A Nonisolated Single-Phase UPS Topology With 110-V/220-V Input–Output Voltage Ratings

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***Abstract*—A circuit configuration of a single-phase nonisolated online uninterruptible power supply (UPS) with 110-V/220-V input–output voltage ratings is proposed, allowing the bypass operation without a transformer even if the input voltage is different from the output voltage. The converter consists of an ac–dc/dc–dc three-level boost converter combined with a double half-bridge inverter. In this type of configuration size, cost and efficiency are improved due to the reduced number of switches and batteries, and also, no low-frequency isolation transformer is required to realize bypass operation because of the common neutral connection. Both stages of the proposed circuit operate at high frequency by using a passive nondissipative snubber circuit in the boost converter and insulated-gate bipolar-transistor switches in the double half-bridge inverter, with low conduction losses, low tail current, and low switching losses. Principle of operation and experimental results for a 2.6-kVA prototype are presented to demonstrate the UPS performance.**

***Index Terms*—Common neutral connection, online uninterruptible-power-supply (UPS) systems, power-factor correction, soft commutation, transformerless UPS.**

I. Introduction

UNINTERRUPTIBLE power supplies (UPSs) are being widely used to supply clean and reliable power to critical loads, such as medical systems, computers, network servers, communication systems, and industrial processes. They also protect sensitive loads against power outages under any normal or abnormal utility power conditions. Among different types of UPS systems, the true online UPS is the superior configuration against most of the problems that occur in the power line, providing adequate power conditioning and load protection [1].

In the conventional online UPS configuration, consisting of a boost rectifier/power-factor corrector or a noncontrolled rectifier, battery bank, an inverter, and a static switch (bypass), an isolating transformer is normally required to properly operate the bypass circuit and also to improve the reliability of the system, since the transformer offers a galvanic isolation to the load from undesirable disturbances of the main supply [2]. This isolation transformer has considerable size and cost when operating at the grid frequency.

Other topologies were proposed as a solution to overcome this problem by using a transformer in a high-frequency dc link [3]–[6]. Although UPS topology, incorporating a high-frequency transformer reduces the weight of the system, it has increased the number of active switches, compromising the system's overall efficiency and reliability.

Transformerless UPS, incorporating a common neutral bus line using a half-bridge converter and inverter in both ac/dc and dc/ac conversions, has attracted special interest for applications in computer and telecommunication systems. This type of circuit is highly cost effective and acceptable due to its total power conversion efficiency improvement and volume and weight reduction [7]–[11].

However, with conventional boost-chopper circuits, higher step-up ratio lowers the boost efficiency. For that reason, a new boost-chopper-circuit configuration, as shown in Fig. 1, has been proposed in [12] and [13]. Although this topology has offered a way to reduce the quantity of connected batteries in series, and also problems associated with battery equalization, step-up ratio, and dc-link bulk capacitor imbalance, it has some disadvantages as follows. AC/DC and DC/AC converter switches are exposed to total dc-link voltage, large reactive power flows during rectifier operation, the bidirectional boost-chopper inductor is larger than the one used in normal mode, and the current through the battery presents discontinuities in the bidirectional converter.

The single-phase three-level rectifier with a half-bridge inverter can be advantageous for many applications [14]. In this converter, only half of the dc-link voltage is applied across the rectifier switches, and the current flows simultaneously through two or three power semiconductors only. Therefore, this converter presents less conduction losses, and a common neutral bus line is connected between the middle point of dc-link capacitors and load, making it possible to realize the bypass operation without an isolating transformer. This topology has a disadvantage in battery-powered mode because it does not provide a path to charge the two dc-link capacitors separately, resulting in dc-link capacitor-voltage imbalance for some load types connected to the inverter.

Fig. 2 shows a modified single-phase three-level rectifier and a half-bridge inverter scheme reported in [15] and [16], with a battery set and a static-switch arrangement that overcome the drawbacks related previously. The main advantages of this configuration include the possibility to correct the dc-link bus capacitor-voltage imbalance, to reduce both the step-up ratio of

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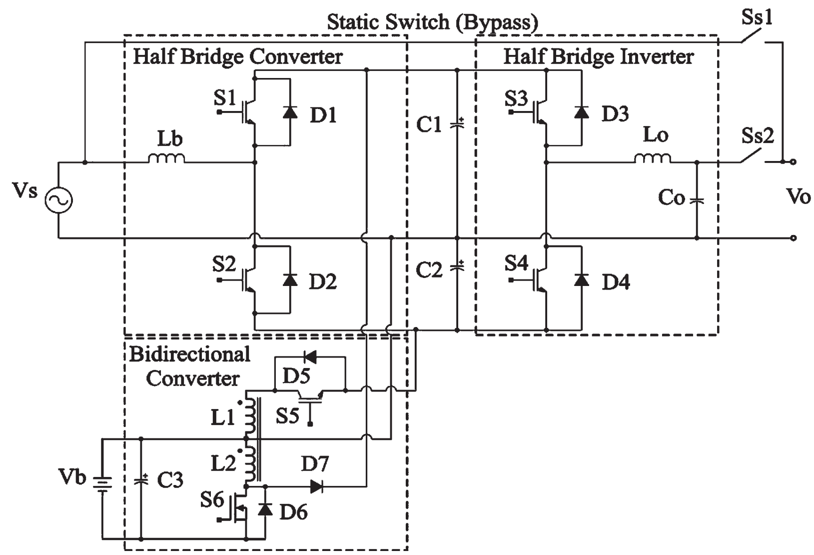

Fig. 1. Single-phase UPS based on half-bridge converter–inverter and a buck-boost-chopper circuit.

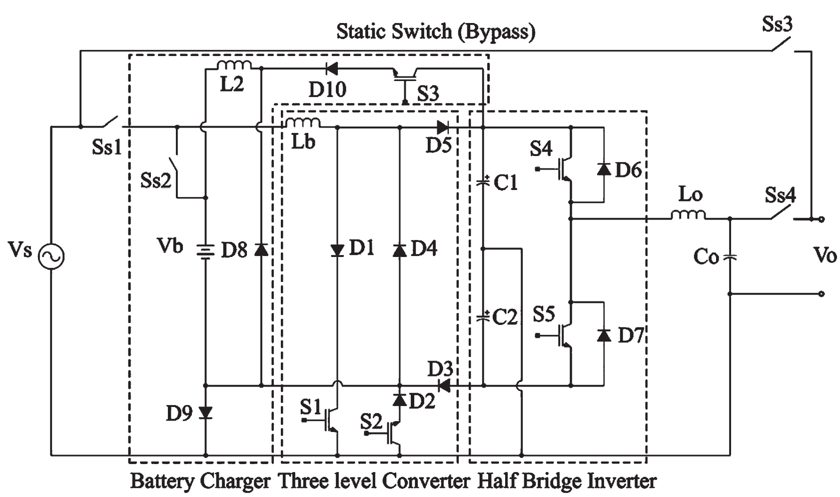

Fig. 2. Modified three-level rectifier with a half-bridge inverter scheme.

the boost converter and the number of battery units necessary for the battery-powered operation mode, and to use fewer active switches compared with the topologies presented in [7], [8], [9], [10], [11], and [12].

