Multiple Feedback Loop Control Strategy for Single-Phase Voltage-Source UPS Inverter

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Abstract— **This paper investigates the performance of multiple feedback loop control strategy for single-phase voltage-source UPS inverter with an L-C filter. In order to select appropriate feedback variables and assess the stability of the closed loop operation of the overall system, the power circuit (inverter and filter plus load) incremental dynamics is investigated using the state-space averaging technique and root locus method. The results of the stability analysis show that a control scheme which employs the filter capacitor current in an inner feedback loop and the load voltage in an outer voltage control loop results in successful operation of the UPS system. Computer simulation results of a single-phase voltage-source half-bridge UPS inverter with a second order filter and R-L load is presented to demonstrate the performance of the proposed control scheme. Experimental verification of a laboratory model of the UPS system is also provided for both linear and nonlinear loads so as to verify the predicted performance of the system. It is shown that the control scheme offers improved performance measures over existing schemes. It is simple to implement and capable of producing nearly perfect sinusoidal load voltage waveform at moderate switching frequency and reasonable size of filter parameters. Furthermore, the scheme has fast dynamic response and high voltage utilization of the DC source.**

I. Introduction

Uninterruptible Power Supplies (UPS) are used to interface critical loads such as computers and communication systems to the utility system. The output voltage of the UPS inverter is required to be sinusoidal with minimum total harmonic distortion. This is usually achieved by employing a combination of pulse width modulation scheme and a second order filter at the output of the inverter.

One way of achieving a "clean" sinusoidal load voltage is by using a sine pulse width modulation (SPWM) scheme [1]. In this technique, the load voltage is compared with a reference sinusoidal voltage waveform and the difference in amplitude is used to control the modulating signal in the control circuit of the power inverter. A more advanced technique employs a programmed optimum PWM scheme which is based on the harmonic elimination technique [1]. These schemes have been shown to perform well with linear loads. However, with non-linear loads the PWM scheme does not guarantee low distortion at the load voltage.

To overcome this drawback, a real-time feedback control scheme using dead-beat control was proposed. This technique employs the capacitor voltage and its derivative in a control algorithm to calculate the duration of the ON/OFF states of the inverter switching devices such that the capacitor voltage is exactly equal to the reference voltage at the next sampling instance. Although this technique has been successfully implemented for single- and three-phase applications, it has the following drawbacks: 1) it is complex to implement; 2) it is sensitive to parameter variations; 3) its control algorithm requires estimation of the load parameters [2].

In order to achieve a control scheme which overcomes the above disadvantages, a current regulated control scheme for DC/AC applications was proposed in [3]. In this technique, the current in the filter capacitor is used as the feedback variable in a two-switch inverter circuit topology to achieve a sinusoidal capacitor current. An outer voltage control loop is also incorporated for load voltage regulation and compensation for imperfections in the implementation of the current control loop.

Although the technique results in a sinusoidal capacitor current, the power circuit configuration and the switching scheme used to implement the technique produce a load voltage which is sinusoidal with DC offset. For UPS applications, the presence of the DC voltage offset is unacceptable.

This paper investigates the suitability of a current-regulated voltage-controlled strategy for a single-phase voltage-source half-bridge inverter with a second order filter. The scheme incorporates an inner capacitor current loop, an outer capacitor voltage loop, a fixed switching frequency and variable duty cycle approach to produce sinusoidal output voltage with minimum harmonic distortion. The fixed switching frequency approach produces a defined frequency spectrum at the inverter output which makes it easier to design an electromagnetic interference filter to prevent interference with communica-

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tion circuits. The proposed scheme has been successfully implemented for a single-phase utility interface system [4].

The paper is organized as follows. Section II provides the steady-state performance of the UPS system under open loop control. A procedure for selecting appropriate feedback variables that result in a stable operation of the closed loop system is provided in section III. Section IV presents the control block of the proposed control strategy, its principle of operation, computer simulation, and experimental verification. Finally, conclusions are drawn in section V.

