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Performance Evaluation of a Proportional-Integral with Proportional-Derivative Feedforward Voltage Control for UPSs

Tiago J. C. Sousa, Vítor Monteiro, Júlio S. Martins, J. C. Aparício Fernandes, João L. Afonso
ALGORITMI Research Centre – University of Minho
Guimarães – Portugal
{tsousa | vmonteiro | jmartins | aparicio | jla}@dei.uminho.pt

***Abstract*—This paper presents a performance evaluation of a proportional-integral (PI) with proportional-derivative (PD) feedforward control for the output voltage of a single-phase off-line uninterruptible power supply (UPS) without using additional sensors. The control system is explained and simulation results are presented to analyze the steady state and transient response of the implemented voltage control. A laboratorial prototype was developed, and acquired experimental results considering linear and nonlinear loads are presented and discussed, corroborating the obtained simulation results.**

***Keywords*—Voltage Source Inverter, Uninterruptible Power Supply (UPS), PI Control, PD Control, Feedforward Control.**

I. INTRODUCTION

Voltage source inverters (VSIs) represent a vital role in today's power systems. The ability to control the output voltage and frequency from a constant dc voltage source made VSIs attractive for electric motor drive systems, such as adjustable speed drives [1][2] and the increasingly proliferative electric vehicles [3][4]. The field of application of VSIs also extends to power conditioning, namely reactive power control [5], current and voltage harmonics suppression by means of shunt and series active power filters and unified power quality conditioners [6][7], and voltage disturbances such as sags and swells, which are commonly handled by dynamic voltage restorers [8] and uninterruptible power supplies (UPSs) [9]. Moreover, the growing paradigm of distributed generation requires an interface with the power grid, which is most commonly accomplished with a VSI, either in grid-connected mode or in islanded mode [10][11]. Besides, this paradigm looks forward towards the imminent trend of smart grids, an essential asset in future power systems [12].

Depending on its purpose, a VSI can be current-controlled or voltage-controlled [13]. The former is commonly applied in grid-connected inverters, where the output voltage cannot be controlled, since it is imposed by the power grid. This approach can be used to interface renewable energy systems with the power grid, where the VSI operates as a sinusoidal current source with the purpose of injecting energy into the grid, and can also be used in shunt active power filters, where the VSI behaves as a harmonic current source in order to cancel the harmonic distortion produced by the downstream connected nonlinear loads. On the other hand, a voltage-controlled VSI, or the so-called stand-alone inverter, operates as a voltage source [14]. The most common application examples of voltage-controlled VSIs include islanded microgrids and UPSs, where the main objective is to produce a sinusoidal voltage with the desired amplitude and frequency to feed a set of linear and/or nonlinear electrical loads.

The performance of the output voltage control of a VSI can be affected by the connected loads. In the presence of linear loads there are no major disturbances in the synthesized voltage. However, nonlinear loads tend to distort the voltage produced by the converter due to harmonic currents absorption, especially when high *di/dt* is involved. To deal with this issue, several control strategies have been applied and enhanced, such as repetitive control [15], deadbeat [16], sliding mode [17], model predictive control [18], and synchronous reference frame [19], where its application for a three-phase UPS system is studied in [20]. However, despite the control performance, computational effort also needs to be considered. This issue and the steady state error for several control techniques are both investigated in [21]. References [22] and [23] inspect the use of multi-loop control techniques for UPS applications, improving the controller response without adding a major computational overhead. However, multi-loop control requires additional voltage or current sensors, since more than one system variable is being measured.