Most topologies with a common neutral pulsewidth-modulation (PWM) boost rectifier in the front end of the UPS system are characterized as voltage doublers [17], requiring a minimum dc-link voltage of 622 V for proper operation of the boost rectifier with a power-factor-correction capability when the utility voltage is 220 Vac. This operating voltage requires higher cost semiconductors and passive components due to higher blocking voltage levels. Moreover, it requires a very high-voltage battery bank, which is generally obtained for this application with the association of them in series connection, which leads to the increase in the storage battery cost and lower reliability.

In this paper, a circuit configuration is proposed that combines the advantages of the presented topologies with common neutral point connection, three-level rectifier, and half-bridge inverter, and at the same time, it can operate for any input–output voltage (110 V/220 V) requirements. This configuration can also be extended for the conventional half-bridge ac/dc converter and other voltage-doubler converters with middle-point dc-link bus capacitors.

II. Proposed UPS Circuit

A. Topology Description

The schematic of the single-phase online UPS with universal input–output voltage is shown in Fig. 3 [18]. Due to the high voltage of the dc link required by the 220-Vac utility supply, an autotransformer with three taps provides the operation of the UPS with 110 Vac. By using this configuration, it is possible to use the topologies proposed with common neutral connection without increasing too much the system's overall cost. The autotransformer is, at least, 50% cheaper and half the weight of the isolating transformer, which is normally bulky and heavy while operating in a commercial ac-line frequency. That solution makes this UPS topology possible to work in any conventional utility ac voltage (110 V/220 V).

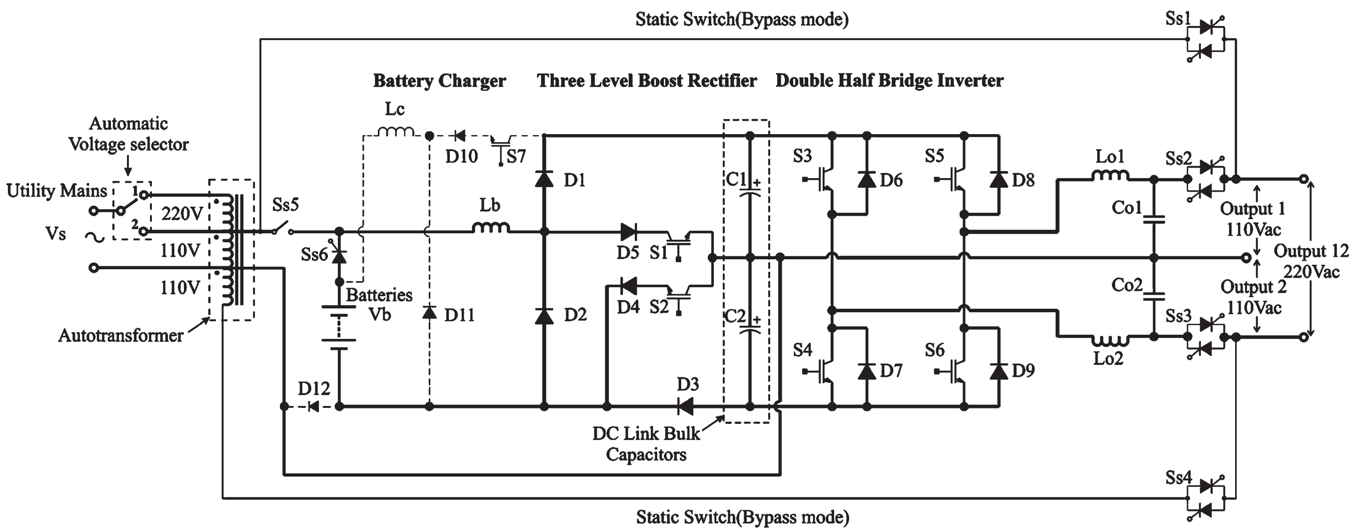

Fig. 3. Proposed nonisolated single-phase online UPS topology with 110-V/220-V input–output voltage.

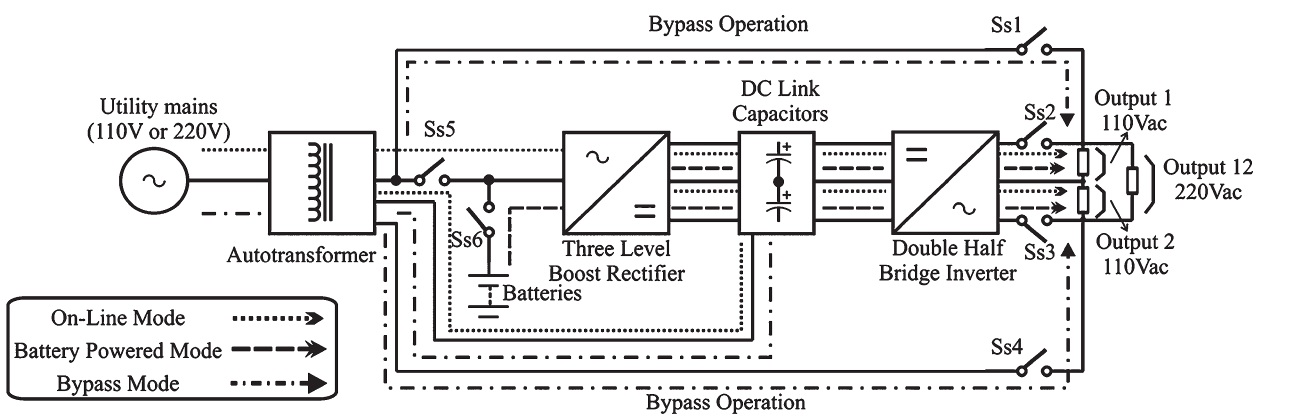

Fig. 4. Operating modes of the proposed UPS.

This scheme also has the capability of supplying two different levels of load voltage. In this system, the two specifications of input voltages fix the two output voltages so that the ratings of output voltages are 110 and 220 Vac.

To achieve this, a double half-bridge circuit [19] provides two outputs of 110 Vac, each one with half of the total output power of the boost converter.

