Figs. 3 and 4, for the single-phase strategy (SPS) algorithm and for the improved single-phase strategy (ISPS) algorithm, respectively. As it can be observed, the LPF output (id_{dc}^{e}) of the ISPS algorithm is faster than the output the SPS algorithm. Therefore, the reference currents (i_{ca}^{*}, i_{cb}^{*}, i_{cc}^{*}) for the series converter will be generated faster too.

Fig. 9 shows the instantaneous active power p_i that flows through the parallel converter for the three strategies presented, such as, Conventional Strategy, Single-Phase Strategy (SPS) and Improved Single-Phase Strategy (ISPS). For ISPS algorithm, besides faster transient response, the power rate handled through the parallel converter is decreased, resulting on the increase of the UPS efficiency. This is possible, because the compensation of the negative and zero sequence current components have not been performed.

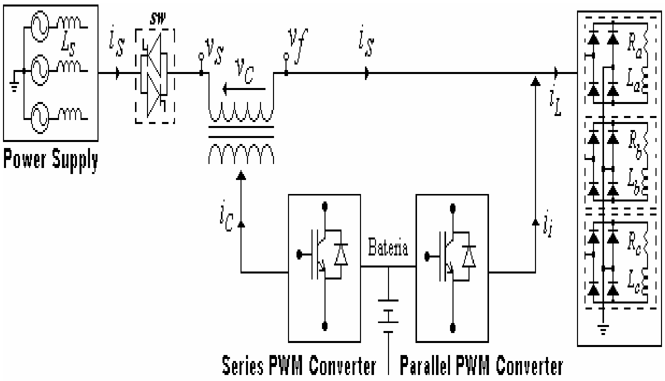


Fig. 5. Line-interactive UPS system feeding unbalanced non-linear loads.

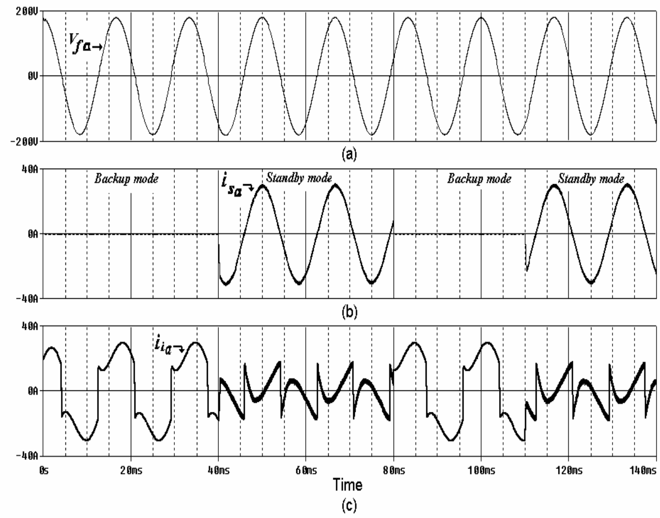


Fig. 6. UPS Transition Modes (phase ‘a’):
(a) Output voltage (v_{fa});
(b) Input current (i_{sa}); (c) Inverter current (i_{ia}).

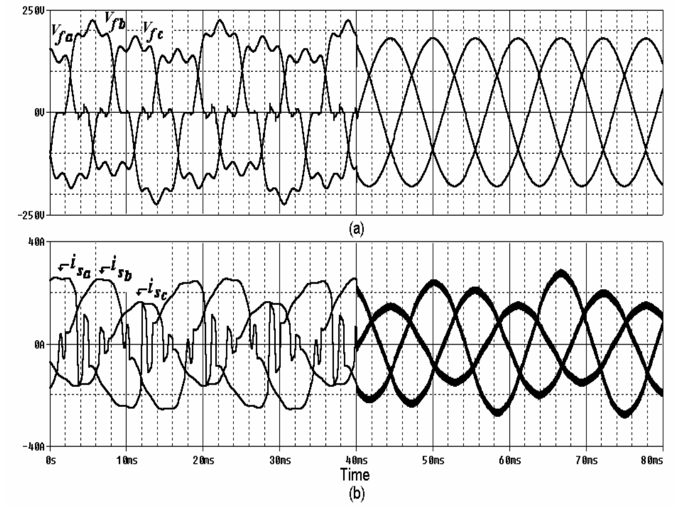


Fig. 7. UPS voltages and currents: (a) Output UPS voltages (v_{fa}, v_{fb}, v_{fc})

(b) Input currents (i_{sa}, i_{sb}, i_{sc}).

