DESIGN OF A 660V / 15 KVA SINGLE-PHASE UPS BASED ON SERIES CONNECTION OF LOW-OUTPUT-VOLTAGE MODULAR UPS

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***Abstract*- Critical loads are usually provided by sources of uninterruptible power supply (UPS). Such devices have output voltages equivalent to levels found in commercial power grids. However, when high output voltages are required there is still no standard solution to achieve the desired level of voltage. This paper proposes the development of a high-output-voltage single-phase UPS based on the series connection of several low-output-voltage modular UPSs. The main idea is to obtain a commercial UPS in one standard module which can connect several modules in series until reaching the required output voltage. This solution allows high-voltage to be obtained employing only available modules and being of low cost it is suitable for industrial application. In this context, this paper introduces some principles regarding the series connection of UPS, which translates into the serial connection of voltage source inverters (VSIs). Furthermore, the study provides the experimental verification of the proposed system through the development of a prototype of 660V and 15kVA, obtained from the connection of three single-phase modules of 220V and 5kVA.**

***Keywords* – High Output Voltage, UPS, Series Connection.**

I. INTRODUCTION

In recent years, the demand for solutions based on system integration has attracted the attention of the power electronics community and the electronics industry [1] [2]. This concept has been applied at three levels: component, module and system integration [3] [4]. The parallel connection of uninterruptible power supplies (UPSs), much researched in recent years [5]–[12], and the series connection of UPSs, proposed in this paper, are examples of solutions that are based on the concept of system integration. This tendency to combine simple systems in order to resolve complex problems has resulted from the need for solutions that provide cost reduction, modularity, low maintenance time and reliability.

In this context, the series connection of UPSs, which translates into the series connection of VSIs, is a recent topic which has great potential. This structure was introduced in [4] and has been explored recently in [3] for inverters with input and output stages within a series connection. Recently, this type of connection has also been studied for the connection of Photovoltaic (PV) inverters. The series connection of UPS was introduced in [26] to obtain an equivalent system of high output voltage and emerges as an attractive option for special applications that require an uninterruptible power supply of medium or high voltage. An advantage of the series connection of UPS is the possibility of employing modular UPSs, as illustrated in Figure 1, which can reduce the cost, designer time and complexity.

A review of the literature reveals that a classic solution to obtain a UPS with an output voltage greater than the voltage provide by the electrical grid employs a standard UPS and a transformer at the output to raise the voltage to the desired value. However, this solution requires a special transformer and a single UPS provides all of the load power. Other solutions reported in the literature are based on three converters: an AC-DC, a DC-DC booster, and a DC-AC. In most cases the differences between the structures are found in the second and third stages. The DC-DC solution was obtained through converter boosters [13] [14] or the series connection of DC-DC converters [15]–[18]. The DC-AC solution has been used for traditional VSIs employing high voltage components [19], or for a multilevel inverter [20]–[25]. The combination of these options creates interesting solutions. Nevertheless, many of them require control and modulation strategies and also the topologies are patented. Additionally, all options reviewed employ the integration of modules, that is, each specification requires a new design for the internal structure of the UPS.

The series connection of UPSs introduced recently in [26] still has many aspects to be explored. In this context, this paper extends the studies on the series connection of single-phase commercial UPSs to design high-output-voltage UPSs.

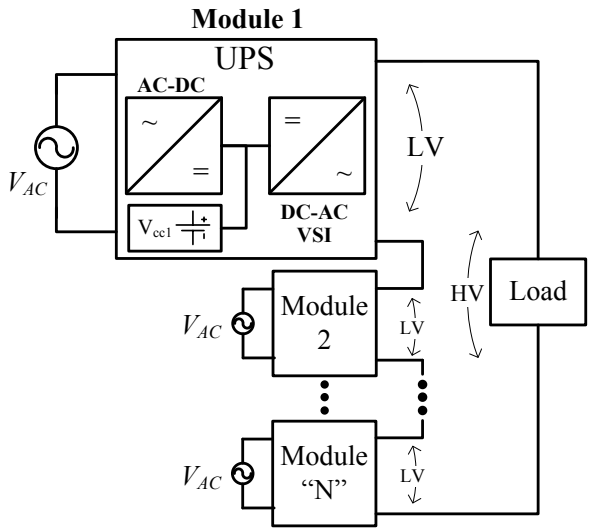


Fig. 1. Topology for high-output-voltage single-phase UPS based on the series connection of low-output-voltage modular UPSs.

Manuscript received 27/01/2012; revised 31/05/2012. Accepted for publication 09/07/2012 by recommendation of the Editor Henrique A. C. Braga.

II. SERIES-CONNECTED SINGLE-PHASE INVERTERS

The series connection of the inverter proposed in this paper is seen in Figure 2. Each single-phase UPS of low output voltage is called a module. Module 1 shows the structure of the power circuit and the block diagram of the control circuit of a low-output-voltage modular UPS. The modules are independent of each other and each one has a voltage control to regulate its output voltage. This study employs the UPS shown in Module 1 since it is a typical commercial UPS.