By synchronizing the operation of both half-bridge inverter legs, it is possible to obtain 220 Vac at the output of the UPS, as shown in Fig. 3. This is obtained by the sum of the two individual output voltages. When using the output 12 only, which is the 220-Vac output, it could deliver a total power of the two half-bridge legs.

If there are loads connected to both 110- and 220-Vac outputs, the system also has the same performance, providing a high-quality sinusoidal voltage to each output and sharing output power while observing the limit of the power capacity of each 110- and 220-Vac output. Two separated control schemes, one for each half-bridge leg, have been used and will be further explained.

To perform bypass operation, four static switches S_{s1}–S_{s4} have been used to connect the ac line directly to the load during system overload or problems with the converter operation. One additional static switch S_{s6} composed by an SCR is used in the battery-powered mode, and electromagnetic contactor S_{s5} is used to commutate between ac-line mode and battery mode. A simple buck converter, also shown in Fig. 3, is used to perform battery-charging regulation.

B. Principle of Operation

The operation of the proposed UPS can be divided in three modes, as shown in Fig. 4, namely, the online mode, which is also sometimes referred as normal mode, the battery-powered mode, and the bypass mode.

1) Online Mode: In accordance with the utility voltage level, an automatic detector sets the UPS for the proper input voltage. For a utility voltage of 220 Vac, the voltage selector should be put in to position 1, allowing the 220-V utility voltage across the autotransformer 220-V winding, and a tap divides the input voltage, providing the boost rectifier with 110 Vac. On the other hand, if the utility voltage is 110 Vac, the voltage selector should be switched to position 2, in which the winding is always supplying the converter with the same input voltage value.

During the online operation mode, S_{s5}, S_{s2}, and S_{s3} are kept on, and S_{s1}, S_{s4}, and S_{s6} are kept off. The control of the

TABLE I
BOOST OPERATION SWITCHING STATES

On-Line operation current path		
Vs cycle	Energy storage in inductor Lb	Energy transfer to DC link bulk capacitors
Positive ( )	Vs ⇒ Lb ⇒ D5 ⇒ S1 ⇒ Vs	Vs ⇒ Lb ⇒ D1 ⇒ C1 ⇒ Vs
Negative ( )	Vs ⇒ S2 ⇒ D4 ⇒ D2 ⇒ Lb ⇒ Vs	Vs ⇒ C2 ⇒ D3 ⇒ D2 ⇒ Lb ⇒ Vs
Battery powered operation current path		
V_{bat}	Energy storage in inductor Lb	Energy transfer to DC link bulk capacitors
(C1 Transfer)	Vb ⇒ Lb ⇒ D5 ⇒ S1 ⇒ S2 ⇒ D4 ⇒ Vb	Vb ⇒ Lb ⇒ D1 ⇒ C1 ⇒ S2 ⇒ D4 ⇒ Vb
(C2 Transfer)	Vb ⇒ Lb ⇒ D5 ⇒ S1 ⇒ S2 ⇒ D4 ⇒Vb	Vb ⇒ Lb ⇒ D5 ⇒ S1 ⇒ C2 ⇒ D3 ⇒ Vb

three-level boost rectifier operating in the boost mode is realized in such a way that it can provide an ac-line current with low total harmonic distortion (THD) and high power factor while maintaining a constant and balanced dc voltage across the dc-link capacitors. The generated current paths and the states of the switches in accordance with Vs of the boost-mode operation are shown in Table I. The double half-bridge inverter operates as two synchronized independent half-bridges, as is well known in the literature, to produce a 220-Vac output by the sum of two 110-Vac outputs in phase.

2) Battery-Powered Mode: When the supervisory circuit detects ac-line failure, contactor S_{s5} is turned off, and switch S_{s6} turns on, transferring the input of the boost converter from the ac utility to the battery bank for boost dc/dc operation, which now functions as described in Table I. In this transition, the dc-link capacitors were designed to provide sufficient energy to the inverters while the battery bank is not connected.

According to the control strategy adopted to the battery-powered mode, the battery bank transfers energy alternatively to each capacitor of the dc link for each half period of the utility voltage. $V_{\rm bat}$ in Table I represents which capacitor will receive energy during the battery-powered operation with its respective current path.

3) Bypass Mode: During overload or any problem in the UPS converters, a supervisory circuit detects the fault and sets the static switches S_{s1} and S_{s4} to ON, whereas S_{s2} and S_{s3} are set to OFF in order to isolate the failure. In addition, contactor S_{s5} is kept off. This provides a zero time transfer ratio. This operation mode is maintained until the fail diagnostics is made by the supervisory circuit.

The autotransformer has three taps; two of them are used to supply the UPS input in 110 Vac, as mentioned above, and the third one is used in the bypass mode, supplying the second half-bridge-leg output with 110 Vac. Even if they are connected with critical loads in 110- and 220-Vac outputs at the same time, no problem occurs due to the difference of input neutral connection. The only thing that must be observed is the output power capacity of each autotransformer winding. The equivalent circuit during this mode is similar to a conventional configuration of an autotransformer with two taps; thus, depending on the load connection, it could be supplied by winding nominal voltage or double winding nominal voltage with respect to the current capacity of the windings.

C. Control Strategy

The proposed UPS control strategy is achieved with an analog scheme using well-known dedicated integrated circuits and a supervisory circuit based on an 8-b high-performance reduced instruction set computing microcontroller PIC16F877.

1) Three-Level Boost-Converter Control: The three-level boost-converter operation control scheme for both the online and battery-powered modes is shown in Fig. 5. A simple control strategy using a UC3854B controller from Texas Instruments is adopted as the main controller, to accomplish a low-distortion sinusoidal ac-line current, using instantaneous average current mode control [20]. An external regulator is used to obtain a voltage-balance compensation signal to be added to the input current reference. During the online mode of operation, the current reference signal is obtained from ac line when the controller switch mode relay is in position 1. Then, in battery operation mode, it is switched to position 2 to provide a symmetric dc reference.

To accomplish capacitor voltage balance in battery-powered mode, this current-waveform reference is necessary. A logic circuit after the PWM signal modulator is synchronized by a microcontroller and used to provide gating signals for S_1 and S_2 switches in both operation modes.

2) Double Half-Bridge Control: Due to the fact that each half-bridge inverter has a separated output, two similar PID controllers were used to provide output-voltage regulation. Fig. 6 shows a complete scheme of the inverter control block. Sinusoidal PWM technique for the closed-loop regulation with an LC filter at the output provides a high-quality sinusoidal voltage to any type of load. A bipolar modulation strategy is adopted, applying a two-level voltage waveform across the input of the LC filter. In the circuit shown in Fig. 6, the reference sine wave generated by the microcontroller is synchronized with the utility and compared with the sampled output voltage; thus, the output voltage is always equal to the reference sine wave of each inverter. The integrator block is responsible for the dc component compensation of the output voltage.