An off-line UPS is a device connected in parallel with the power grid that only provides load protection when power outages occur, and therefore it is deactivated during most part of the time. Nevertheless, an off-line UPS can provide shunt active filtering during normal operation of the power grid, since its power structure and connection are the same as those of a shunt active power filter. For this purpose, two current sensors are needed, namely for the connected loads and for the produced output current. In this context, this paper presents a proportional-integral (PI) with proportional-derivative (PD) feedforward voltage control scheme applied in a single-phase off-line UPS with shunt active filtering capability, taking into consideration the tradeoff between output voltage quality, number of sensors and control complexity. The implemented control allows a relatively fast dynamic response, meaning that a low-distortion output voltage can be attained in the presence of nonlinear loads without additional sensors. In the scope of this

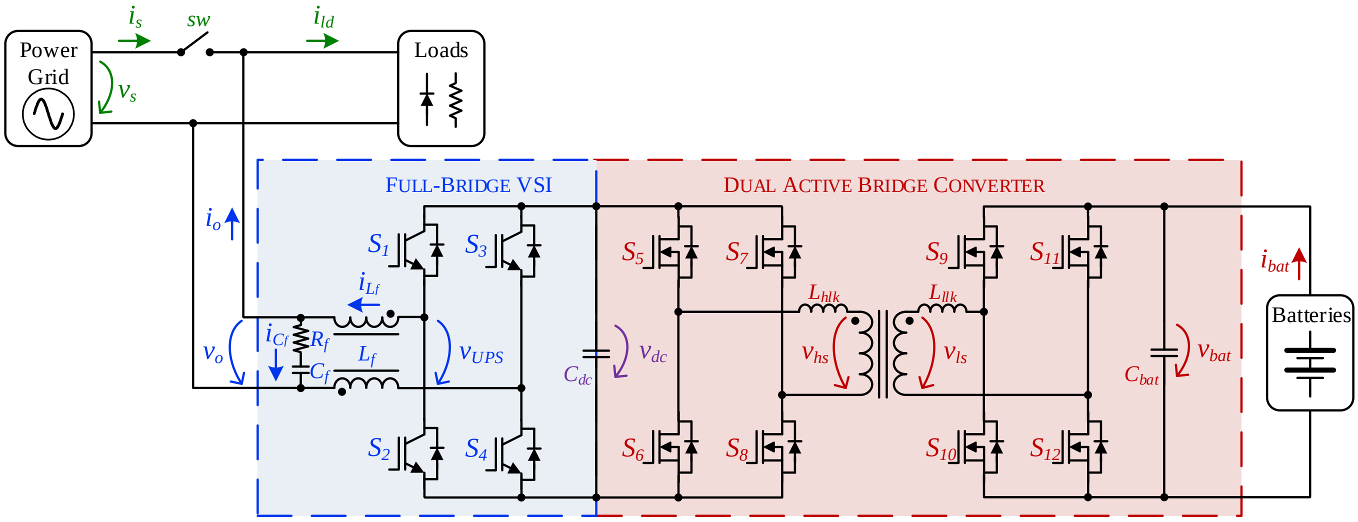

Fig. 1. Topology of the developed single-phase off-line uninterruptible power supply (UPS).

paper, only the backup operation of the UPS is taken into account.

The paper is organized as follows. Section II describes the developed control structure as well as the power system. Section III presents computational simulations to evaluate the developed control under different scenarios. The developed prototype and experimental results are shown in Section IV and conclusions are addressed in Section V.

II. SYSTEM DESCRIPTION

This section presents the topology of the single-phase off-line UPS, as well as the developed voltage control for the backup mode. As mentioned before, the grid normal operation is not considered in the scope of this paper.

A. UPS Topology

Generally, an off-line UPS consists of a dc-ac converter to produce the necessary voltage to feed the loads and an additional converter to charge the batteries, which is a bidirectional isolated dc-dc converter in the chosen topology. Fig. 1 depicts the referred topology and its connection to the power grid. The dc-ac converter consists of a full-bridge VSI (switches S_1 to S_4), while the dc-dc converter consists of a dual active bridge converter (switches S_5 to S_{12}). The dc-link (C_{dc}) is shared by both converters. In the figure, it is visible an extra switch (*sw*) to disconnect the loads from the power grid when a power outage occurs. A power rating of 4.6 kW was considered for the UPS, corresponding to a maximum output current rms value of 20 A for a 230 V, 50 Hz power system.