A required specification for the modules in Figure 2 is that the isolation voltage between the transformer coils needs to be higher than the total output voltage (V_o).

A. Principle of Operation

The output voltages of all modules of Figure 2 are connected in series and, therefore, the output voltages of the inverters from the UPSs are directly connected in series. An inverter can be simplified by having one voltage source and thus the series connection behavior of UPSs is similar to the series connection of voltage sources, as exemplified in Figure 3 (a). Voltage sources have the advantage of working naturally in series even if they are of different magnitudes, phases and frequencies. In the specific case of inverters, however, they must not receive active power flow.

On analyzing a small system of two series-connected UPSs, the behavior of each one and the resultant output voltage applied to the load are shown in Figure 3 (b)**.** The active and reactive power flow in the voltage sources 1 (V_{o1}) and 2 (V_{o2}) are defined by (1), (2), (3) and (4), where V_{o1} and V_{o2} are the magnitudes and ϕ_{12} is the phase between the voltage sources. Figure 3 (c) illustrates the phasors of both voltages.

$$P_1 = \frac{V_1^2 + V_1 \cdot V_2 \cdot \cos(\phi_{12})}{R_o} \quad (1)$$

$$Q_1 = -\frac{V_1 \cdot V_2 \cdot \sin(\phi_{12})}{R_o} \quad (2)$$

$$P_2 = \frac{V_2^2 + V_1 \cdot V_2 \cdot \cos(\phi_{12})}{R_o} \quad (3)$$

$$Q_2 = -\frac{V_1 \cdot V_2 \cdot \sin(\phi_{12})}{R_o} \quad (4)$$

Equations (1) to (4) show that if ϕ_{12} is null the reactive power flows between the sources are null and all of the active power supplied by the sources is to the load. Therefore, there are no active power flows between the sources. The equations also show that if ϕ_{12} is null the relation between the magnitudes determines the active power supplied by each source to the load. These characteristics also apply to other types of load.

Another important consideration is that small variations in the magnitude and phase of the sources do not generate a significant change in their power flows. This is because the active power flow is mainly dependent on the magnitude and the reactive power flow on the phase. This characteristic leaves the system more robust.

The circuit of Figure 2 presents this important characteristic when the voltage references of all UPSs are synchronized, because it is possible to obtain all voltages in phase and with the same magnitude. Consequently, the exchange of power between the inverters is avoided and the power load sharing among the UPSs is proportional to the magnitude of their output voltages. In Figure 2, the synchronism of the reference voltages is carried out through a common bus communication, which provides the V_{ref} signal for all UPSs connected in series.

Therefore, the resultant V_o of the output voltage in Figure 2 is the sum of all the voltages, as seen in (5). In situations of non-load operation, the structure in Figure 2 is an open circuit and has no current circulation. However, under load operation it has the current circuit of Figure 2, which is the same for all of the modules. Therefore, the power supplied to the load is defined by (6), as a function of the I_o and output voltage of all modules. Equation (6) shows that the total power of the load is divided among the UPSs, proportionally to their individual voltages. Through (6) it is also possible to demonstrate that the total power of the load is the sum of the power supplied by all UPSs, as defined in (7), (8) and (9).

$$V_o = V_{o1} + V_{o2} + \cdots V_{oN} \quad (5)$$

$$S_o = V_{o1} \cdot I_o + V_{o2} \cdot I_o + \cdots V_{oN} \cdot I_o \quad (6)$$

$$S_o = S_{o1} + S_{o2} + \cdots S_{oN} \quad (7)$$

$$P_o = P_{o1} + P_{o2} + \cdots P_{oN} \quad (8)$$

$$Q_o = Q_{o1} + Q_{o2} + \cdots Q_{oN} \quad (9)$$

One of the main advantages of the serial connection is that small variations among the output voltages of the inverters do not cause significant imbalances in the power load sharing. Therefore, in the proposal of Figure 2 there is no need to add a new control system to carry out the series connection of the VSIs. The instantaneous voltage control already present in the modular UPSs, with their voltage references synchronized, is sufficient to ensure proper power load sharing among the converters.

B. High-Output-Voltage UPS

The high-output-voltage UPS proposed in this paper is obtained by summing the output voltages of all low-output-voltage UPS, as described in (5). In this way, an equivalent UPS of high output voltage is built from "N" UPS of low-output voltage. An UPS can be transformed into a standard module and any voltage specification can be achieved with the series connection of "N" standard UPSs. This proposal reduces the designer time and cost and makes use of commercially available structures. The use of modules facilitates the maintenance and the replacement of units.

Another advantage of the series connection of inverters is that the load power is shared among them and thus the inverters can be designed for lower power. Moreover, for UPSs, the series connection distributes the energy backup in smaller battery banks which are present in each module.