II. Analytical Model of the Open Loop System

Figure 1 shows the circuit diagram of the single-phase half-bridge voltage-source UPS inverter. It consists of load filter (L_f and C_f) and an R-L load. The system

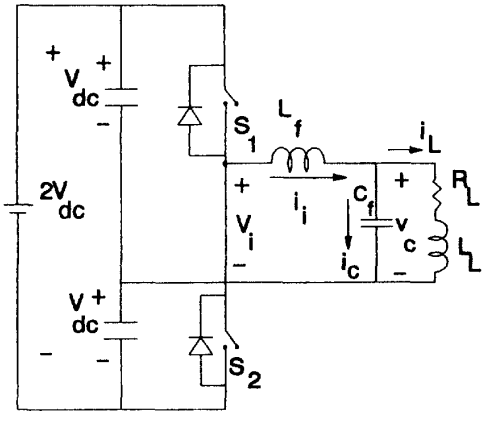

Figure 1: The single-phase half-bridge UPS inverter

differential equations can be written in state-space form as:

$$\frac{d}{dt}\begin{bmatrix} i_i(t) \\ i_l(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} \frac{-R_f}{L_f} & 0 & \frac{-1}{L_f} \\ 0 & \frac{-R_l}{L_l} & \frac{1}{L_l} \\ \frac{1}{C} & \frac{-1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_i(t) \\ i_l(t) \\ v_c(t) \end{bmatrix} + \begin{bmatrix} \frac{V_{dc}(2S_1^*-1)}{L_f} \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

Where $S_1^* = 1$ when S_1 is ON and $S_1^* = 0$ when S_1 is OFF.

Steady-State Performance

Equation (1) is discontinuous due to the presence of the switching function S_1^*. One way of studying the system performance and characterizing its behavior is to solve Eq. (1) numerically and simulate the system behavior at various operating points and system parameters. This method has the disadvantage of being computationally intensive.

On the other hand, an averaged-time continuous model of the UPS system can be obtained for Eq. (1) by assuming that the inverter switching frequency, f_s, is much higher than the frequency of the modulating signal, $v_m(t)$. Thus the discontinuous switching function S_1^* is replaced by its average value, $d_1(t)$, as

$$d_1(t) = \frac{1}{2}\left(\frac{v_m(t)}{V_t} + 1\right) \quad (2)$$

where V_t is the amplitude of the carrier waveform

For a modulating signal given by

$$v_m(t) = V_m \sin(\omega_m t), \quad (3)$$

the system state-space averaged continuous equation can be obtained by substituting the discontinuous switching function, S_1^*, in Eq. (1) by its average value in Eqs. (2) and (3). The resultant system equation is obtained as

$$\frac{d}{dt}\begin{bmatrix} i_i(t) \\ i_l(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} \frac{-R_f}{L_f} & 0 & \frac{-1}{L_f} \\ 0 & \frac{-R_l}{L_l} & \frac{1}{L_l} \\ \frac{1}{C} & \frac{-1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_i(t) \\ i_l(t) \\ v_c(t) \end{bmatrix} + \begin{bmatrix} \frac{M\ V_{dc}\sin(\omega_m t)}{L_f} \\ 0 \\ 0 \end{bmatrix} \quad (4)$$

where M is the modulation index and is given by

$$M = \frac{V_m}{V_t} \quad (5)$$

The first row of Eq. (4) indicates that the averaging process replaces the effect of the inverter switching nature with a controllable sinusoidal voltage source of magnitude $M\ V_{dc}$. It should be noted that Eq. (4) is valid only through the linear range of operation, i.e. $M \leq 1.0$.