Since the presented off-line UPS operates as shunt active power filter during the normal state of the power grid, sensors for measuring the loads current (i_{ld}) and the output current (i_o) are needed. The power grid voltage (v_s) needs to be measured both in normal and backup modes, so that power outages can be detected and proper synchronization can be performed for the injection of the compensating current. Also, for the voltage control during the backup mode, a sensor must be used to measure the output voltage of the UPS (v_o). Although not considered in this paper, the normal operation mode can additionally charge the batteries (simultaneously or not with the shunt active filtering operation), thus sensors are needed for the batteries voltage (v_{bat}) and current (i_{bat}).

It can be seen that the VSI is connected to the power grid by means of a passive filter composed by a mutually coupled inductor (L_f), a capacitor (C_f) and a resistor (R_f). The operation as shunt active power filter (during normal grid operation) is mostly influenced by the inductive component of the passive filter, being possible to neglect the capacitive (and therefore resistive) element without sacrificing the performance of the current control. However, when voltage is the controlled variable, i.e., during the backup operation of the UPS, the capacitive part has a major role in the control performance. Both issues could be solved by using sufficiently large values of L_f and C_f, but that would decrease the cut-off frequency of the passive filter and decline the performance of the shunt active filtering capability, inhibiting the compensation of higher order current harmonics. As a result, the passive filter sizing must follow a compromise relationship between the desired operation modes. Considering a switching frequency of 50 kHz for the VSI with a unipolar pulse-width modulation (PWM) scheme, which doubles the ripple frequency to 100 kHz, the chosen values for the passive filter were 1.2 mH for L_f and 10 μF for C_f. The resonant frequency of the filter (f_0) is given by:

$$f_0 = \frac{1}{2\pi\sqrt{L_f\, C_f}}, \tag{1}$$

where a value of 1.45 kHz is obtained. The resistor R_f does not interfere with f_0, but it has the purpose of damping the gain around this frequency, otherwise instability can occur in the power converter and control system. For this purpose, a value of 8 Ω was selected for R_f. The damping factor (ζ) of the filter can be calculated according to:

$$\zeta = \frac{R_f}{2}\sqrt{\frac{C_f}{L_f}}, \tag{2}$$

whereby a value of 0.365 is obtained. Fig. 2 shows the Bode plot of the designed passive filter, where it can be seen that the maximum gain is approximately 4.8 dB at 1.3 kHz.

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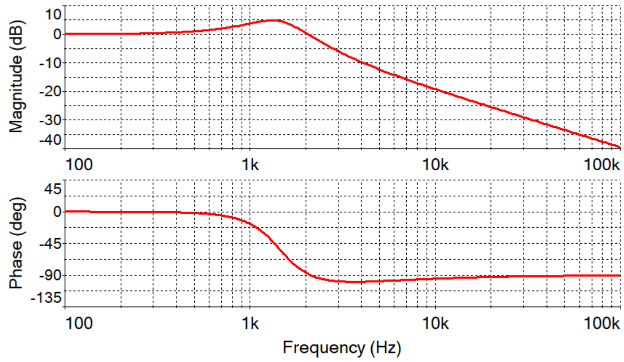

Fig. 2. Bode plot of the selected RLC passive filter for the UPS.

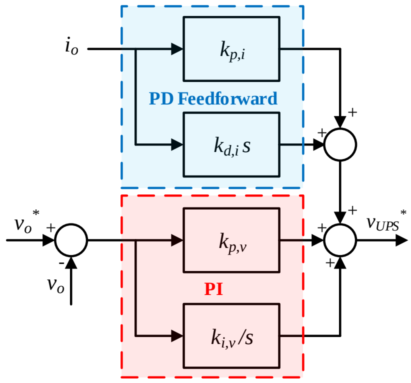

Fig. 3. Block diagram of the implemented PI with PD feedforward voltage control.

B. Control System

The control system of the off-line UPS comprises two main tasks: (1) The regulation of the dc-link voltage, which is accomplished by the dual active bridge converter; (2) The control of the output voltage of the UPS, performed by the VSI. The main focus of this section is addressing the latter task.

