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A Hybrid Parallel Active Filter / Off-Line UPS Unit for Computer Loads

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***Summary*: A hybrid parallel active filter / off-line uninterruptible power supply (UPS) system is proposed. The hybrid system contains a single inverter which acts as a parallel active filter during the normal mode of operation (when the AC supply is available); and also supplies the load with energy from the UPS back-up battery during the back-up mode of operation (when the AC supply is not available or is beyond the preset tolerance). In both modes of operations the inverter is controlled in such way so that the line current is a pure sinusoid. This is to improve the input power factor and to eliminate the current harmonics in the first mode and to remove any stress on the back-up battery caused by the discharging during the second mode of operation. A full simulation results and an experimental setup is presented together with a closed loop control algorithm.**

Key words:
active filters, UPS systems, computer power supplies, current harmonics

1. INTRODUCTION

In little more than 15 years, electricity power quality has grown from obscurity to a major issue. Particularly, the increasing penetration of power electronics-based loads is creating a growing concern for harmonic distortion in the AC supply system [1]. For example the current in each phase in a large office building, where there are a several hundreds of computers, contains a significant level of third harmonic [2]. This causes a high current in the neutral conductor – normally with balanced linear load the neutral conductor would have to carry almost zero current. There have been cases where the neutral conductor has got very hot causing fire! [3]. Consequently, power conditioning equipment is becoming more important not only for electric utilities but also for their customers. Majority of these power conditioning devices are placed at the point of the incoming supply where the level of current harmonics is significant, and it is the responsibility of the customers whether to use them or not [4]. However, there is more and more pressure nowadays on computer power supply manufacturers to integrate such power conditional devices within their computer power supplies.

Equally important for computer loads nowadays is the availability of the power supply and this is the reason for the increase demand in UPS systems in offices, banks, etc... One of the most popular UPS systems in such applications is the off-line system [5]. In an off-line UPS, the critical load (computer) is normally powered from the mains supply, and a small mains-driven charger keeps the UPS's batteries topped-up. An on-line filter is used to reduces spikes and RFI in the supply before it is supplied to the load and, under these conditions, the inverter does nothing. When the quality of the mains supply falls below a certain level, the inverter starts-up virtually instantaneously and takes over the task of supplying the critical load from the battery.

This paper presents a hybrid parallel active filter / off-line UPS unit which can be integrated in computer power supply. A block diagram of such proposed system is shown in Figure 1.

2. THE PROPOSED CONFIGURATION (ACTIVE FILTER MODE)

The circuit topology of the proposed system is shown in Figure 2. It consists of non-linear load with a switching function $u_1(t)$ and an active filter which can be divided into an inverter with a switching function $u_2(t)$, a bidirectional buck boost converter and a battery set.

In this mode of operation, the inverter acts as a parallel active filter. It inverts through the switching function $u_2(t)$ the dc battery voltage; hence it injects the appropriate current in the PCC to achieve a unity power factor. Furthermore it charges the capacitor to the desired value. Figure 3 shows a model of the circuit in this mode of operation.

The following equations can be derived from Figure 3:

$$c\frac{dv_{dc}}{dt} = -i_f u_2(t) \tag{1}$$

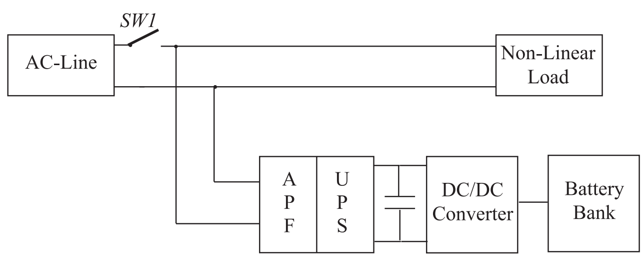


Fig. 1. Block diagram of a hybrid active filter / off-line UPS system

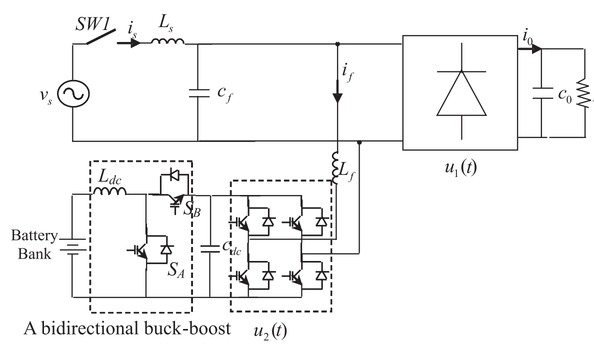


Fig. 2. A hybrid active filter / off-line UPS system topology

$$v_{cf} = v_s - L_s \frac{di_s}{dt} \quad (2)$$

$$L_f \frac{di_f}{dt} = v_{cf} - v_{dc} u_2(t) \quad (3)$$

$$c_f \frac{dv_{cf}}{dt} = i_s - i_f - i_0 u_1(t) \quad (4)$$

Substituting from equation (2) into equation (4):

(5)

Substituting from equation (1) into equation (5):

(6)

Equation (6) shows that the switching function $u_2(t)$ has to be determined in order to obtain a sinusoidal .