The microcontroller with an external D/A converter composed by an R2-R network generates a sine wave reference synchronized with the utility voltage. The main feature of this control strategy is that the sinusoidal reference voltage for each half-bridge controller is 180° out of phase from each other in order to provide a sum of the two output voltages when supplying the load at 220 Vac. If the reference signals are delayed with another angle, the second voltage value which results from the sum of the two output values could be adjusted.

III. PASSIVE NONDISSIPATIVE SNUBBER CIRCUIT APPLIED IN THE FRONT-END CONVERTER

The passive nondissipative snubber circuit presented in [21] was employed to achieve soft commutation during turn on and turn off in both active switches in the three-level converter, increasing the system's overall efficiency in any operation mode

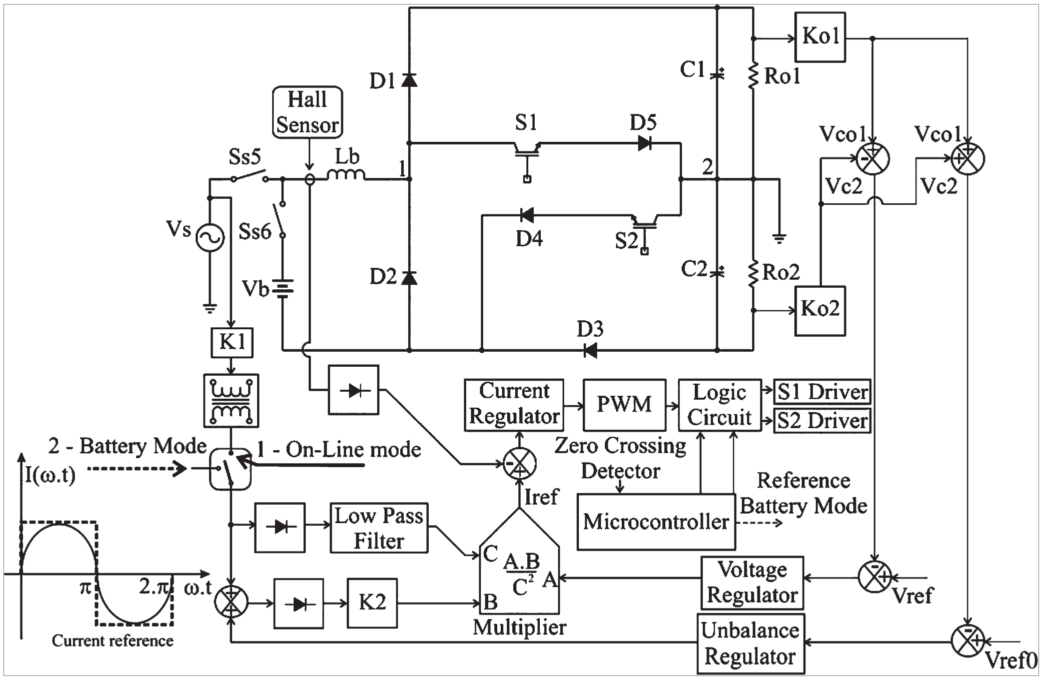

Fig. 5. Three-level boost-converter control block.

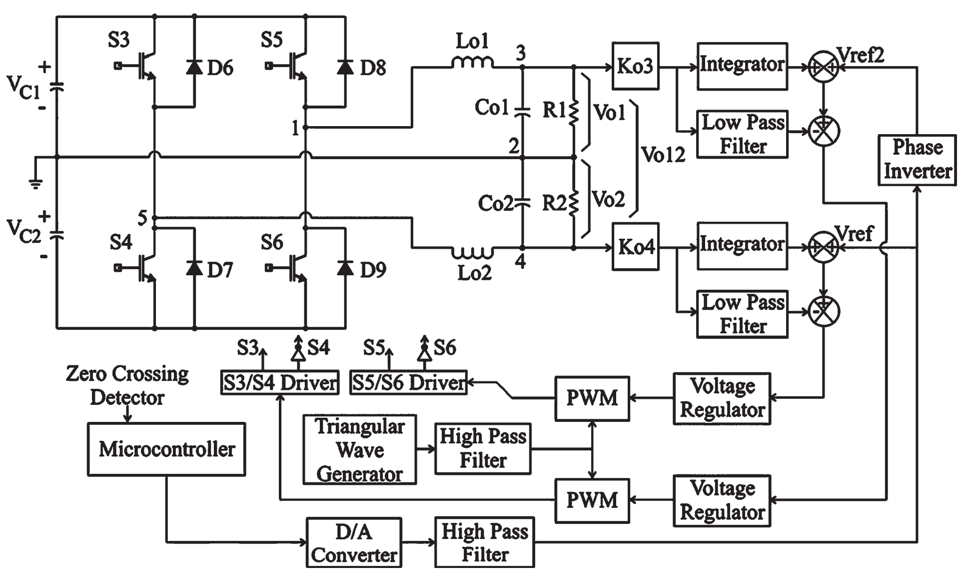

Fig. 6. Double half-bridge control block.

and allowing the increase of switching-frequency operation of the three-level boost converter.

Fig. 7 shows the turn-on–turn-off snubber-circuit topology applied to the three-level boost converter. The passive components used for each boost diode (D1 and D3) are shown within the dashed line. The recovery mechanism in diode D2 does not need to be minimized because during the negative cycle of the utility, it is conducting (online mode) and during the battery-powered mode, it is always blocked. A detailed description, operation, and design procedure is also presented in [21].

Compared with the utilization of SiC devices in order to minimize boost-switch commutation problems, this snubber circuit is very reliable and provides a considerable cost reduction because it is mainly composed of passive components.

IV. Experimental Results

The proposed nonisolated single-phase online UPS with 110-V/220-V input–output voltage design specifications is shown in Tables II–V. The switching frequency of both converters was assumed $f_s = 50$ kHz. The experimental results consist of relevant voltage and current waveforms and also curves that demonstrate the performance of the proposed UPS.