1) Dc-Link Voltage Control

In order to synthesize a voltage with the desired amplitude, a VSI must have a dc-link voltage (v_{dc}) greater than the peak value of the required output voltage (v_o). Therefore, the dual active bridge converter is controlled with the purpose of maintaining v_{dc} in an established reference value to assure the proper operation of the VSI. For this purpose, a phase shift modulation [24] regulated by a PI controller was implemented. However, in the scope of this paper, this issue is not analyzed. More details of the applied control can be found in [25].

2) Output Voltage Control

As aforementioned, a PI with PD feedforward voltage control is used to achieve proper transient response and low-distortion output voltage without needing additional hardware. Although many of the multi-loop voltage control schemes use either the inductor current (i_{Lf}) or the capacitor current (i_{Cf}) of the passive filter, the developed system uses the total output current (which is equal to the loads current in the backup mode). Considering:

$$i_{L_f} = i_{C_f} + i_o \tag{3}$$

$$v_o = v_{C_f} + v_{R_f} = v_{UPS} - v_{L_f}, \tag{4}$$

where v_{Lf}, v_{Cf} and v_{Rf} are the filter inductor, capacitor and resistor voltage drop, respectively, and v_{UPS} is the pre-filtered UPS output voltage, the state space model of the VSI with the passive filter can be defined by:

$$\begin{bmatrix} \frac{dv_{C_f}}{dt} \\ \frac{di_{L_f}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C_f} \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} \end{bmatrix} \begin{bmatrix} v_{C_f} \\ i_{L_f} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{L_f} \end{bmatrix} v_{UPS} + \begin{bmatrix} -\frac{1}{C_f} \\ \frac{R_f}{L_f} \end{bmatrix} i_o. \tag{5}$$

The input of the model is v_{UPS}, while i_o is regarded as a disturbance in v_o. As the feedback variables consist of v_o and i_o, the realized controller applies a PI control for v_o and a feedforward component for i_o, which is achieved using both the instantaneous value and its digital derivative. Since high di/dt is the main source of distortion in the produced voltage, the use of a derivative control component in the measured current aims to compensate possible deviations of the desired voltage with considerable rapidness. A proportional component is also necessary because the deviation of the voltage from its reference increases with the load demand, as it is common in any power supply system. Hence, the developed control does not fit into the multi-loop control strategies, since there is only one feedback loop (for voltage), which is followed by a feedforward component (for current). Fig. 3 depicts a block diagram of the referred voltage control.

For the feedforward controller gains, a pole zero cancelling based on PD control was applied [26]. The loop transfer function ($H(s)$) can be defined as:

$$H(s) = \frac{1}{s^2 + 2\,\zeta\,\omega_0\,s + \omega_0^2}, \tag{6}$$

where $\omega_0 = 2\pi f_0$. According to (1) and (2), $H(s)$ is given by:

$$H(s) = \frac{1}{s^2 + \frac{R_f}{L_f}s + \frac{1}{L_f C_f}}. \tag{7}$$

On the other hand, the PD controller transfer function can be defined as:

$$G_{PD_i}(s) = k_{d_i}\,\frac{s^2 + \frac{k_{p_i}}{k_{d_i}}s}{s}. \tag{8}$$

Therefore, pole cancelling can be achieved by making:

$$\frac{k_{p_i}}{k_{d_i}} = 2\,\zeta\,\omega_0 = \frac{R_f}{L_f}. \tag{9}$$

In spite of not being a PD controller, since the action is not performed on an error value but in the variable itself, the PD gains respect the calculated ratio, once a feedforward controller transfer function is $1/G_{PDi}$.