Assuming that the resistance associated with the filter inductor is negligibly small, the equivalent circuit of the averaged UPS system is as shown in Fig.2. The system steady-state variables are obtained from Fig.2 using phasor analysis as follows:

$$\vec{I}_i = \frac{V_{dc}\vec{M}}{\vec{Z}_i}, \quad (6)$$

$$\vec{V}_c = V_{dc}\vec{K}\vec{M}, \quad (7)$$

$$\vec{I}_c = \frac{V_c}{-j\ X_{cf}}, \quad (8)$$

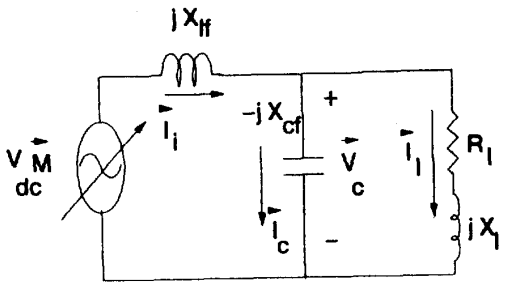

Figure 2: Equivalent circuit of the averaged UPS system

and,

$$\vec{I}_l = \frac{\vec{V}_c}{\vec{Z}_l} \tag{9}$$

where

$\vec{M}$ is the phasor representation of the modulating signal $M\sin(\omega_m t)$

$\vec{I}_i$, $\vec{V}_c$, $\vec{I}_c$, $\vec{I}_l$ are the steady-state variables of the inverter output current, capacitor voltage and current, and load current respectively,

$$\vec{Z}_i = \frac{X_l X_{cf} + X_{lf}(X_{cf} - X_l) + j\, R_l(X_{lf} - X_{cf})}{R_l + j\,(X_l - X_{cf})} \tag{10}$$

$$\vec{K} = \frac{X_l - X_{cf} - j\, R_l X_{cf}}{X_l X_{cf} + X_{lf}(X_{cf} - X_l) + j\,(R_l X_{lf} - R_l X_{cf})} \tag{11}$$

Equations (6) through (11) give the system steady-state variables in terms of the load parameters and filter components.

III. Stability Analysis of the UPS system

In order to successfully close the control loop on the capacitor voltage and make it follow a sinusoidal waveform, the incremental dynamics of the power circuit is studied first. Assuming that the variation in the duty cycle is slower than the bandwidth of the control loop, the effect of incremental changes in the duty cycle on the power circuit variables can be studied in a quasi static manner [5]. This is carried out using the state-space averaging technique, [6], and root locus method.

The equations describing the incremental dynamics of the power circuit are obtained as:

$$\frac{\begin{bmatrix} \hat{v}_c \\ \hat{i}_c \end{bmatrix}}{\hat{d}} = \frac{\frac{2V_{dc}}{L_f}\begin{bmatrix} \frac{1}{C}(s + \frac{R_l}{L_l}) \\ s(s + \frac{R_l}{L_l}) \end{bmatrix}}{s^3 + \frac{R_l}{L_l}s^2 + \frac{1}{C}(\frac{1}{L_l} + \frac{1}{L_f})s + \frac{R_l}{L_f L_l C}}, \tag{12}$$

where $\hat{v}_c$, $\hat{i}_c$, $\hat{d}$ indicate incremental changes in the capacitor voltage, current, and the duty cycle respectively.

Figure 3 shows the root locus of the incremental dependence of the capacitor voltage and current due to incremental changes in the duty cycle. Figure 3.a shows that for a simple feedback of the capacitor voltage, the control system exhibits oscillatory behavior in the capacitor voltage. Such behavior is unacceptable for UPS operations.