An important aspect of the high-output-voltage UPS is the bypass operation mode. As the load voltage is greater than that of the electrical grid, the UPS needs a transformer in the bypass circuit. Another point relates to the situation where one module needs to be disconnected from the system. In this case, the system can either work in bypass mode or a specific control places the inverter output in short circuit and increases the output voltage of other modules.

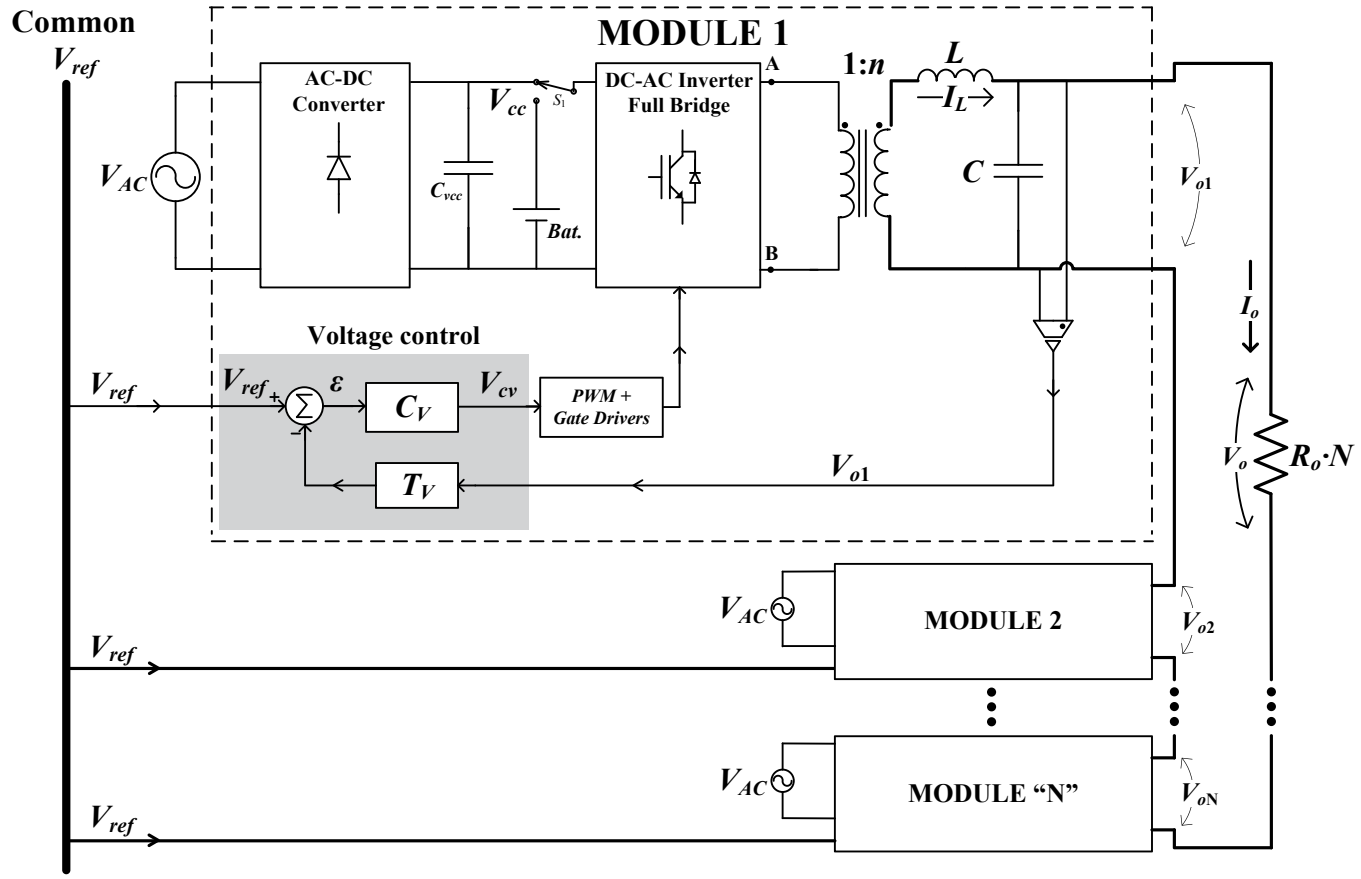


Fig. 2. Proposal for a high-output-voltage single-phase UPS based on the series connection of low-output-voltage modular UPSs.

