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Accurate Modelling of an Online Uninterrupted Power Supply

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***Abstract* – The power quality in most European Union countries is threatened by several factors such as the energetic crisis, solar flares, high penetration of renewable sources, etc. One possible solution for households and small industrial consumers is the uninterrupted power supplies (UPS). This technology is already available on the market, but sizing it according to consumer needs is always challenging. In this paper, a UPS model is developed that can be used to determine the suitable battery technology and size and also evaluate the power consumption and quality.**

Keywords-UPS; battery model; power quality; power electronics

I. INTRODUCTION

In the current context, where the energetic crisis is leaving its mark on most European countries, household consumers and industrial ones are expected to suffer from a lack of power or low-quality power service [1]–[3]. While renewable power sources offer an alternative to the increased demand, they do not solve the power quality issue. Even worse, they introduce high-power harmonics into the grid [4]–[6]. One possible solution is the full implementation of UPSs, which offer clean output voltage and low total harmonic distortion (THD). These devices have already been in use for several years and are mandatory in critical services like hospitals, airports and data centres, but with the increase of sensitive electronics in regular homes, they bring a feasible alternative [4], [7]–[9].

Several types of UPSs are available on the market, each with pros and cons based on their configuration. The most basic type is the offline version which consists of a battery charger, a battery bank, an inverter and a static switch. In a typical operation, the UPS is powered by the main line and charges the battery bank while the inverter is in standby mode. When a power failure occurs, the main line is disconnected by the static switch, and the battery bank feeds power into the now online inverter. The response time for this type of UPS it is around ten milliseconds. The second version combines the battery charger and the inverter into a bidirectional converter called an interline UPS. This technology has the main advantage of a short response time, which comes with a price in complexity and viability. The third version (online UPS), the most popular one, keeps the separated structure with a battery charger and inverter but modifies the operation mode. Now, the main line feeds the charger all the time, which powers the battery and supplies energy to the inverter. This organization assures a low complexity topology while maintaining a low response time, usually around four milliseconds [7].

This configuration is a mature technology, but an aspect that needs to be considered is the optimal sizing of the UPS with respect to the load and the minimal functional time. To address this, in most cases, the manufacturer offers an online estimator which only considers the active power drawn by the load and the needed working time. This sizing method usually produces larger outputs than needed, representing a waste of consumers' energy and money [6], [10], [11]. In this paper, we present a new sizing methodology based on Matlab/Simulink model developed from the data offered by a large UPS manufacturer. The model uses the same input data but permits a more detailed analysis regarding the battery technology, the working time and the current and voltage THDs. The main contributions of the paper are

- Developing a functional model for an online UPS topology that can be used for a wide range of input values – section 2;
- Developing a battery model for several technologies capable of powering the UPS – section 3;
- Validating the developed model using real data from a commercially available UPS – section 4.

II. UPS FUNCTIONAL MODEL

The starting point for the developed model was the datasheets and service manuals for an APC Smart-UPS model 1500VA [12]. This UPS is equipped with an internal lead-acid battery of 48 V and 9Ah and an additional battery of 48 V and 18Ah. It assures the backup power for a server room used by a small company. Besides these, data power information from the site was recorded and compared with the values provided by the software of the UPS. From these data, when a power down occurs, the UPS can sustain a load of 400 W for 20 minutes when both batteries are fully charged.

While this was the starting point for the model, its structure is general enough to accommodate an entire range of online UPSs with minor modifications. The presented values were extracted from the service manual and are for a UPS of 1500 VA, but they can be easily modified for any output power.