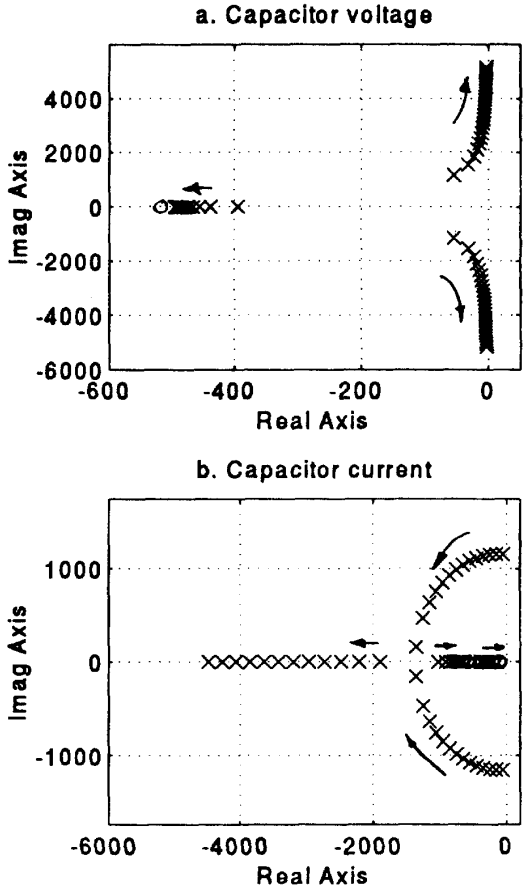

Fig. 3: Root Locus of the power circuit incremental dynamics

The root locus for a simple feedback operation of the capacitor current (Fig. 3.b) shows that a feedback control involving the capacitor current results in moving the system poles further to the left of the S-plane. Thus, a stable operation of the control system can be achieved. Therefore, the capacitor current is chosen as the feedback variable of the closed loop system.

Although choosing the capacitor current as the feedback variable results in a stable operation of the closed loop UPS and ensures sinusoidal capacitor current, it does not guarantee sinusoidal capacitor (load) voltage, especially when the inverter output voltage is non-sinusoidal. Therefore, in order to achieve sinusoidal capacitor voltage and current, an outer capacitor voltage feedback loop is also used.

IV. The proposed UPS Control System

A. General Features

The resultant configuration of the proposed control scheme offers many advantages for UPS system applications. The inner current loop provides an inherent peak current limit in the power circuit. In addition, since the capacitor current represents the rate of change of the load voltage, the control scheme is capable of predicting and correcting variations in the load voltage, and thus providing a fast dynamic response. Furthermore, the outer voltage loop regulates the load voltage and ensures that the load voltage is sinusoidal within the acceptable THD.

Figure 4 shows the UPS system with an inner current loop and an outer voltage loop. The capacitor voltage variable is obtained in the control circuit by integrating the actual capacitor current . The error signal $e_c(t)$ is obtained from successive comparison of the capacitor voltage and current with their respective reference signals. The inverter switching pattern is then obtained from a comparison of $e_c(t)$ and a fixed frequency triangular waveform. The resultant switching pattern, which has a fixed switching frequency with variable duty cycle, produces a sinusoidal load voltage with very low harmonic content.

B. Computer Simulation

The UPS system is simulated to obtain the capacitor voltage and current waveforms. Closed-form solutions (of Eq. (1)) of the power circuit variables, namely; the inverter output current, $i_i(t)$, the capacitor voltage, $v_c(t)$, and current, $i_c(t)$, and load current, $i_l(t)$ within a switching interval (ON/OFF) were obtained using a symbolic computation package MAPLE V [7]. The closed-form solution and the control algorithm were employed to obtain the switching instants of the inverter switches.