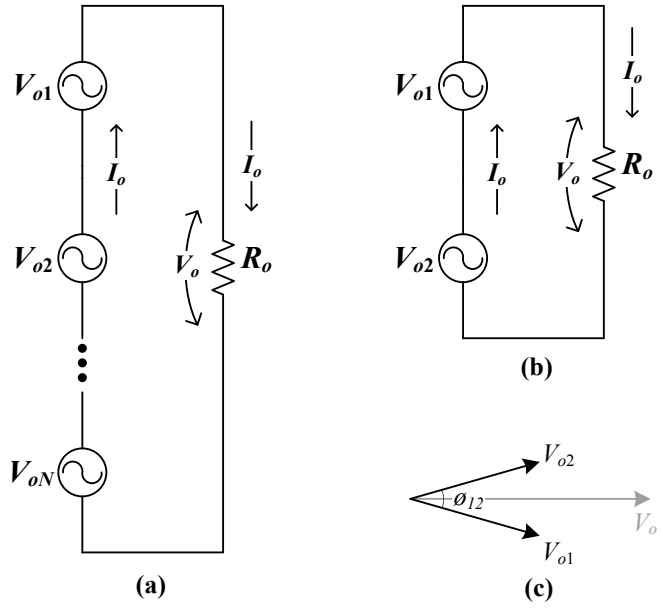


Fig. 3. (a) Behavior of "N" series-connected inverters; (b) Behavior of two series-connected inverters; and (c) Phasors of output voltages of two series-connected inverters.

C. Control Strategy of a Modular Single-Phase Inverter

The modules of the structure in Figure 2 have only the traditional instantaneous voltage control. Module 1 shows in detail the voltage control diagram. Controller C_v comprises a proportional–integral–derivative (PID) and a low-pass filter (LPF), as defined in (10). In this equation z_1 and z_2 are the zeros, p_1 is the pole and K_{cv} is the gain of the controller. This control strategy ensures a regulated output voltage at each module, for linear and non-linear loads. In addition, as the voltages of V_{o1} and V_{o2} up to V_{oN} are regulated, it is possible to affirm that the resulting voltage V_o is also regulated and responds appropriately to linear and non-linear loads.

$$C_v(s) = K_{cv} \cdot \frac{(s+z_1)\cdot(s+z_2)}{(s+p_1)\cdot s} \tag{10}$$

The structure shown in Module 1 may present problems associated with the dc level in the primary winding of the transformer due to the fact that the voltage sensor is in the secondary winding. There are many ways to solve this problem and one is through a control loop, as proposed in [27] and [28]**.** However, since the focus of this study is the series connection of the inverter, this point will not be addressed herein.

III. DYNAMICS ANALYSIS OF THE SERIES-CONNECTED INVERTERS

This section analyzes the dynamic response of the equivalent structure obtained through the series connection of VSIs. This study seeks to find the simplified circuit of Figure 2, shown in Figure 4 (a), which considered all inverters as equal.

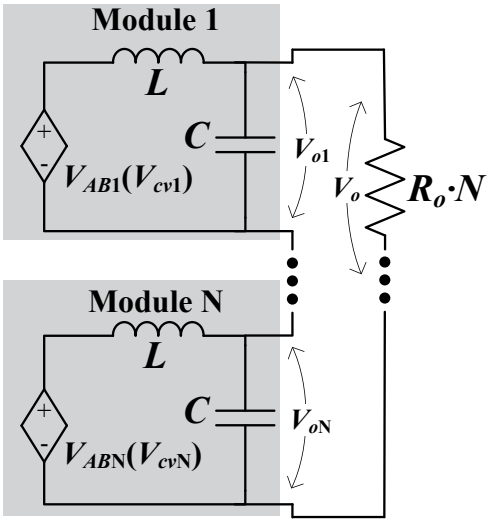
A. Small-Signal Model

The small-signal model of the inverter shown in module 1 of Figure 4 (a) is seen in (11) (which is the classic VSI model).

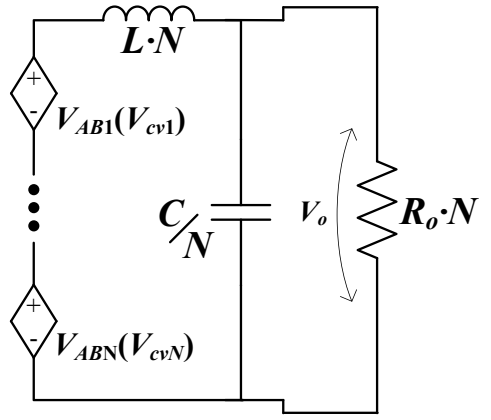
$$H_1 = \frac{1}{s^2 \cdot L \cdot C + s \cdot \frac{L}{R_o} + 1} \tag{11}$$

Based on the analysis of the circuit of Figure 4 (a) the equivalent circuit of Figure 4 (b) is found, which represents the equivalent circuit of series-connected inverters. The output impedances from the inverters (LC filters) are all connected in series. Therefore, the equivalent circuit in Figure 4 (b) has an inductance "N" times larger and a capacitance "N" times smaller, where "N" is the number of inverters connected in series. The small-signal model of Figure 4 (b) is shown in (12) and this result is very interesting because H_{VSI_series} is equal to the model for one inverter found in (11). Thus, the structure of series-connected inverters has the same dynamic response as one isolated inverter.

$$H_{VSI_series} = \frac{1}{s^2 \cdot L \cdot \cancel{N} \cdot \frac{C}{\cancel{N}} + s \cdot \frac{L \cdot \cancel{N}}{R_o \cdot \cancel{N}} + 1} \tag{12}$$



(a)



(b)

Fig. 4. Dynamic analysis of the series-connected inverters. (a) Model of "N" inverters. (b) Resulting model for "N" inverters.