Single phase PQ theory [6] is used for current harmonics, reactive power compensation and capacitor voltage regulation.

In this theory the supply voltage and the load current are sensed and used for harmonic current identification as follows:

$$v_s(t) = v_r(t) + jv_i(t) \quad (7)$$

$$v_s'(t) = -v_i(t) + jv_r(t) \quad (8)$$

$$i_L(t) = i_r(t) + j\,i_i(t) \quad (9)$$

$$i_L'(t) = -i_i(t) + j\,i_r(t) \quad (10)$$

Where:

- $v_s(t)$ and $i_L(t)$ — are the instantaneous load voltage and the instantaneous load current respectively,
- $v'(t)$ and $i'(t)$ — are the instantaneous load voltage and the instantaneous load current that, are shifted by $\pi/2$ with $v(t)$ and $i(t)$ respectively.
- $v_r(t)$ and $i_r(t)$ — are the real parts of $v(t)$ and $i(t)$ respectively.
- $v_i(t)$ and $i_i(t)$ — are the imaginary part of $v(t)$ and $i(t)$ respectively.

The instantaneous active and reactive power are given by the following expression:

$$\begin{bmatrix} p(t) \\ q(t) \end{bmatrix} = \begin{bmatrix} v_r(t) & v_i(t) \\ -v_i(t) & v_r(t) \end{bmatrix} \begin{bmatrix} i_r(t) \\ i_i(t) \end{bmatrix} \quad (11)$$

The instantaneous power is divided into three components:

$$p(t) = \overline{p}(t) + \tilde{p}(t) + \overline{p}_c(t) \quad (12)$$

Where $\overline{p}(t)$: is the instantaneous power desired by the load, $\tilde{p}(t)$ is the instantaneous harmonic power that will be compensated by the active filter and $p_c(t)$ is the instantaneous power demanded for charging the capacitor which can be given:

$$p_c = \frac{d}{dt}\left(\frac{1}{2} C_{dc}.V_{dc}^2\right) \quad (13)$$

$$p_c = C_{dc}.V_{dc-ref} \frac{d}{dt}(Vdc) \quad (14)$$

$$V_{dc}(s) = \frac{p_c(s)}{V_{dc-ref} C_{dc} s} \quad (15)$$

The reference current contains the harmonic current, the reactive current, and the current required for charging the capacitor 'C_{dc}'. It can be expressed as follows:

$$i_F^* = \frac{v_r(t).\tilde{p}(t) + v_r(t).p_c(t) - v_i(t).q(t)}{v_r^2(t) + v_i^2(t)} \quad (16)$$

It can be seen from equation (16), that the compensator current can be divided into three components. Figure 4 shows the reference current computation method which based on single-phase PQ theory including the voltage regulation capacitor.

Due to the safety problem with regard to maintaining high voltage at the battery terminals [7], a bidirectional DC/DC converter shown in Figure 5 is used. In this mode of operation the buck converter (consists of a switch S_B, a diode D_A and an inductor L_{dc}) steps down the high voltage across the capacitor c_{dc} to the low battery voltage $V_{bat} = V_{dc}/D_B$, where D_B is the duty cycle of switch S_B.

3. THE PROPOSED CONFIGURATION (OFF-LINE UPS SYSTEM MODE)

When the AC line is beyond the present tolerance, the static switch S_{W1} in Figure 1 disconnects the load from the AC line. Hence the load is supplied by the battery set through