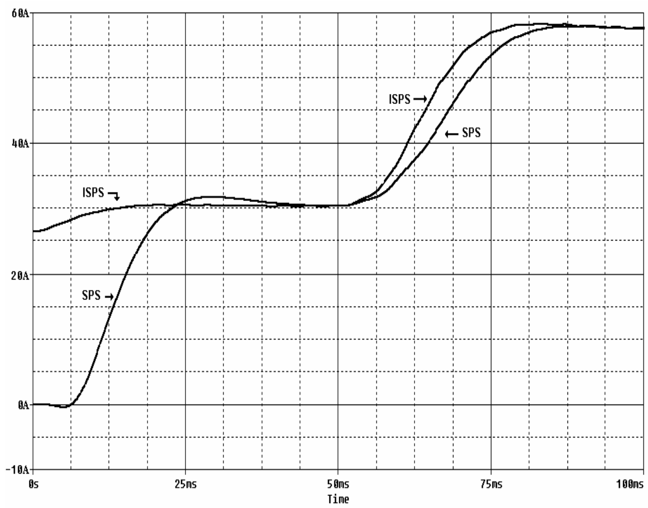
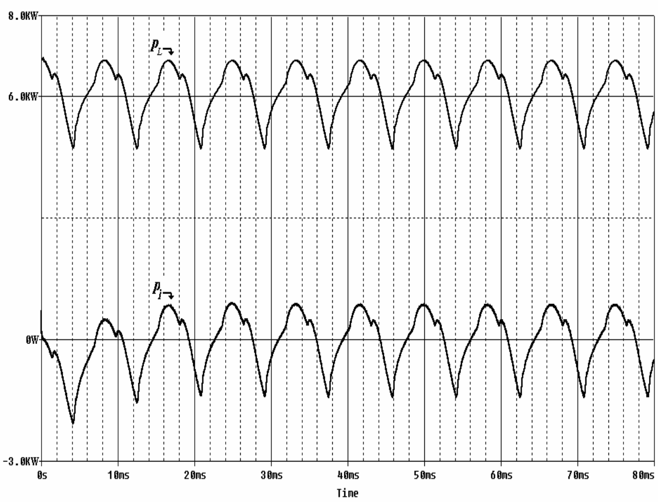
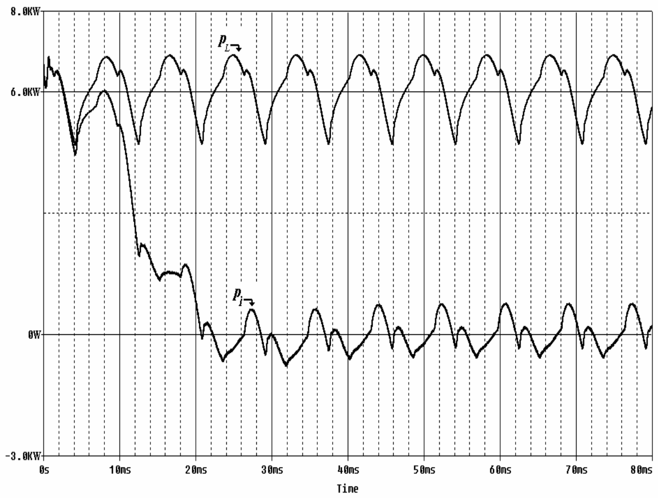


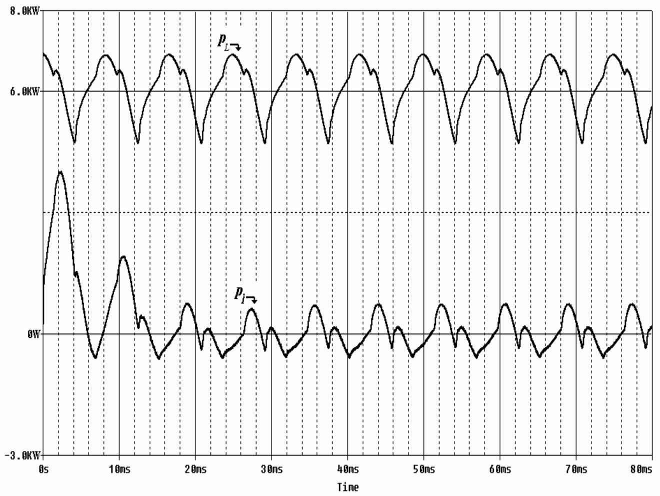
Fig. 8. Low-Pass Filter output signal (id_{dc}^{e}) for SPS and ISPS algorithms.