B. Dynamic Response

Equation (13) defines the closed-loop transfer function (CLTF) of "N" inverters as seen in Figure 2. The transfer function (CLTF) of (13) describes the output voltage of each module in relation to the reference voltage. On substituting (13) in (5), (14) is obtained, which describes the CLTF of the "N" inverters connected in series. Thus, equation (14) describes the resulting output voltage, V_o, as a function of the reference voltage, V_{ref}, common to all inverters.

$$\frac{V_{o1}}{V_{ref}} = \text{CLTF}_{inv1} \quad \frac{V_{o2}}{V_{ref}} = \text{CLTF}_{inv2} \quad \cdots \quad \frac{V_{oN}}{V_{ref}} = \text{CLTF}_{invN} \tag{13}$$

$$\frac{V_o}{V_{ref}} = \text{CLTF}_{inv1} + \text{CLTF}_{inv2} + \cdots \text{CLTF}_{invN} \tag{14}$$

Figure 5 plots an example of the Bode diagram for the three different structures seen in Figure 2. The first, with one inverter; the second, with two inverters; and the third, with three inverters connected in series. The curves of Figure 5 are drawn with the transfer functions (7) and (8), and they consider that all inverters are equal. The curves of Figure 5, for one, two or three series-connected inverters, have the same frequency band with constant gain, the same resonant frequency and equal damping. The only difference between the curves in Figure 5 is the static gain of V_o in relation to V_{ref}, which increases proportional to the number of inverters connected in series. This is to be expected because the output voltage V_o increases when more inverters are connected in the system. The Bode phase diagram was also analyzed and presented the same response for the three cases.

IV. SERIES-CONNECTED THREE-PHASE INVERTERS

The purpose of this section is to extend the principle of series connection to three-phase inverters, with the focus on its application in a three-phase UPS. A possible structure for the three-phase connection is shown in Figure 6. The inverters are isolated through a three-phase transformer and have an LC filter (typical structure used in UPS). The secondary coils of transformers are not connected to each other and thus the series connection of the inverters is possible.

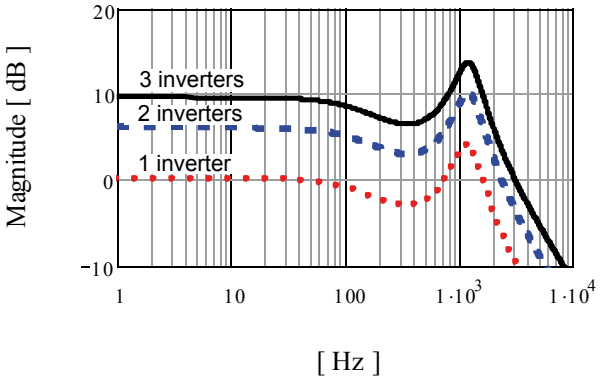


Fig. 5. Bode magnitude diagram of one, two and three inverters connected in series.

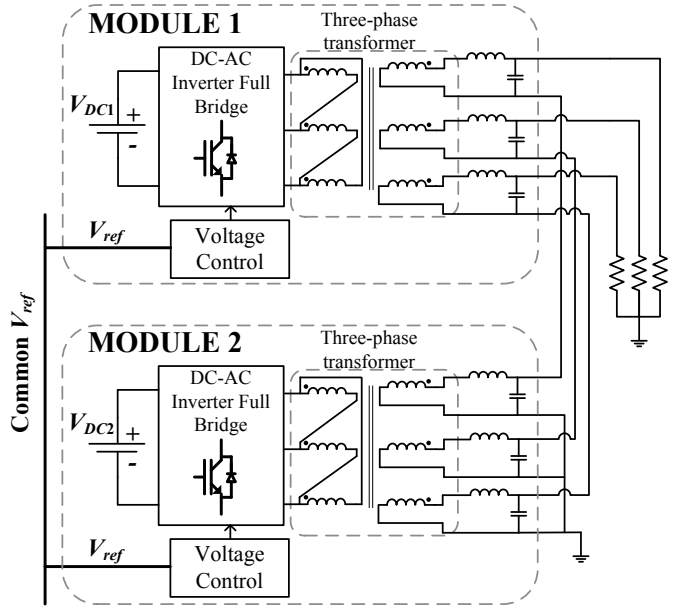


Fig. 6. Proposal for a high-output-voltage three-phase UPS based on the series connection of three-phase inverters.

V. EXPERIMENTAL RESULTS

In order to verify the proposal of this paper a prototype with three 5 kVA UPSs connected in series was built. The structure tested can be seen in Figure 2, the photograph in Figure 7 shows the prototype with modules 1, 2 and 3 and Table I provides the main specifications for the design. The switching frequency was 10 kHz in all VSIs.