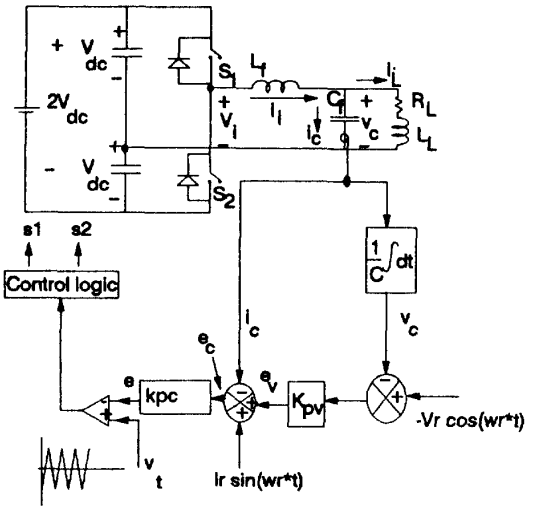

Fig 4: The proposed control scheme of the single-phase UPS inverter

The following system parameters were used;

L_f = 5.0 mH, C_f =180.0 μF,
k_{pc}=1.0 k_{pv}=5.0, f_s=3.2 kHz,
V_{dc}=60.0 V, Z_l=10.0 Ω at 0.8 pf lagging.

Equations (6) to (11) were used to obtain the desired steady-state variables (reference waveforms). The modulation index was determined from (7) such that a voltage gain of 92.0% of the input DC voltage, V_{dc}, was achieved.

The capacitor voltage and current waveforms in the proposed UPS system are shown in Figs. 5.a and 5.b. Figure 5.a shows that the capacitor (load) voltage is nearly perfect sinusoidal waveform after a quarter cycle from "cold" start of the power circuit. The figure also shows that the proposed control scheme has high voltage gain (92% of V_{dc}). The filter capacitor works as a trap for higher order harmonics (Fig. 5.b) and produces a nearly perfect sinusoidal waveform at the load voltage with minimum steady-state error.

C. Experimental Results

A prototype experimental module of the proposed UPS (Fig. 4) was built to verify the operation of the control strategy. Both the actual capacitor voltage and current in the power circuit were sensed, filtered and used as the

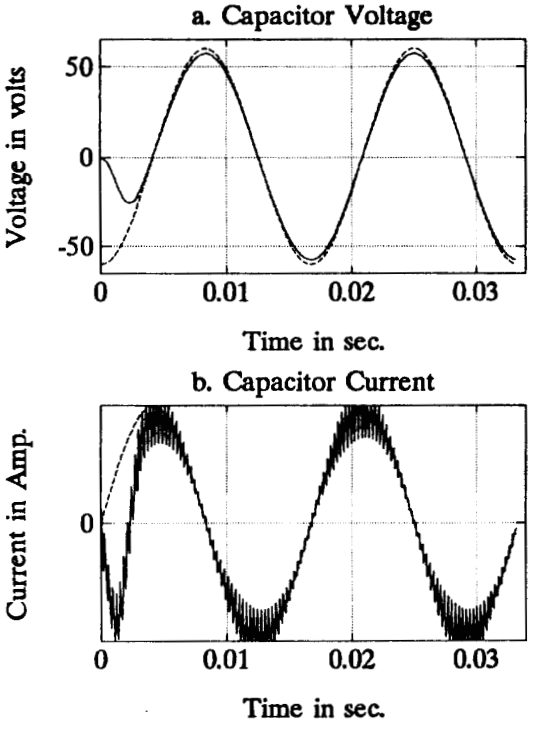

Fig 5: Computer simulation of the capacitor voltage and current waveforms of the proposed UPS system: a) Capacitor voltage and b) Capacitor current (dashed line: reference waveform, solid line : simulated waveform)

control variables. The experimental results were obtained for the same system parameters as the computer simulation results.

Fig. 6 shows the transient response from "cold" start to full load of the proposed UPS system. The upper trace shows the capacitor voltage and the lower trace shows the capacitor current. The capacitor current was recorded by observing the voltage drop across a current shunt of 10.0 mΩ resistance. The figure shows that the system takes about a quarter cycle to reach the steady-state values of the capacitor voltage and current. Figures 5 and 6 show that the simulation and experimental results are in good agreement. The steady-state load voltage and current waveforms of the UPS system are depicted in Fig. 7. The figure shows that the control strategy is capable of producing a nearly perfect sinusoidal load voltage at moderate switching frequency. Figure 8 shows the frequency spectrum of the capacitor (load) voltage. The capacitor voltage has a THD of 2%.