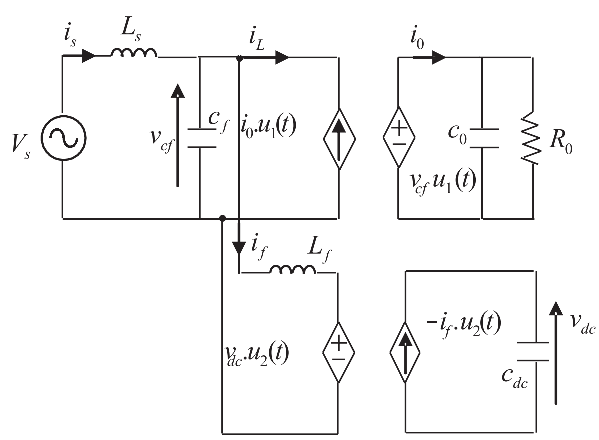


Fig. 3. Modelling of the circuit in the active filter mode

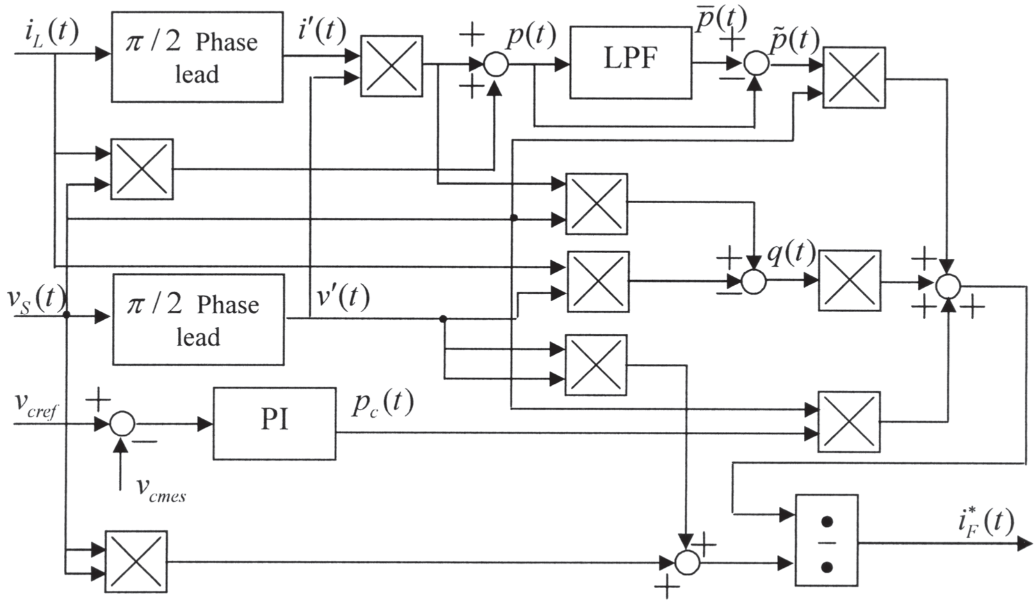


Fig. 4. Bloc diagram of current reference identification method

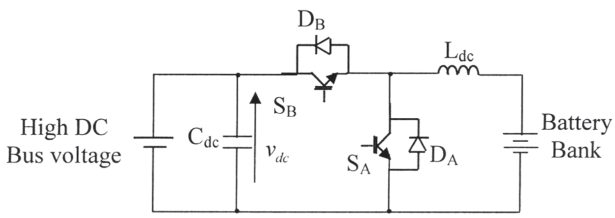


Fig. 5. A bidirectional buck-boost DC/DC converter

the step up converter and the inverter [7], until the AC line is available again. Figure 6 shows the configuration of the circuit in this mode.

In this mode of operation the boost converter, consists of a switch S_A, a diode D_B and an inductor L_{dc}, steps up the low voltage from the battery V_{bat} to the high capacitor voltage $V_{dc} = V_{bat}/1–D_A$. where D_A is the duty cycle of switch S_A.

Figure 7 illustrates the model of the circuit in this mode of operation. The battery voltage is inverted, through the inverter and the switching function $u_2(t)$, into v_{cf}. This voltage is filtered by L_f and c_f and then subjected to the switching function $u_1(t)$ of the AC/DC rectifier. The inverter current from this model can be evaluated as follows:

$$i_{cd} = c_{dc}\frac{dv_{cd}}{dt} = -i_f.u_2(t) \qquad (17)$$

$$i_f = i_0.u_1(t) - c_f\frac{dv_{cf}}{dt} \qquad (18)$$

$$v_{cf} = v_{cd}.u_2(t) + L_f\frac{di_f}{dt} \qquad (19)$$

Substituting from equation (19) into equation (18):

$$i_f = i_0.u_1(t) - c_f\frac{dv_{cd}}{dt}u_2(t) - c_f.v_{cd}\frac{du_2(t)}{dt} + L_f.c_f\frac{d^2 i_f}{dt} \qquad (20)$$

and substituting equation (17) into (20):

$$L_f c_f\frac{d^2 i_f}{dt} + \left(\frac{c_f}{c_{dc}}u_2^2(t) - 1\right).i_f = c_f.v_{cd}\frac{du_2(t)}{dt} - i_0.u_1(t) \qquad (21)$$

It is denoted from equation (21), that the magnitude and the shape of the inverter current in this mode depend on:

L_f and c_f — parameters of LC output filter of the inverter.
c_{dc} — the dc-link capacitor.
$u_1(t)$ and $u_2(t)$ — are the switching functions of the AC/DC rectifier and the inverter respectively.