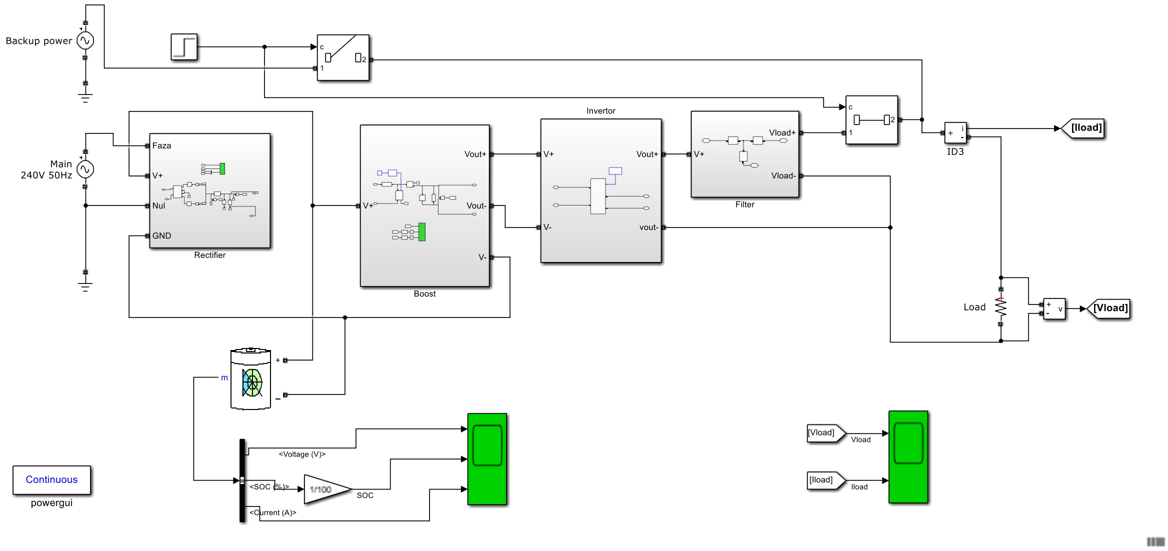

Figure 1. Online UPS block diagram

The UPS model was implemented using Matlab Simulink/Simscape – Electrical library components.

The main advantage of the developed model is that it allows for a thorough analysis of different working conditions. The developed block diagram – Fig. 1, contains all the major blocks presented in the manufacturer data for the UPS used as a model.

The model consists of five functional blocks as follows

- The rectifier receives the main input voltage of 230 VAC and produces a 60 VDC voltage to charge the battery and power the load;
- The battery pack consists of lead-acid 48 V and 30 Ah maximum capacity;
- The boost converter increases the DC voltage up to 350 V;
- The inverter converts the DC voltage into a 230 VAC signal;
- The passive filter assures the power quality of the output voltage.

When the main line is on, and the power is fed into the rectifier, it converts it into a DC signal that charges the battery pack and powers the boost converter. The converter raises the value of the DC voltage and sends it to the inverter, which converts it back into an AC signal whose RMS value is 230 V. The passive filter smooths the signal so a sinusoidal signal can be obtained When the main line is down, the rectifier is off, and the battery automatically powers the rest of the components. An auxiliary power source was added to add more flexibility to the design.

A. *The rectifier*

After a close analysis of rectifier topologies used in UPSs was concluded that the most common structure is a symmetrical half-wave rectifier [7], [13], [14]. This topology (Fig. 2), works in conjunction with a median point transformer whose windings are powered in antiphase, so at any given time, only one diode will be in conduction.

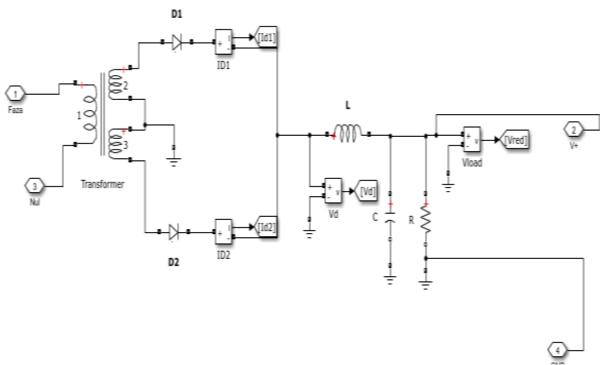

Figure 2. The rectifier structure

The values used for each component are presented in Table 1.