The prototype with three series-connected inverters provides an output voltage V_o of 660 V_{rms} (3x220 V_{rms}), which corresponds to a peak voltage of 933 V_{peak}. It was tested under non-load and under resistive, inductive and non-linear loads. The results are shown in the waveforms of Figures 8 to 15. These figures display the total output voltage (V_o), the voltages in the modules 1 (V_{o1}), 2 (V_{o2}) and 3 (V_{o3}) and the load current (I_o).

Figure 8 presents the results for the test carried out under non-load conditions. The measured values for V_{o1}, V_{o2}, V_{o3} and V_o were 220 V, 219 V, 221 V and 660 V, respectively. The waveforms represent 1% of the total harmonic distortion (THD). These results demonstrate that the proposed connection functions properly and thus the desired output voltage of the series connection of three UPSs is obtained.

The results for the test carried out under resistive load can be seen in Figures 9 and 10. The voltages V_{o1}, V_{o2}, V_{o3} and V_o are shown in Figure 9 and their measured values were 214 V, 214 V, 215 V and 643 V, respectively. The measured THD of these waveforms were 2.6%. The static regulation was 3%. The power load supplied is 13.18 kW and the resistive load current (I_o) is shown in Figure 10 together with V_{o1}, V_{o2} and V_o. The results show that it is possible to correctly regulate the output voltage V_o through the individual control of each UPS, in other words, by controlling the voltages V_{o1}, V_{o2} and V_{o3}.

The test results obtained under an inductive load of 9.45 kVA and power factor of 0.62 are shown in Figures 11 and 12. The voltages V_{o1}, V_{o2}, V_{o3} and V_o are given in Figure 11 and their measured values were 222 V, 223 V, 223 V and 668 V, respectively. The inductive load current (I_o) is given in Figure 12 and its value is 14 A. This figure also displays the voltages V_{o1}, V_{o2} and V_o. It can be seen that the load current is not in phase in relation to V_{o1}, V_{o2}, V_{o3} and V_o, however, both voltages are still in phase and properly regulated.

Fig. 7. Photograph of the prototype with three 5 kVA inverters (modules) connected in series.

TABLE I
Design Specifications

V_{AC} = 220 V_{rms}	T_V = 0.016	$V_{o1}/V_{o2}/V_{o3}$= 220 V_{rms}
n = 1.63	K_{Cv} = 14.7	$S_{o1}/S_{o2}/S_{o3}$= 5 kVA
L = 1100 µH	z_1 = 888 Hz	N = 3
C = 36 µF	z_2 = 328 Hz	V_o= 660 V_{rms}
V_{ref} = 5 V (peak)	p_1 = 34050 Hz	S_o= 15 kVA

Figures 13 and 14 show the test under a non-linear load of 8.3 kVA and with a crest factor of 2.5. The voltages V_{o1}, V_{o2}, V_{o3} and V_o are shown in Figure 13 and their measured values were 216 V, 217 V, 217 V and 650 V while the THD values were 3.2%, 3.2%, 3.0% and 3.1%, respectively. The value for the load current (I_o) is 12.7 A (32 A peak) and it can be seen in Figure 14 that this also presents V_{o1}, V_{o2} and V_o. It can be noted that the system regulates V_o properly, even for this type of load.

A dynamic test was also performed, in which one step of 0 to 50% load (resistive) was applied. Figure 15 shows the voltages V_{o1}, V_{o2} and V_o and load current I_o during the test. The output voltage V_o has the same dynamic response as the voltages V_{o1} and V_{o2}, verifying the theoretical study. Moreover, the transient voltage response is smooth, demonstrating the robustness of the system.

VI. CONCLUSIONS

This paper proposed a simple solution to building a high-output-voltage UPS based on the series connection of inverters. The theoretical study demonstrated that the equivalent UPS maintains the dynamic characteristics and total output voltage of the inverters. Moreover, the load-power is shared naturally among all inverters, without the need to introduce new control strategies. Thus, it is possible to carry out the series connection of low-output-voltage, modular, commercially available and low cost UPSs, and thereby obtain an equivalent UPS of high output voltage.

The experimental results obtained for a 15 kVA prototype verified the principles of this proposal. Furthermore, this strategy is also attractive for other applications, at low and high voltages. One example of where the principle of series connection in UPS could be applied is the Brazilian market. A manufacturer could have a standard UPS designed for an output-voltage of 127 V and then use two UPS in series connection to attend regions where the electrical grid is 220 V.

The series connection of inverters is a recent research topic and there are still many aspects to be addressed in future studies. These include a control system that allows the connection and disconnection of the inverters and compensates the output voltage acting on the other inverters, new options for bypass operation when the load voltage is not the same as the electrical grid voltage and a study on modulation strategies for inverters.