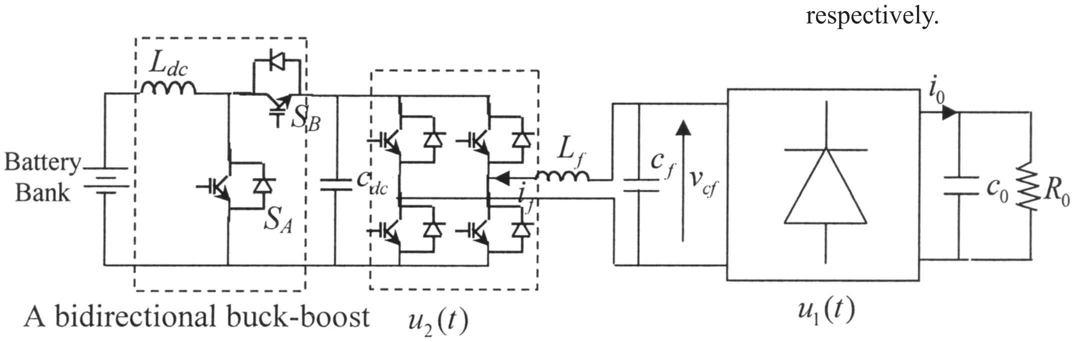


Fig. 6. Off-line UPS system topology

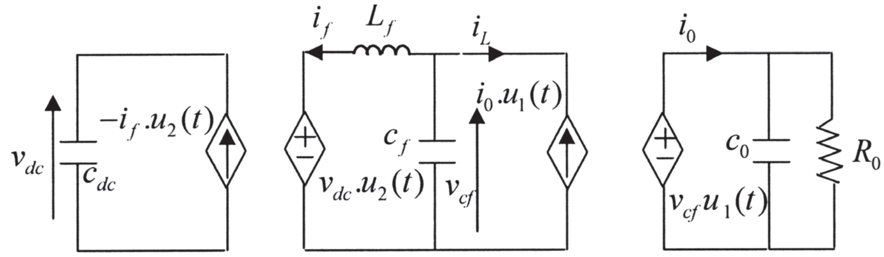


Fig. 7. Modelling of the proposed circuit in the UPS mode

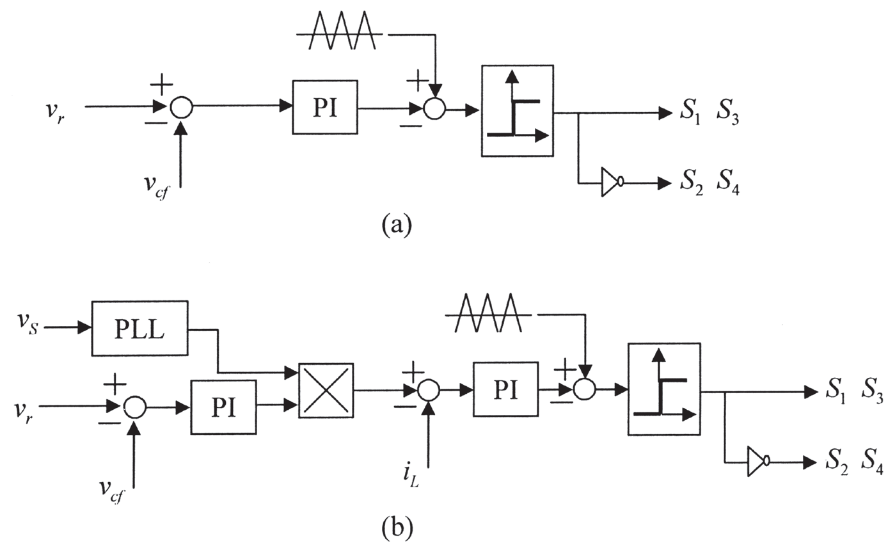


Fig. 8. Block diagram of the used control techniques in off-line UPS mode: a) voltage regulation, b) current and voltage regulation

Two control strategies have been applied: the first uses a single feedback loop and PI controller to regulate the output voltage through the inverter. The second uses two closed loops, an inner and an outer loop, therefore it regulates the output voltage and provides a pure sinusoidal line current which resulting in removing any stress on the buck up battery. The output voltage feed-back is compared with a sine wave reference signal using a PLL (phased locked loop). The error signal is compensated by a PI controller to produce the current reference signal, the sensed current through the inductor L_f is compared with the reference signal, and the error signal is compared with triangular waveform after being compensated by the PI regulator. Hence the control signal is generated providing a constant switching frequency. The block diagrams of both control strategies are shown in Figures 8a and 8b.

4. SIMULATION RESULTS

To verify the performance of the proposed hybrid active filter /off-line UPS system, the simulation of the whole system is carried out using MATLAB-SUMILINK package.

The parameters used in the simulation are as follows:

- AC supply voltage = 240Vrms (50Hz)
- DC capacitor C_0=500uF, load resistance R_0 =40 ohm
- DC-link capacitor C_{dc}= 600uF
- AC-capacitor C_f= 50uF, filter inductor L_f=3.2mH
- buck boost inductor L_{dc} = 0.8mH, battery bank voltage = 48 V.

Figure 9d shows the uncompensated load current, Figure 9b illustrates the filter current (after 0.205 sec).

The supply current is shown in Figure 9c before compensation (t<0.0205) and after compensation (t>0.205 sec).

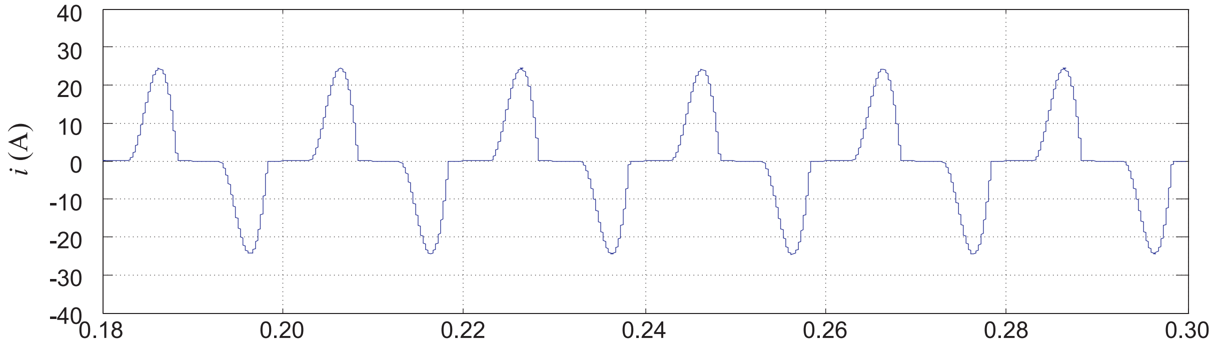
Figure 7d illustrates the zero phase shift between the supply voltage and the compensated current, which displays the non-real power generation ability of the active filter.