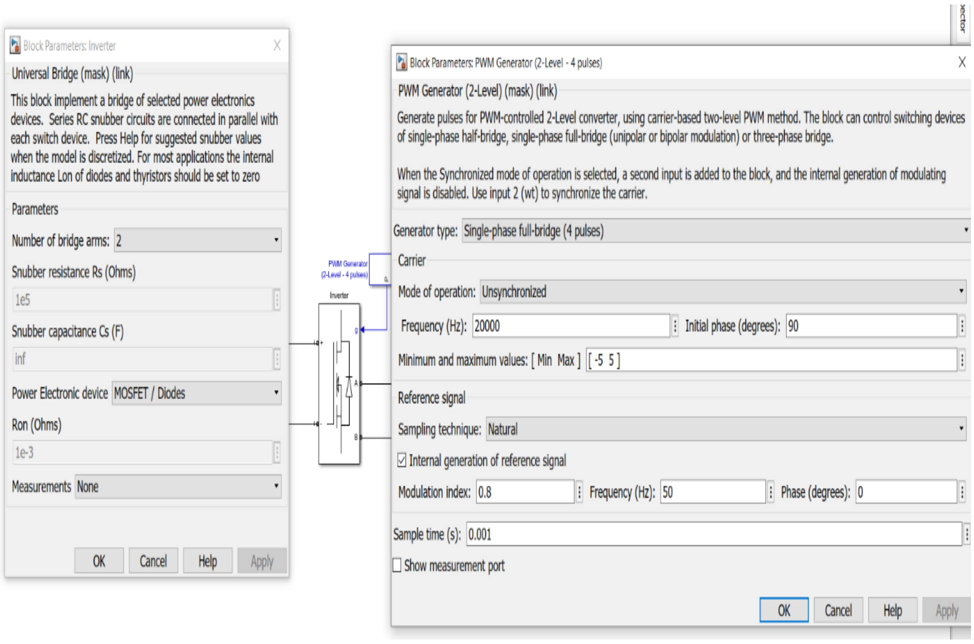

Figure 3. The inverter configuration

TABLE I. THE RECTIFIER COMPONENTS

No.	**Component**	**Value**
1	Input transformer voltage	230 V
2	Transformer ratio	4:1
3	Primary winding inductance	0.01 H
4	Diode voltage drop	0.7 V
5	Output inductance	200 mH
6	Output capacitance	100 µF
7	Output resistance	5 Ω

B. The boost converter

It has a classical topology (Fig. 4), with only one switch controlled by a PWM signal, one diode and an inductance.

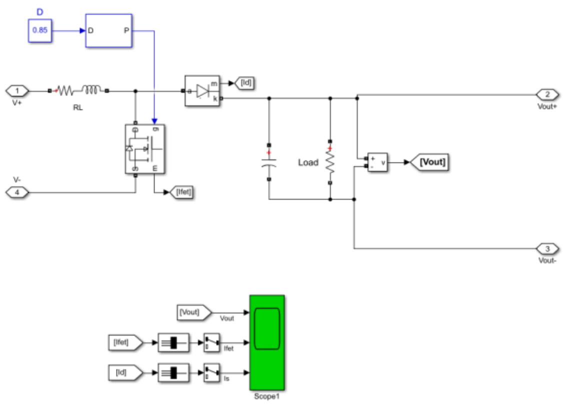

Figure 4. The boost converter structure

There are three distinct states in its functionality S-on, D-off; S-off D-on; S-off, D-off. In the first case, the switch is turned on, making the inductor accumulate energy while there is no output voltage. In the 2nd phase, the switch will be turned off, and the inductor energy will be released through the diode to the output. In the last case, all components are off, so there is no output voltage and no energy stored in the inductor.