1) Waveforms and Curves for the Online-Mode Operation: The online-mode operation experimental results were realized with two different types of load. The results shown in Figs. 8–12 were obtained by connecting a pure resistive load in each type of load connection accordingly to the desired output rated voltage (110 or 220 Vac). The results shown in Figs. 13–21

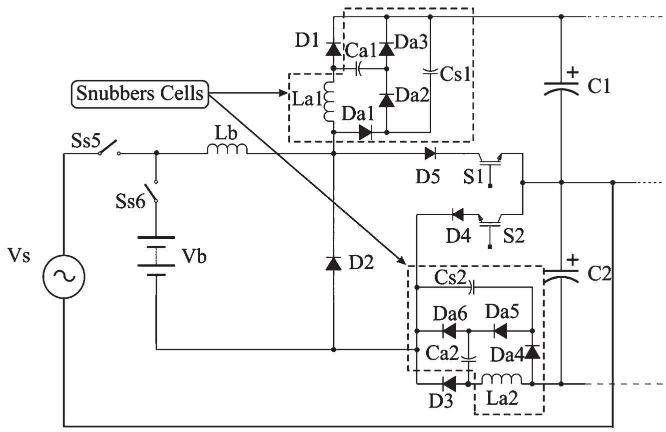

Fig. 7. Passive nondissipative snubber-circuit scheme applied in the three-level boost converter.

TABLE II
DEVELOPED UPS SPECIFICATIONS

Input voltage	1Ø 110V / 220V ±15%
Output voltage	110V(Vo1, Vo2) / 220V(Vo12)
Grid Frequency	50 / 60Hz
Output Power Capacity	1.3kVA per Half Bridge Inverter
Input Power Factor	0.99
Output Power Factor	0.7 – 1.0
DC Link Voltage	440V
Number of Batteries (In series)	9 (12V/7Ah)
AC Static Switches (S_{S1}-S_{S4})	BTB41
Static Switch (S_{S6})	40TPS08

TABLE III
PARAMETERS OF THE UPS AC/DC CONVERTER

Boost Inductor	L_b = 330μH
DC Link Capacitors	C1 = C2 = 3000μF
Diodes D_1, D_2, D_3, D_4 and D_5	HFA25TB60
Switches S_1 and S_2	APT40GT60BR

TABLE IV
PARAMETERS OF THE UPS INVERTERS

Filter Inductors	L_{o1} = L_{o2} = 280μH
Filter Capacitors	C_{o1} = C_{o2} = 60μF
Switches S_3, S_4, S_5 and S_6 with Co-pack Diodes D_6, D_7, D_8 and D_9	IRGP35B60PD

TABLE V
PARAMETERS OF THE NONDISSIPATIVE SNUBBER CIRCUIT

Resonant Inductors	L_{a1} = L_{a2} = 0.9μH
Polypropylene Film Capacitors	C_{a1} = C_{a2} = 47nF C_{S1} = C_{S2} = 680nF
Diodes D_{a1}, D_{a2}, D_{a3}, D_{a4}, D_{a5} and D_{a6}	MUR860

were obtained when the inverters were supplying nonlinear loads with a crest factor of three and a power factor of 0.65. The nonlinear load used for the tests complies with the requirements of IEC62040-3.

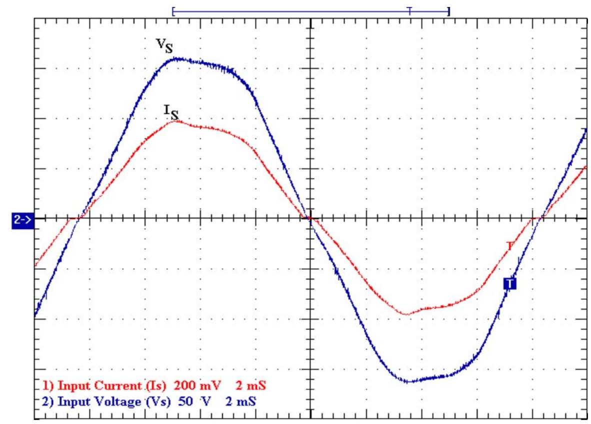

Fig. 8. Input voltage V_S and input current I_S (50 V/div; 20 A/div; 2 ms/div).

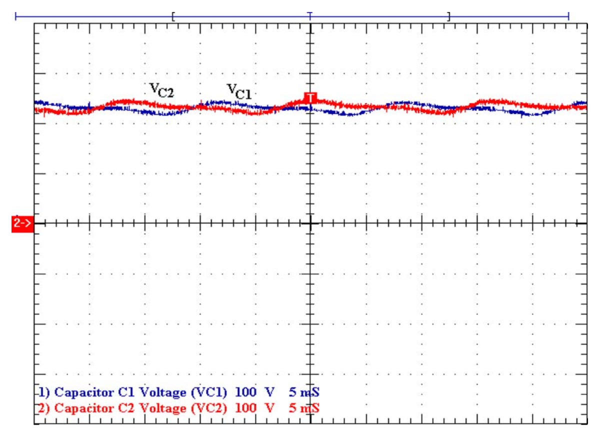

Fig. 9. DC-link capacitor voltage (V_{C1}; V_{C2}) (100 V/div; 5 ms/div).

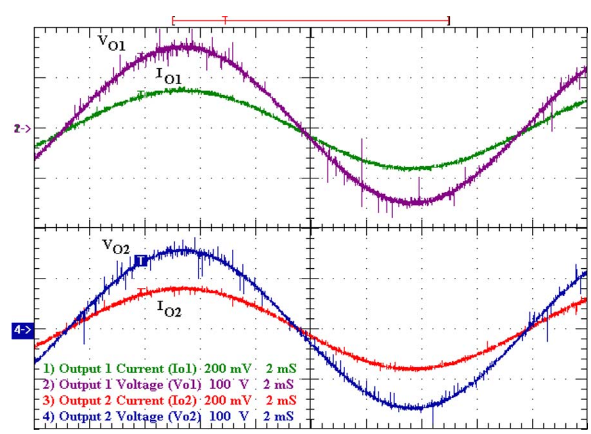

Fig. 10. Output voltages and currents for 110-V load (100 V/div; 20 A/div; 2 ms/div).

The input voltage and the input current are shown in Figs. 8 and 13, respectively, where a high power factor with low THD was obtained. For the UPS operation with nonlinear loads connected at the inverter output, the THD of the input current was measured and compared with the limits required by the IEC61000-3-2 Standard. Fig. 14 shows that the proposed system complies with the IEC61000-3-2 Standard.