Figure 10 illustrates the results in both modes of operation (active filter mode and off-line mode). In Figure 10a, a typical computer load current is shown in the active filter and in the off-line UPS modes. The filter current and the supply current are shown in Figures 10b and 10c. It is obvious from these Figs that the power failure took place between 0.5 sec < t < 0.6 sec. it is important to illustrate the battery current in this case (Fig. 8) for future reference (next paragraph).

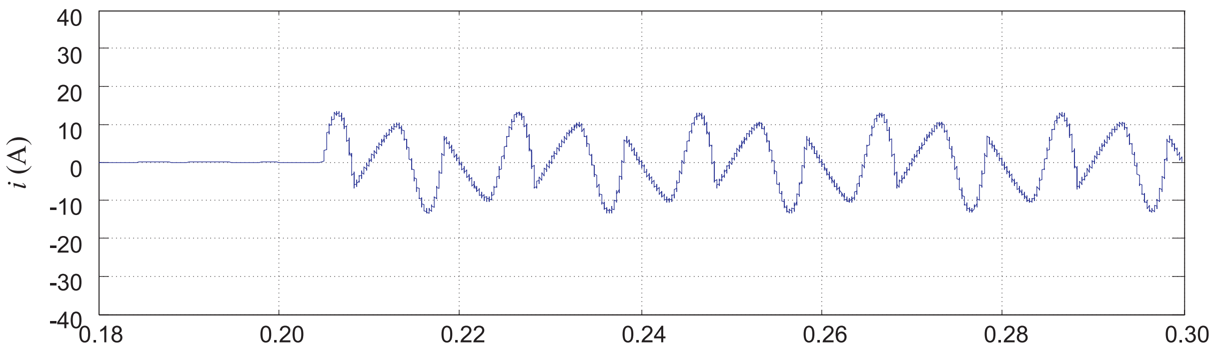
In order to reduce the stress on the buck up battery, the inverter in the off-line mode is controlled to maintain a sinusoidal inverter current waveform. This is achieved by using the control technique shown in Figure 8b. As it can be seen from comparing Figures 10d and 11d that the battery current has almost halved.

5. HARDWARE SET-UP IMPLEMENTATION ON THE DSP MICRO-CONTROLLER BOARD

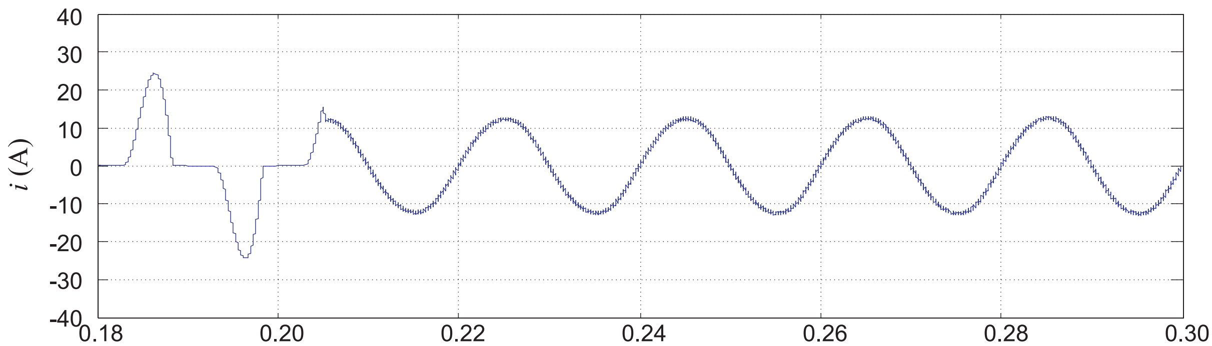
The control algorithms in active filter mode and off-line UPS mode are implemented on a DSP micro-controller board (TMS 320 LF2407A)