III. Simulation Results

This section depicts the computational simulation results obtained in PSIM 9.1 with the implemented voltage control, where both steady state and transient analysis are evaluated. In order to inspect the performance of the voltage control with a reliable simulation model and close to a real system, a dead-time of 500 ns was considered for the VSI switches, as well as a

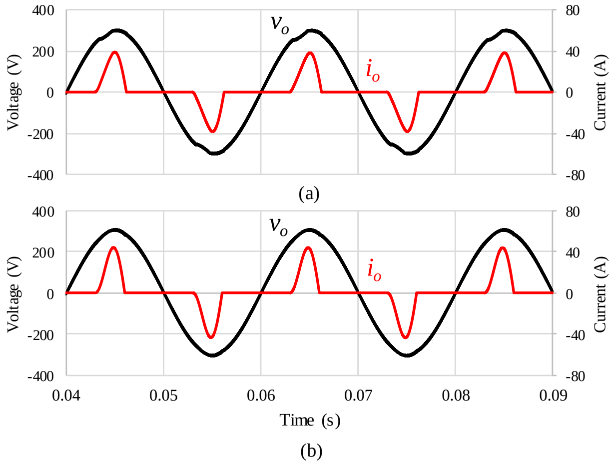

Fig. 4. Steady state performance comparison of the UPS using:(a) Single PI voltage control; (b) PI with PD feedforward voltage control.

20 mΩ dc-link capacitor internal resistance and a 100 mΩ internal resistance for inductor L_f. The modulation index was set to 0.9.

A. Steady State Analysis

Fig. 4 shows a performance comparison between a single PI controller and the implemented PI with PD feedforward voltage control in steady state for the same connected load, which is a diode rectifier with capacitive output filter (470 µF) plus resistive load (40 Ω) and inductive input filter (1 mH). As it can be seen, the single PI controller allows some voltage distortion caused by a rapid increase of the nonlinear load current (i_o), while the PI with PD feedforward controller is capable of reducing the total harmonic distortion (THD) of the output voltage (v_o) from 2.5% to 1.1%. An increase in the peak value of i_o is also noticeable (from 39 A to 44 A) due to the improvement on v_o waveform.

B. Transient Analysis

Fig. 5 depicts the transient response of the UPS towards a load connection. Initially there is only one connected load, which is a diode rectifier with inductive output filter, consuming 3.65 kW of active power with i_o presenting a THD of 46%. This type of nonlinear load is characterized by high di/dt when the fed voltage crosses the zero value. As it can be seen, the output voltage of the UPS (v_o) shows a slight zero crossing distortion, although its THD has a low value (1.03%). The figure also scrutinizes the applied controller components, where it can be seen the proportional and integrative components used in v_o control loop (v^*_p and v^*_i, respectively), the proportional and derivative feedforward components of i_o (i^*_p and i^*_d, respectively) and the total output of the controller (v_{UPS}^*), which is the sum of the four aforementioned components and means the applied duty-cycle to the arbitrated positive leg of the VSI. As it can be observed, both v^*_p and i^*_d present high spikes in the zero crossings of v_o, meaning the controller action to compensate the v_o distortion.

Another nonlinear load is connected at instant 0.045 s, namely a diode rectifier with capacitive output filter and inductive input filter. The chosen instant means the worst-case scenario for this type of load, since it corresponds to 90º of v_o,