DC-link capacitor voltages are shown in Figs. 9 and 15. The UPS control maintains balanced voltages in upper and lower dc-link capacitors even if the type of the inverter load is

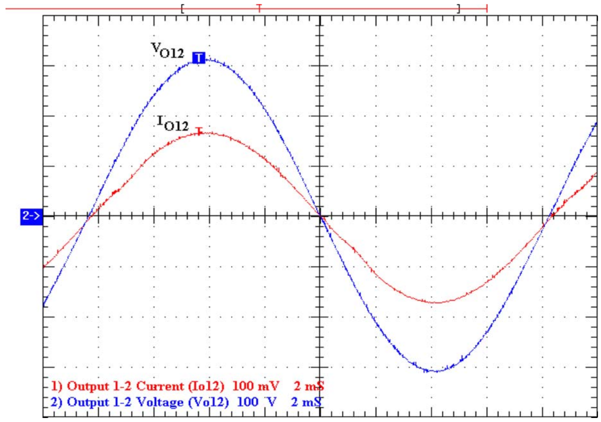

Fig. 11. Output voltage and currents for 220-V load (100 V/div; 10 A/div; 2 ms/div).

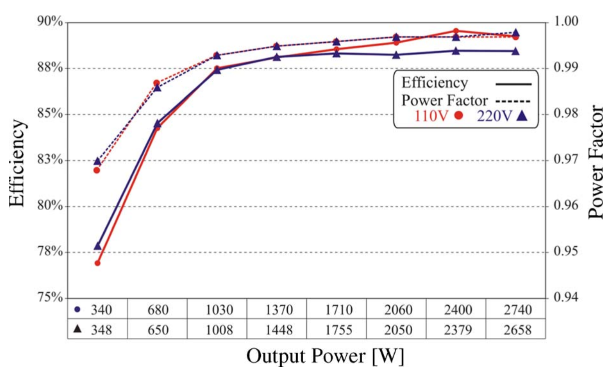

Fig. 12. Measured efficiency and input power factor of the UPS as a function of output power.

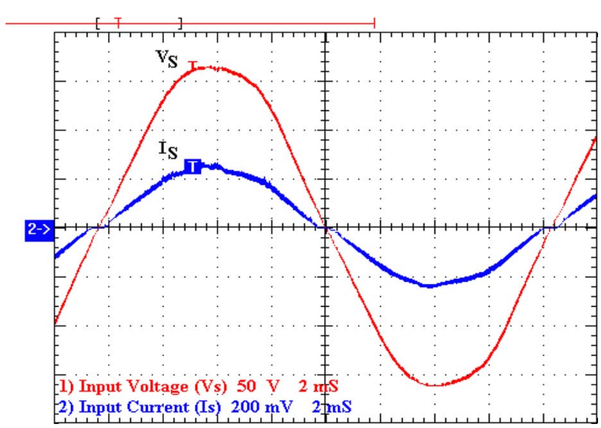

Fig. 13. Input voltage V_S and input current I_S (50 V/div; 20 A/div; 2 ms/div).

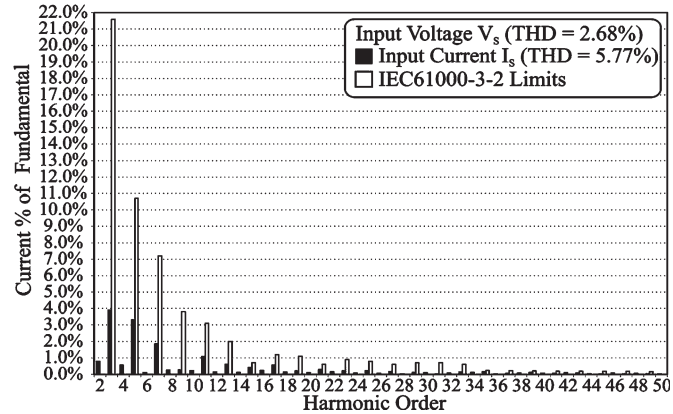

Fig. 14. Harmonic contents of I_S (Fig. 13) compared with the standard IEC61000-3-2.

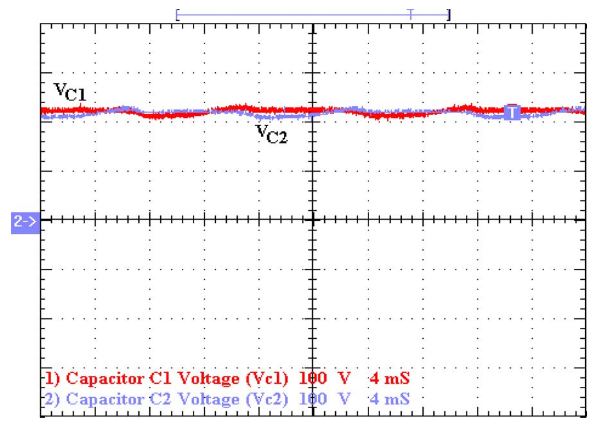

Fig. 15. DC-link capacitor voltage (V_{C1}; V_{C2}) (100 V/div; 4 ms/div).

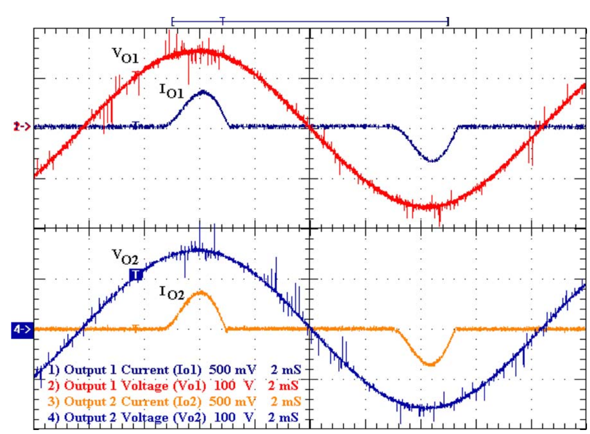

Fig. 16. Output voltages and currents for 110-V load (100 V/div; 50 A/div; 2 ms/div).

modified. The output voltages and currents are shown in Figs. 10, 11, 16, and 19, where it can be seen that a high-quality sinusoidal voltage waveform is supplied by the inverter, independently of the characteristic of the connected load. Figs. 10 and 16 show the waveforms for full-load operation at each output of the inverters, resulting in a 110-V rms supply, and Figs. 11 and 21 show the condition for full load in both outputs, resulting in a 220-V rms supply, as shown in Fig. 3. In addition, in Fig. 16, the measured harmonic content of the output V_{O1} voltage was 0.53%, whereas the current was 119.25%. In Fig. 17, the measured harmonic content of the output V_{O12} voltage was 0.59%, whereas the current was 132.86%.

The UPS efficiency and power factor versus output power for linear load characteristics are shown in Fig. 12, where indicated voltage (110 V or 220 V) refers to the output types of connection. According to the experimental results in the online mode, the proposed UPS achieved a high efficiency even for high-frequency switching operation of both converters.