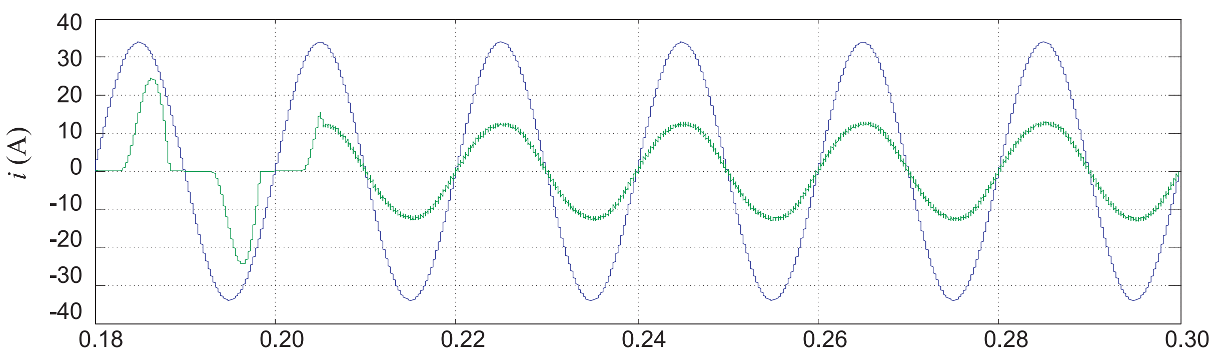
(a)



(b)



(c)



(d)

Fig. 9. Current waveforms in active filter mode: a) load current, b) active filter current, c) supply current (after compensation), d) supply voltage and supply current (after compensation)

Figure 12 shows the basic overall block diagram of the experimental set up in the laboratory.

The input signals to the DSP micro-controller across its ADC interface are; the supply voltage v_s, the load current i_L, the inverter current i_F, the dc-link voltage across the dc capacitor v_{dc}, the sin waveform signal $\sin(\omega t)$, and the inverter output voltage v_{cf}, after being sensed and conditioned.

Using the six analogue input signals and one hardware interrupt, the real time control algorithm for the hybrid

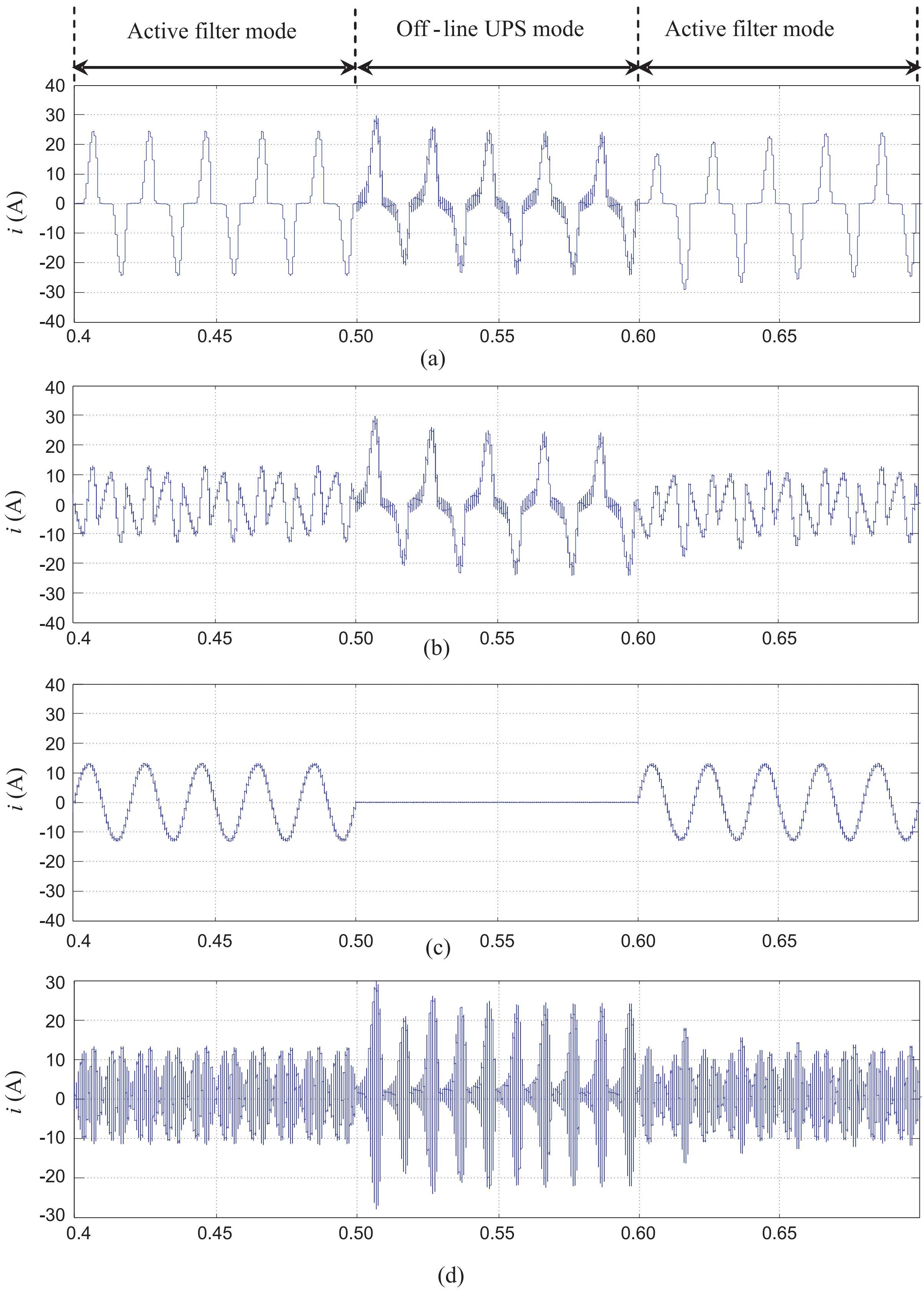


Fig. 10. Current waveforms of the hybrid active filter/off-line UPS system with regulation of the output voltage of the inverter in the off-line UPS mode: a) load current, b) active filter current, c) supply current, d) battery current

APF/off-line UPS system generates the appropriate signals through the digital output port. The control signals are then applied to the IGBT's drivers of the APF/UPS achieving a unity power factor and providing uninterrupted reliable power supply.