(a)



(b)



(c)

Fig. 9. Instantaneous Active Power of the Load (p_L) and Instantaneous Active Power of the Parallel Inverter (p_i): (a) Conventional Strategy; (b) Single-Phase Strategy (SPS); (c) Improved Single-Phase Strategy (ISPS).

V. CONCLUSIONS

An improved algorithm based on SRF method, applied to a three-phase line-interactive uninterruptible power supply system with series and parallel active power line conditioning capabilities has been presented. The reference currents, obtained from the SRF-based controller, are used to compensate the reactive power and to eliminate harmonic currents generated by non-linear loads, in a three-phase, four-wire system. Three strategies, employed to generate the reference currents, are discussed, such as, the SRF conventional strategy, the SRF single-phase strategy and the improved SRF single-phase strategy. When the improved SRF single-phase strategy is applied, the phase-delay introduced by the proposed algorithm decreases. Therefore, both the transient time and the dynamic response of the system become faster than the SRF single-phase strategy. Thus, the reference currents for the series converter are also generated faster. In the proposed algorithm, the negative and zero sequence components in the fundamental frequency were not taken into account. Thereby, the efficiency of the three-phase UPS system increases when it is feeding unbalanced single-phase non-linear loads

REFERENCES

[1] Gruzs, T. M., “A Survey of Neutral Currents in Three-Phase Computer Power Systems,” IEEE Transactions on Industry Applications, Vol. 26, No. 4, pp. 719-725, 1990.

[2] Quinn, C. A. and Mohan N., “Active Filtering of Harmonic Currents in Three-Phase, Four-Wire Systems with Three-Phase and Single-Phase Non-Linear Loads,” *In Proceedings of* APEC, pp. 829-836, 1992.

[3] Quinn, C. A. and Mohan N., Mehta H., “A Four-Wire, Current-Controlled Converter Provides Harmonic Neutralization in Three-Phase, Four-Wire Systems,” *In Proceedings of* APEC, pp. 841-846, 1993.

[4] Thomas T., Haddad K, Joós G. and Jaafari A., “Performance Evaluation of Three-Phase Three and Four Wire Active Filters,” *In Proceedings of* IAS, pp. 1016-1023, 1996.

[5] Silva, S. A. O., Donoso-Garcia, P. F., Cortizo, P. C., and Seixas, P. F., “A Three-Phase Line-Interactive UPS System Implementation with Series-Parallel Active Power-Line Conditioning Capabilities,” IEEE Transactions on Industry Applications, Vol. 38, No. 6, pp. 1581-1590, 2002.

[6] Silva S. A. O., Donoso-Garcia P. F., Cortizo P.C. and Seixas P. F., “A Line-interactive UPS System Implementation with Series-Parallel Active Power-Line Conditioning for Three-Phase, Four-Wire Systems,” ELSEVIER - Electrical Power and Energy Systems 26, pp.399-411, 2004.

[7] Silva, S. A. O., Modesto, R. A., “Active Power Line Compensation Applied to a Three-Phase Line Interactive UPS System Using SRF Method,” *In: Proceedings of* PESC, pp. 2358-2362, 2005.

[8] Villalva, M. G., Ruppert F. E., “Four-Wire Shunt Active Power Filter with Adaptive Selective Current Compensation,” *In: Proceedings of* PESC, pp. 347-353, 2005.

[9] Camargo, R., Pinheiro, R., “Three-Phase Four-Wire Shunt Active Filter to Reduce Voltage and Current Distortions on the Distribution Systems,” *In Proceedings of* IECON, pp. 1884-1889, 2006.

[10] Liu, J., Yang, J., Wang, Z., “A New Approach for Single-Phase Harmonic Current Detecting and its Application in a Hybrid Active Power Filter”, *In Proceedings of* IECON, pp. 849-854, 1999.