Figure 9 shows the dynamic response of the UPS system for 100 % step change in the load from no-load to full-load. The figure shows that the system exhibits very fast dynamic response with excellent load voltage regulation from no-load to full-load, and with very little change in the load voltage at the point of applying the full load, indicating that the control scheme ensures a 'stiff' load voltage.

The system performance with non-linear loads is shown in Figs. 10 and 11. The non-linear load was chosen as a full-bridge rectifier feeding a resistive load of 10 Ω (Fig.10) , and R-L load, R=20.0 Ω and L=16.0 mH, (Fig. 11). The load current was recorded by observing the voltage drop across the load resistance using $\frac{1}{50}$ attenuation oscilloscope probe.

Figures 7 to 11 show that the proposed control scheme is capable of supplying both linear and non-linear loads with excellent voltage regulation and minimum distortion in the load voltage.

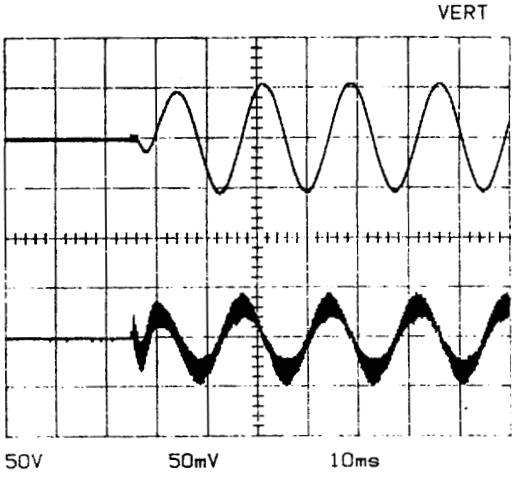

Fig. 6: Experimental results of the transient response of the proposed UPS system: Upper trace: capacitor voltage, Lower trace: capacitor current.

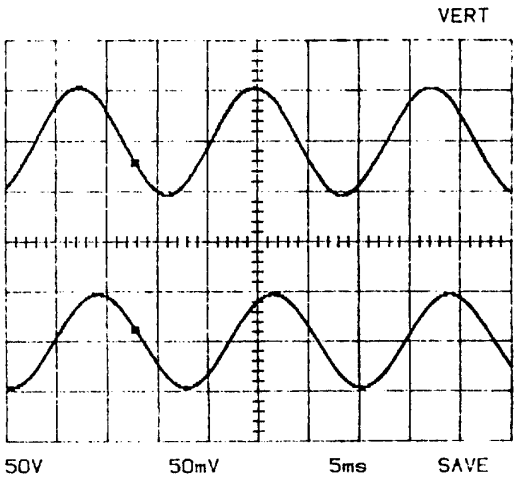

Fig. 7: Experimental results of the steady-state response of the proposed UPS system: Upper trace: capacitor voltage, Lower trace: capacitor current.

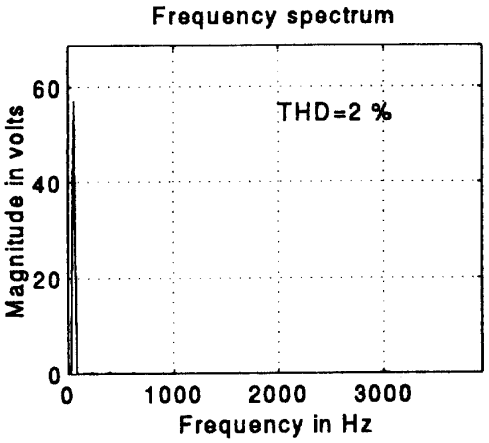

Fig. 8: Frequency spectrum of experimental results of the steady-state capacitor voltage.