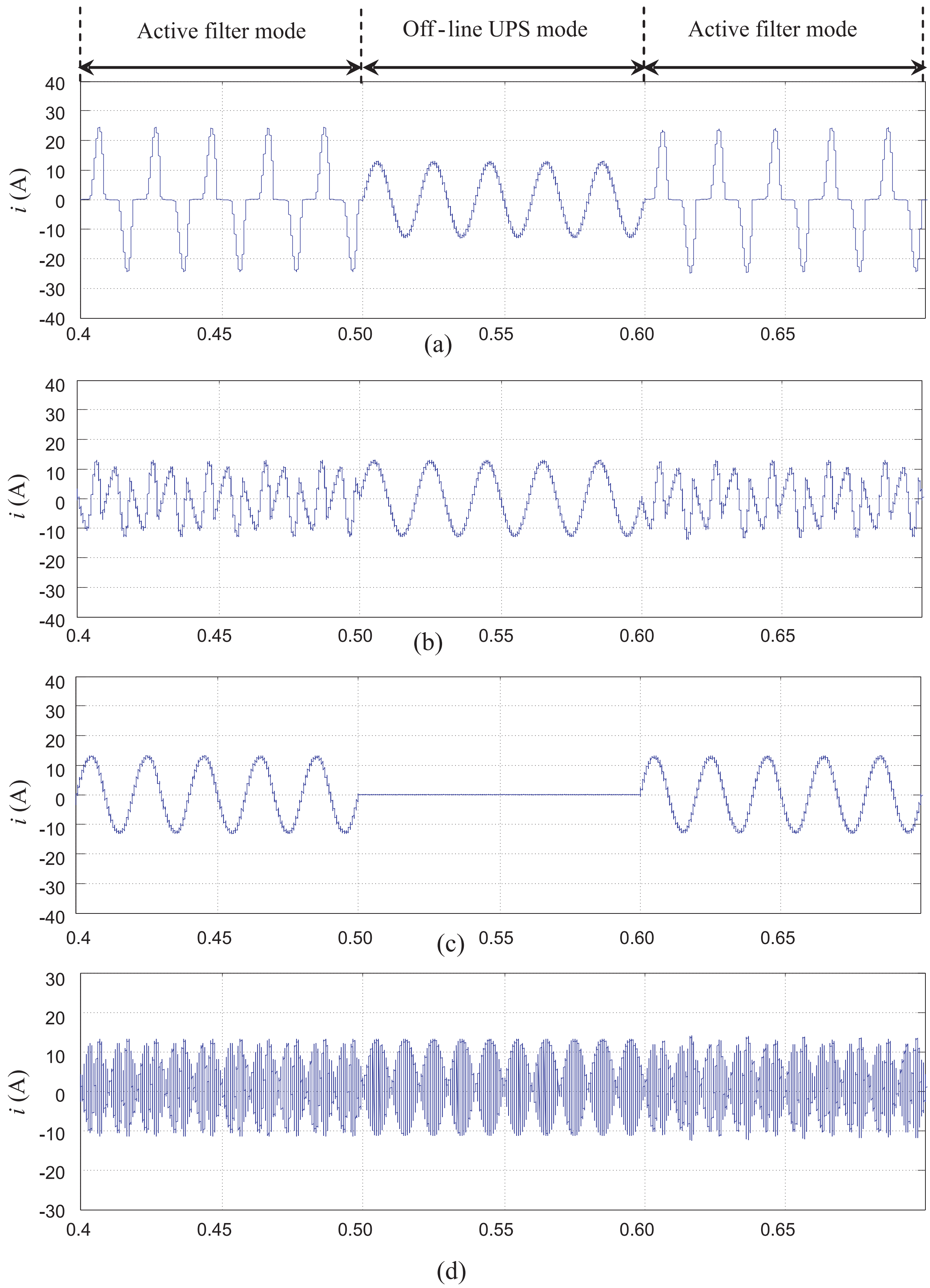


Fig. 11. Current waveforms of the hybrid active filter/off-line UPS system with regulation of current and output voltage of the inverter in the off-line UPS mode: a) load current, b) active filter current, c) supply current, d) battery current

6. CONCLUSION

In this paper, a proposed hybrid parallel active filter /off-line UPS unit for computer loads is presented. Harmonic mitigation, reactive power compensation and battery charging are achieved in active filter mode of operation where the inverter acts as an active filter using the single phase PQ theory control strategy. Furthermore an uninterrupted