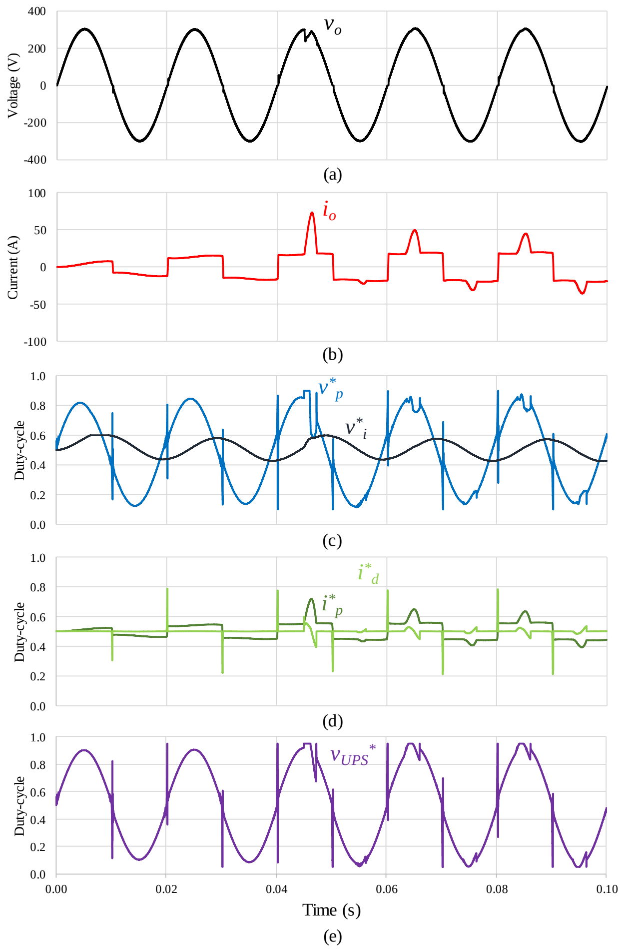

Fig. 5. Transient response of the UPS using the PI with PD feedforward voltage control for the connection of a nonlinear load at instant 0.045 s: (a) Output voltage (v_o); (b) Output current (i_o); (c) Proportional (v^*_p) and integral (v^*_i) components of the voltage control loop; (d) Proportional (i^*_p) and derivative (i^*_d) components of the current feedforward control; (e) Controller total output ($v_{UPS}{}^*$).

i.e., its maximum value. Consequently, the load absorbs a peak of 73 A, with v_o dropping to 239 V. At this point, it is visible that the controller saturates, but v_o reaches back to its reference after 1.25 ms. The THD of v_o during the transient, i.e., considering only the full-cycle from 0.04 s to 0.06 s, is 4.4%. The connected load absorbs an active power of 930 W in steady state, whereby the UPS provides a total active power of 4.58 kW (99.6% of the nominal power). The measured THD of v_o is 1.3%, while i_o portrays a final THD of 38%.

IV. Experimental Validation

In this section, the laboratorial prototype developed for the single-phase off-line UPS is presented, as well as the obtained experimental results concerning the output voltage control. The obtained laboratorial results confirm the controller performance depicted in the computational simulations, validating the control system in a real environment.

A. Developed Prototype

In order to validate the presented voltage control scheme, a small-scale prototype was developed. Fig. 6 shows the referred

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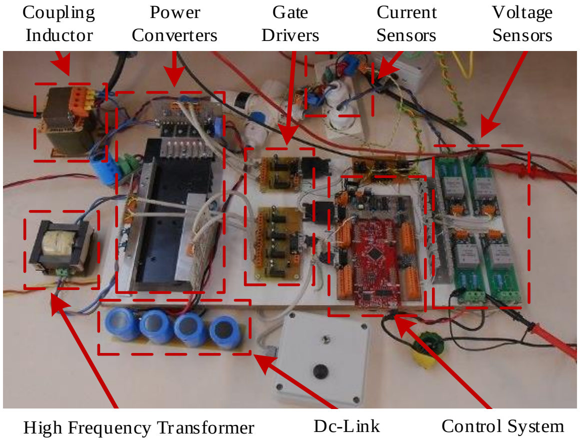

Fig. 6. Single-phase off-line UPS developed laboratorial prototype.

prototype mounted in the laboratorial workspace. As it can be seen, four voltage sensors are used, namely for the measurement of the power grid voltage (v_s), the UPS output voltage (v_o), the dc-link voltage (v_{dc}) and the batteries voltage (v_{bat}). For measuring currents, three sensors were applied, namely for the loads current (i_{ld}), the UPS output current (i_o) and the batteries current (i_{bat}). The employed digital control structure uses the TMS320F28377S DSP from Texas Instruments. To switch the power semiconductors, six isolated half-bridge gate drivers ADUM3223 from Analog Devices were used. In the VSI were used 4 IKW40N65H5 IGBTs from Infineon Technologies operating at a switching frequency of 50 kHz. The dual active bridge uses 4 IPP50R190CE MOSFETs from Infineon Technologies in the high-voltage bridge and 4 PSMN015-60PS MOSFETs from NXP Semiconductors on the low-voltage bridge, all operating at a switching frequency of 100 kHz.