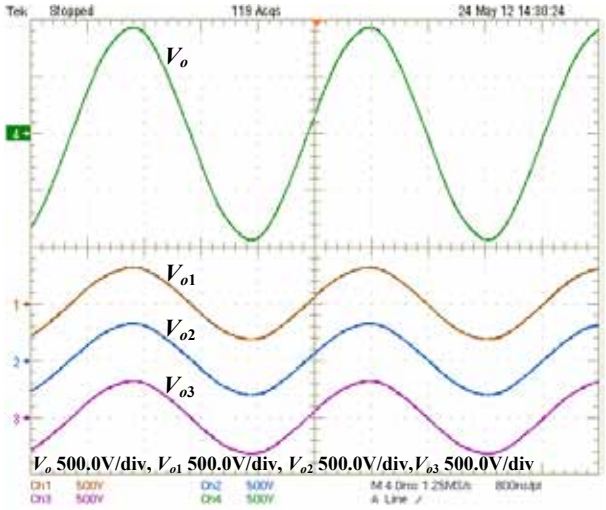


Fig. 8. Experimental results under non-load operation. Output-voltages of the UPS (V_o), module 1 (V_{o1}), module 2 (V_{o2}) and module 3 (V_{o3}).

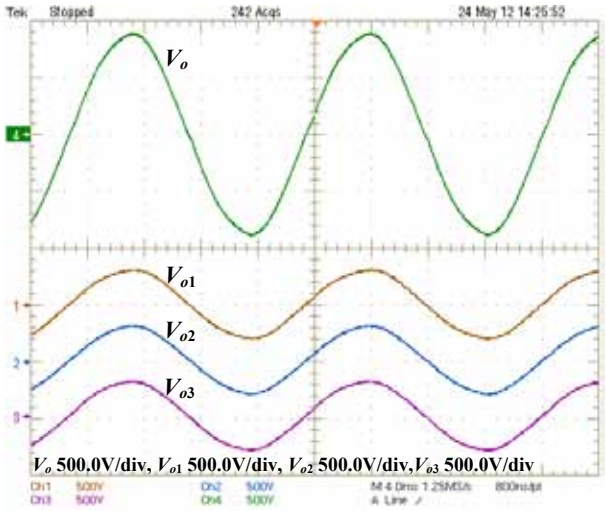


Fig. 9. Experimental results under resistive load operation. Output-voltages of the UPS (V_o), module 1 (V_{o1}), module 2 (V_{o2}) and module 3 (V_{o3}).

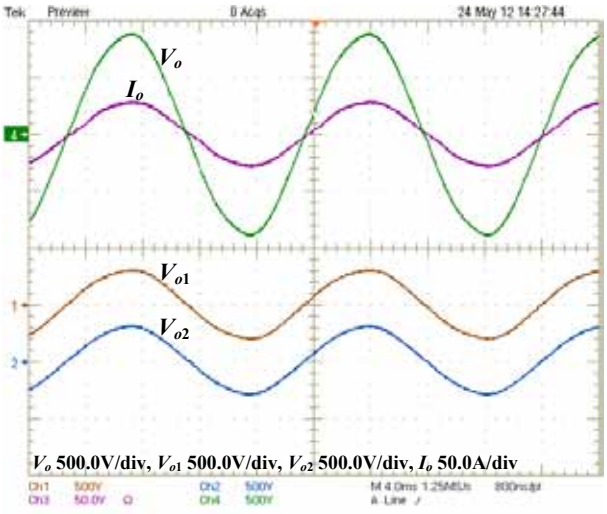


Fig. 10. Experimental results under resistive load operation. Output-voltage of the UPS (V_o), load current (I_o) and output-voltages of module 1 (V_{o1}) and module 2 (V_{o2}).

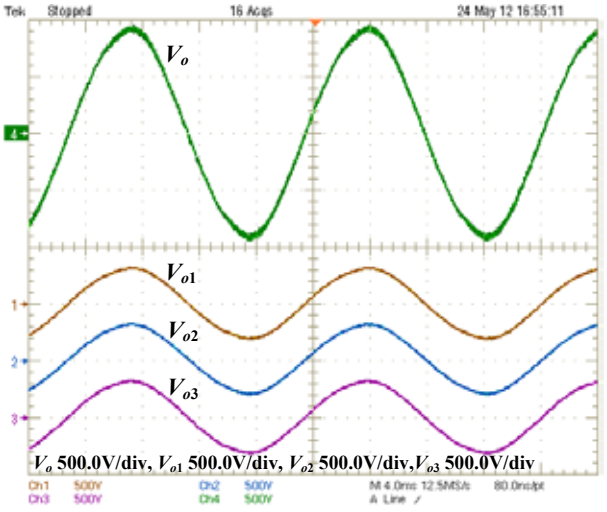


Fig. 11. Experimental results under inductive-load operation. Output-voltages of the UPS (V_o), module 1 (V_{o1}), module 2 (V_{o2}) and module 3 (V_{o3}).