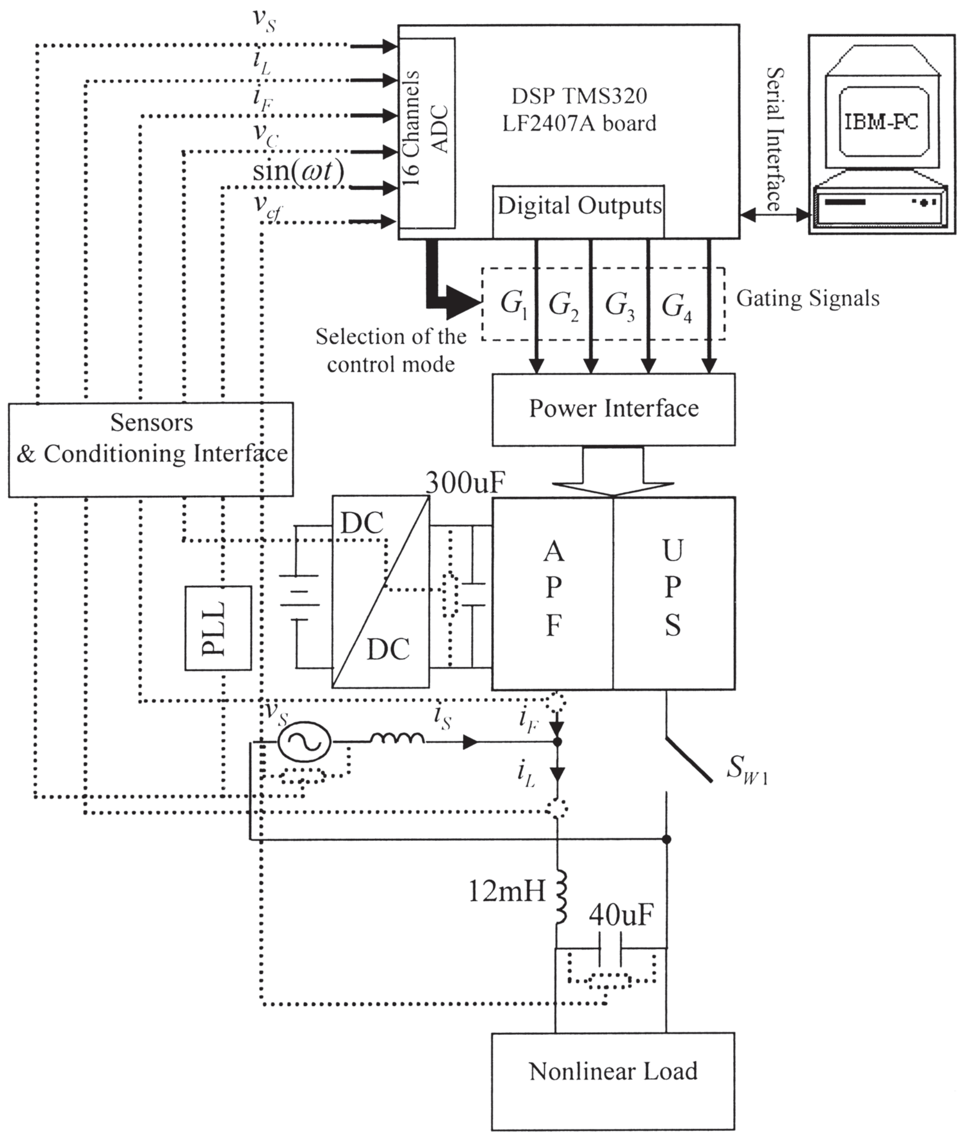


Fig. 12. Hardware set-up imlementation on the DSP micro-controller boar

and reliable power supply system is provided in the off-line UPS mode using feedback loop control to regulate the output voltage and to provide a pure sinusoidal line current.

Overall results show the effectiveness and efficiency of the proposed system.

REFERENCES

1. El-Habrouk M., Darwish M.K, Mehta P.: *Active power filters—A review.* 2000. Proc. IEE—Elect. Power Applicat., vol. 147, no. 5, pp. 403–413.
2. *Power Quality Survey*, BSRIA, report 14419/1, may 1999.
3. Pearson C.C., Uthayanan V.: *The BSRIA power quality guide, application guide.* AG2/2000, July 2000.
4. Ando I., Takahashi I., Tanaka Y., Ikehara M.: *Development of high efficiency UPS having active filter ability composed of a three arms bridge.* 1997. Industrial Electronics, Control and Instrumentation. IECON 97. 23rd International Conference.
5. Bekiarov S.B., Emadi A.: *Uninterruptible power supplies: classification, operation, dynamics and control*. In proceeding of the 17 th IEEE Applied power electronics Conference, Dallas, TX, March 2002, pp. 597–604.
6. Tarafdar Haque M. *Single-phase PQ theory for active filter.* TENCON '02. Proceedings. 2002 IEEE Region 10 Conference on Computers, Communications, Control and Power Engineering Volume 3, 28–31 Oct. 2002 Page(s):1941–1944
7. Emadi A., Nasiri A., Bekiarov S.B.: *Uninterruptible power supplies and active filters.* CRC PRESS 2005.

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