B. *Experimental Results*

To validate the obtained simulation results, a sinusoidal reference voltage with a peak value of 50 V was used, as well as a dc-link voltage with a reference value of 80 V. The output voltage control was verified towards two types of loads. In addition, since the voltage values involved in the experimental proceeding are reduced when compared to the simulation, a translation of the voltage and current values was made. Therefore, instead of maintaining the values of load power, the values of impedance were matched, so that similar load current waveforms can be attained between real loads and the simulated loads with a close voltage/current ratio. In this context, the performance of the controller can be evaluated in a similar way.

Fig. 7 shows the obtained experimental results with the UPS feeding a linear load, which is a 9 Ω resistor. It can be seen that the load current (i_o) has a peak value of 5 A and the same waveform as the UPS output voltage (v_o), which has a peak value of approximately 45 V. It can be seen that v_o is practically sinusoidal, presenting a THD of 1.4%.

Fig. 8 depicts the obtained experimental result of the UPS in the presence of a nonlinear load. This load is comprised by a diode rectifier with capacitive output filter (470 µF) connected in parallel with a 50 Ω resistor. The input of the diode rectifier is connected in series with a 250 µH inductor, whose low value allows a fast increase in the absorbed current (i_o). The peak value of i_o is about 4 A, with the UPS output voltage (v_o) presenting a

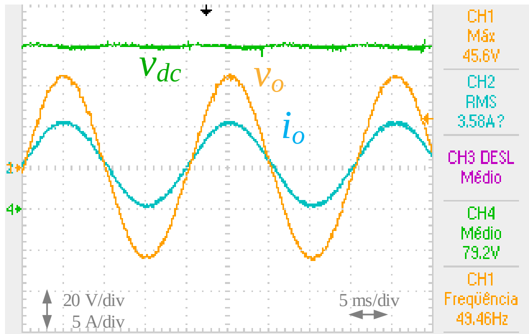

Fig. 7. Experimental results of the developed UPS under linear load: Output voltage (v_o); Output current (i_o); Dc-link voltage (v_{dc}).

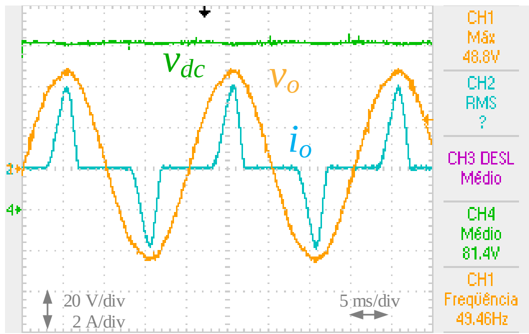

Fig. 8. Experimental results of the developed UPS under nonlinear load: Output voltage (v_o); Output current (i_o); Dc-link voltage (v_{dc}).

peak value of 49 V and a THD of 1.9%. As it can be noted, the voltage controller compensates the voltage reduction caused by the distorted current.

V. CONCLUSIONS

A proportional-integral (PI) with proportional-derivative (PD) feedforward voltage control applied in a single-phase off-line UPS with shunt active filtering capability is presented. The presented scheme does not require additional voltage or current sensors, since the UPS can operate as a shunt active power filter during the power grid normal operation. Besides, the use of a PD feedforward control component in the measured output current offers an improved transient response under nonlinear loads with high harmonic distortion and high *di/dt*. In order to validate the developed control, a small-scale laboratorial prototype was developed. Experimental tests were performed under linear and nonlinear loads, and the validity of the PI with PD feedforward voltage control was verified. The evaluated control, as well as the additional hardware needed for the UPS backup operation, can be applied in a regular single-phase shunt active power filter, enhancing its functionalities. On the other hand, a current sensor can be added to a regular single-phase off-line UPS, allowing shunt active filtering capability in the normal mode of operation, and also improving the voltage control in the backup mode, using only two sensors.

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