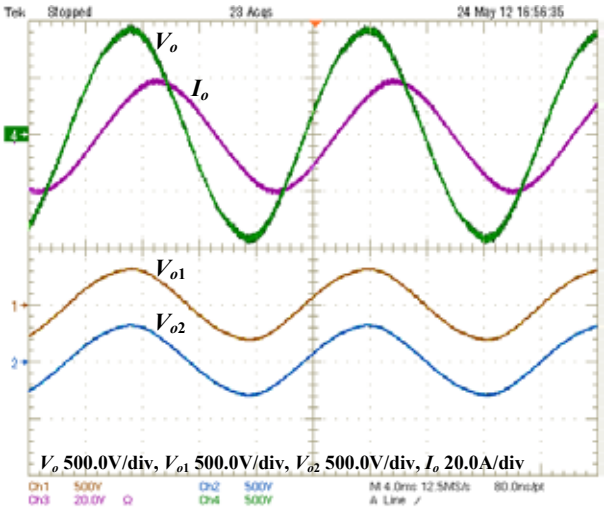


Fig. 12. Experimental results under inductive-load operation. Output-voltage of the UPS (V_o), load current (I_o) and output-voltages of module 1 (V_{o1}) and module 2 (V_{o2}).

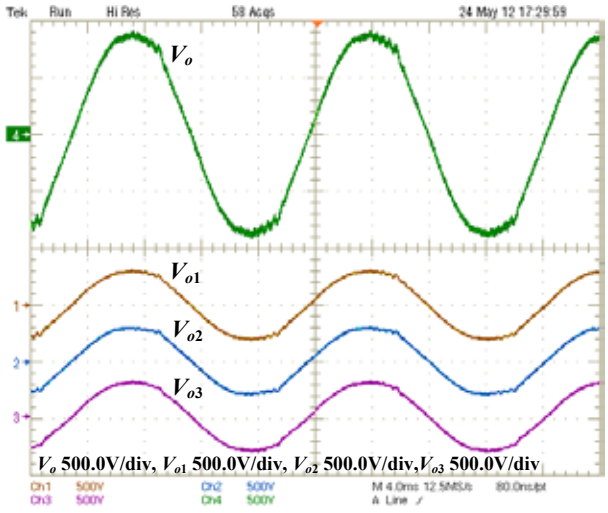


Fig. 13. Experimental results under non-linear load operation. Output-voltages of the UPS (V_o), module 1 (V_{o1}), module 2 (V_{o2}) and module 3 (V_{o3}).

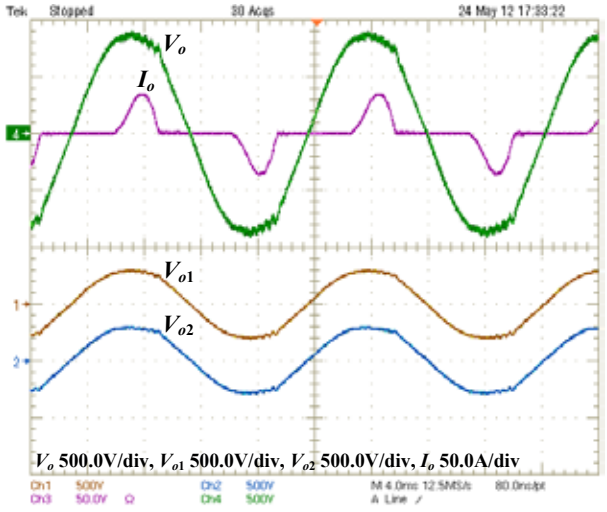


Fig. 14. Experimental results under non-linear load operation. Output-voltage of the UPS (V_o), load current (I_o) and output-voltages of module 1 (V_{o1}) and module 2 (V_{o2}).

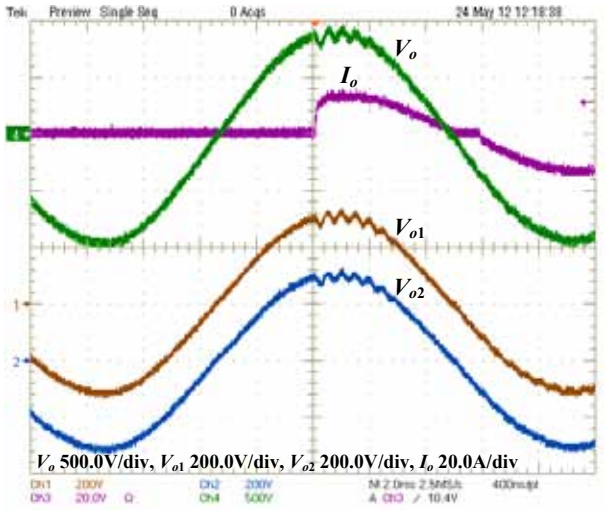


Fig. 15. Analysis of dynamic response of UPS during one resistive load step. Output-voltage of the UPS (V_o), load current (I_o) and output-voltages of modules 1 (V_{o1}) and module 2 (V_{o2}).

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