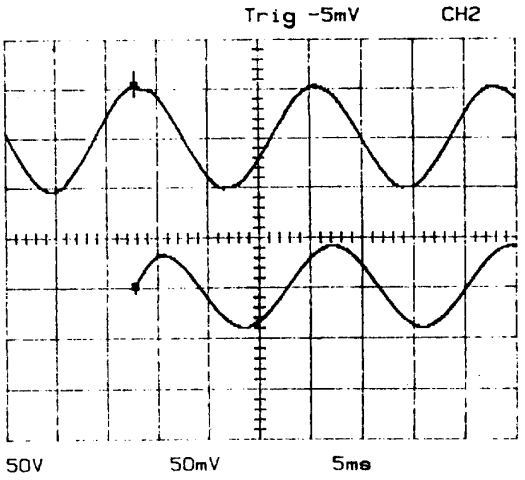

Fig. 9: Experimental results of the dynamic response of the proposed UPS system for a 100 % step change in the load: Upper trace: capacitor voltage, Lower trace: capacitor current.

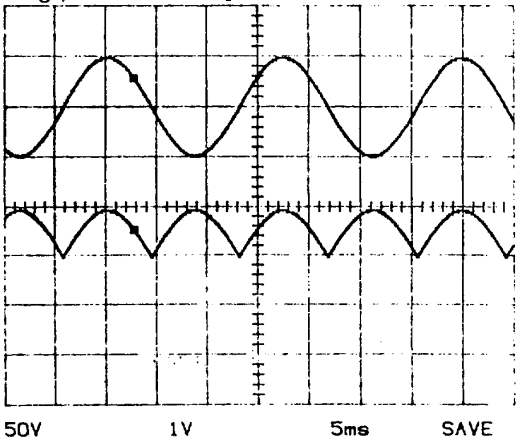

Fig. 10: Experimental results of the proposed UPS system feeding a full-bridge rectifier with a resistive load: Upper trace: capacitor voltage, Lower trace: load current.

VI. Conclusions

A multiple feedback loop control strategy for single-phase voltage-source UPS system has been described in the paper. The system performance under open-loop control strategy was first studied to obtain the steady state performance of the UPS system. The power circuit incremental dynamics was then investigated to assess the system stability and select appropriate feedback variables in the closed loop system. The stability analysis showed that a feedback control system with an inner capacitor current control loop and an outer capacitor voltage feedback loop results in a successful operation of the UPS system. The proposed control strategy offers many features which are attractive for UPS applications. In addition to the basic features of most feedback control systems, such as insensitivity to parameter variations and robustness, the scheme is capable of producing nearly perfect sinusoidal

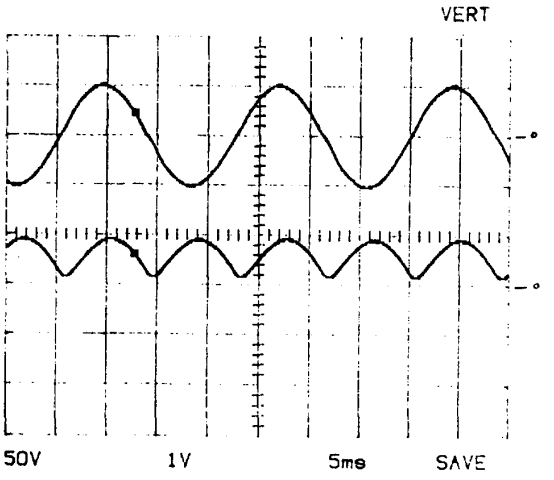

Fig. 11: Experimental results of the proposed UPS system feeding a full-bridge rectifier with an R-L load: Upper trace: capacitor voltage, Lower trace: load current.

load voltage at any load power factor with excellent load voltage regulation. The scheme also possesses very fast dynamic response and lends itself to both linear and non-linear load applications.

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