Compared with the systems shown in Figs. 1 and 2 that present an efficiency of 88.8% and 87.7%, respectively, for the

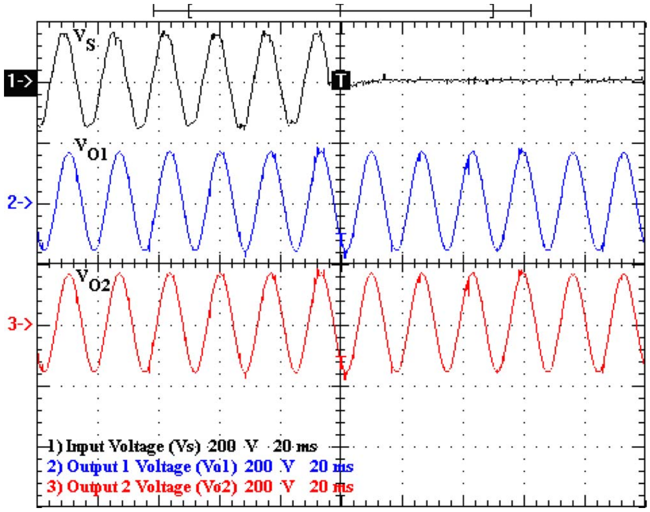

Fig. 17. UPS transition from normal operation mode to battery mode. From top to bottom: Input voltage V_S and output voltages for 110-V load. (200 V/div; 20 ms/div).

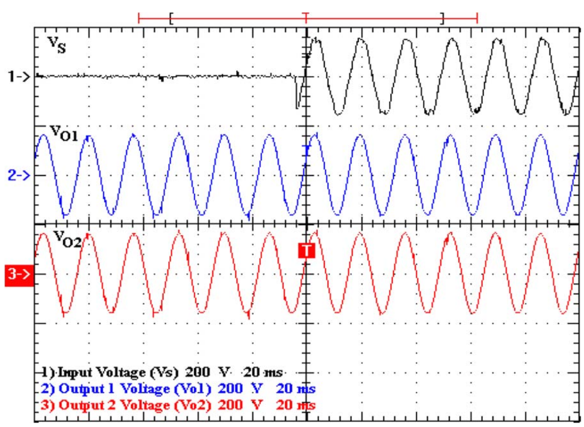

Fig. 18. UPS transition from battery-mode operation to normal mode. From top to bottom: Input voltage V_S and output voltages for 110-V load (200 V/div; 20 ms/div).

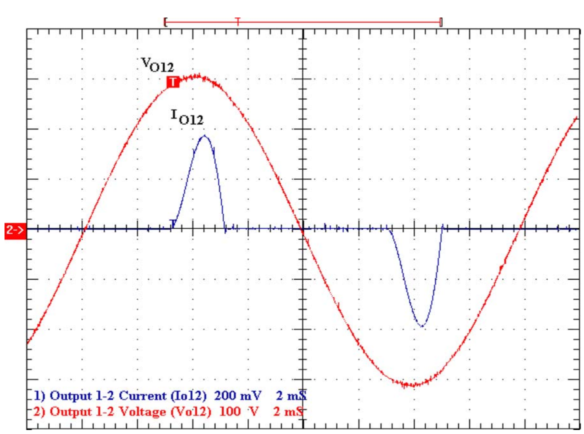

Fig. 19. Output voltage and current for 220-V load (100 V/div; 20 A/div; 2 ms/div).

online mode, the proposed system achieved an almost equal performance considering its cost benefit and higher commutation frequency of the converters.

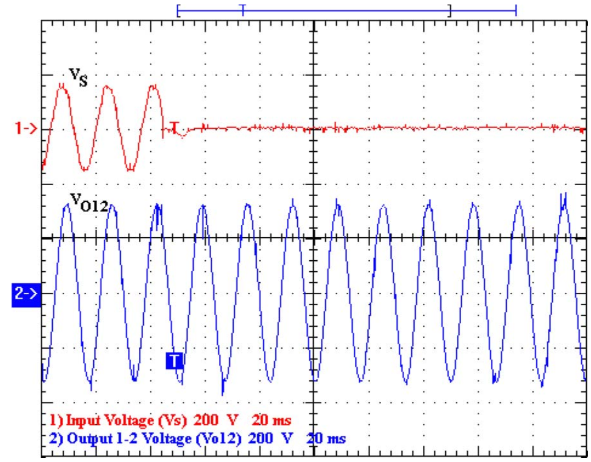

Fig. 20. UPS transition from normal operation mode to battery mode. From top to bottom: Input voltage V_S and output voltages for 220-V load (200 V/div; 20 ms/div).

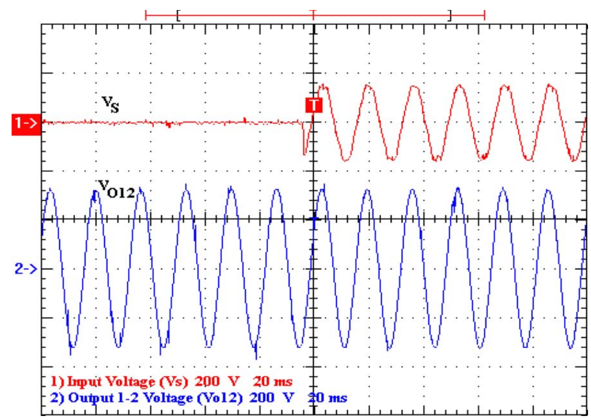

Fig. 21. UPS transition from battery-mode operation to normal mode. From top to bottom: Input voltage V_S and output voltages for 220-V load (200 V/div; 20 ms/div).

The utility input voltage as well as the output 1 and 2 voltage waveforms for full-load operation in a 110-V rms supply are shown in Fig. 17 when the UPS transition occurs from normal operation mode to battery mode. Note that the load voltage continues to regulate even if the ac main fails. When the utility voltage is finally restored, the load-voltage behavior is almost the same, as shown in Fig. 18. The same performance is obtained for the full-load operation in a 220-V rms supply, as shown in Figs. 20 and 21, respectively.

2) Waveforms and Curves for the Battery-Mode Operation: The experimental results for the battery-powered mode were carried out only for the nonlinear load connected at the output of the inverters, except for the characteristic shown in Fig. 25 that was obtained with resistive load. The battery-set voltage was adjusted around 108 V, which represents the rated voltage during intermediate test conditions.

The characteristics of the nonlinear load were the same as used in the online-mode operation. Fig. 22 shows the voltage and current in the battery bank for the loads connected at the 110-Vac outputs and loads connected at the 220-Vac output. As shown in Fig. 22, by using the average current mode control, a continuous dc current with a low ripple has been drawn from

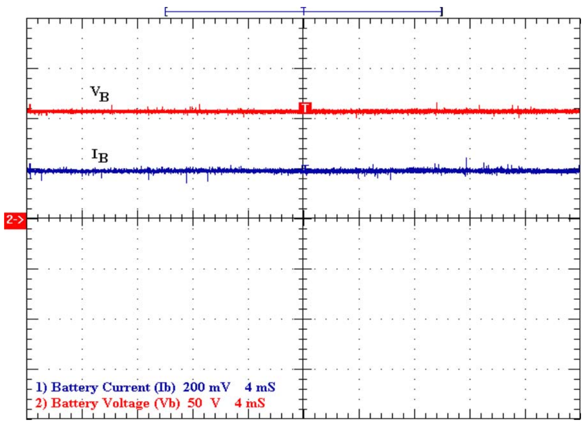

Fig. 22. Battery-bank voltage V_B and current I_B. (50 V/div; 20 A/div; 4 ms/div).

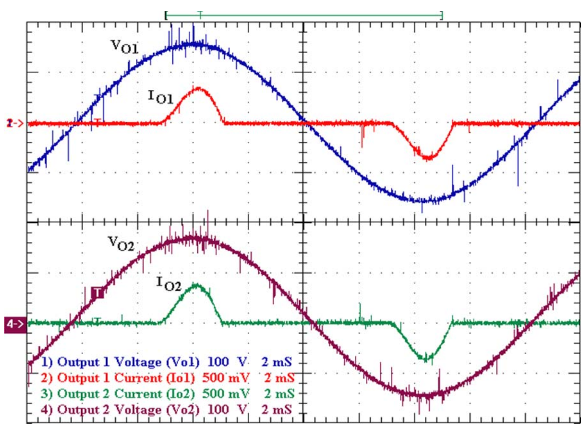

Fig. 23. Output voltages and currents for 110-V load (100 V/div; 50 A/div; 2 ms/div).

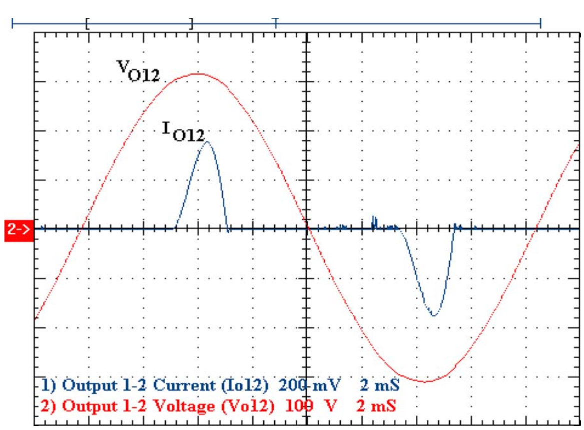

Fig. 24. Output voltage and current for 220-V load (100 V/div; 20 A/div; 2 ms/div).

the battery set, blocking the pulsed current required by the inverter operation, thus enhancing the reliability and life of the battery set.

Output voltages and currents are shown in Figs. 23 and 24. Like the online operation mode, inverters are operated with the same performance. The efficiency curve for this operation mode as a function of output power for the two output types of connection (110 V or 220 V) can be seen in Fig. 25. Most of the nonisolated UPS topologies proposed in the literature do

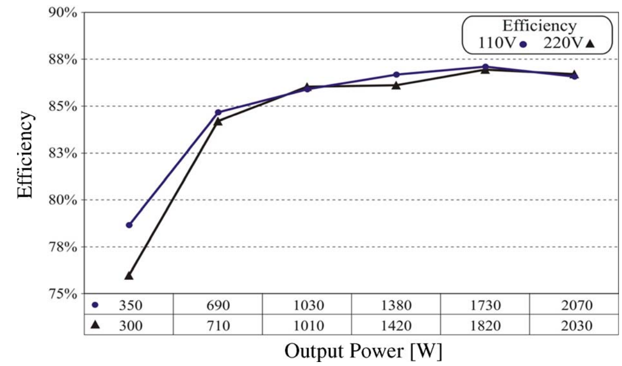

Fig. 25. Measured efficiency in the battery-powered mode as a function of output power.

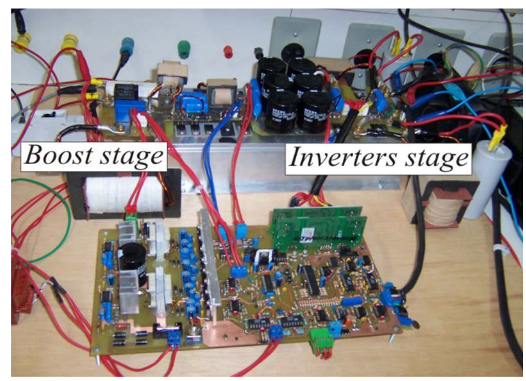

Fig. 26. UPS laboratory prototype.

not show their efficiency curves while the UPS is operating in this mode.

Thus, compared only with Fig. 1, which claims an efficiency of 86% during the battery-powered mode, the topology proposed here achieved good efficiency, and this efficiency even could be improved if insulated-gate bipolar transistors (IGBTs) of the ac/dc converter were replaced for IGBTs with lower conduction losses. If discrete IGBTs with symmetric block capability were available, the number of diodes of this structure could be minimized, lowering the conduction losses in the online mode and mainly in the battery-powered mode.

A picture of the developed prototype is shown in Fig. 26, where both the conversion stages and the control board can be seen.

V. Conclusion

This paper has proposed a nonisolated single-phase 110-V/220-V input–output voltage rating UPS with a configuration that overcomes the problem associated with voltage-doubler topologies when supplied by 220 Vac of the mains.

Another advantage of the proposed topology is the possibility of supplying two different voltage ratings at the UPS output, without reducing the system's overall efficiency and reliability. No isolating transformer is required to realize bypass operation, even if the voltage rating of the load is different from the mains voltage.

A passive nondissipative snubber circuit was used to improve the three-level boost-rectifier efficiency while operating in both the online and battery modes, reducing di/dt of the reverse recovery mechanism in boost diodes and high current peak through the switches. Experimental results were presented to verify the performance of the proposed UPS system. This system performance could be enhanced if discrete IGBTs with lower conduction losses and symmetric block capability were available. Thus, the number of diodes of this structure could also be minimized.

The major problems of this structure are the quantities of static switches and diodes, increasing the cost and decreasing its efficiency. Alternately, in order to increase its efficiency, the commutation frequency of both converters could be reduced.

Therefore, based on experimental results and compared with other topologies proposed in literature, it is possible to conclude that the topology proposed here is very efficient and attractive for computer and telecommunication industries and other applications.

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