The values used for each component are presented in Table 2.

TABLE II. THE BOOST CONVERTER COMPONENTS

No.	**Component**	**Value**
1	Coil inductance	50 µH
2	Coil resistance	1 mΩ
3	Switch type	MOSFET
4	Switch resistance	1 mΩ
5	Diode voltage drop	0,7 V
6	Capacitance	200 µH

C. The inverter

It is a single-phase full bridge inverter with four IOSFET transistors (Fig. 3), controlled by a PWM ɪarrier-based two-level PWM method.

The inverter was chosen as a generic single-phase ɭlock; its setup is presented in Fig.

ʼ. *The L-C-L filter*

Because the inverter output signal has a high harmonics content, an L-C-L passive filter – Fig. 5, was added to produce a sinusoidal-like voltage output [15].

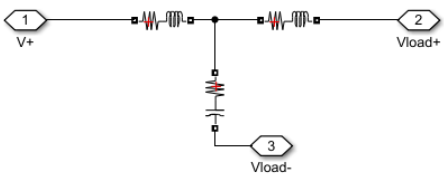

Figure 5. The L-C-L filter configuration

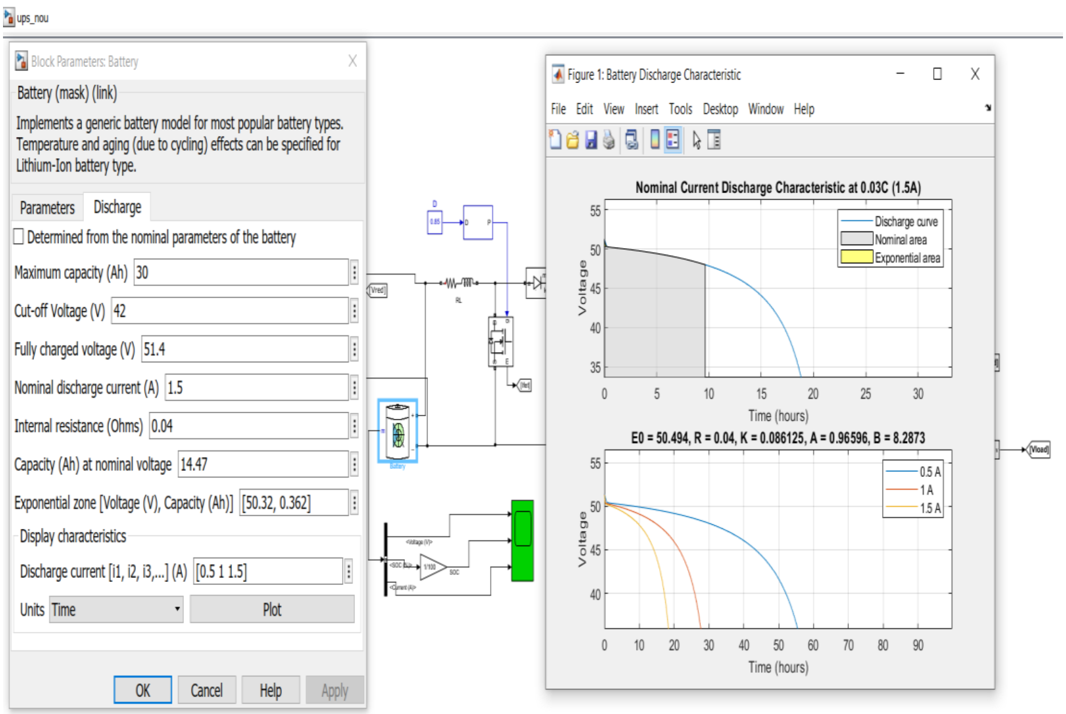

Figure 6. Implementation of the 30 Ah lead-acid battery

It is constructed from three RLC branches with inductances of 3 mH, resistances of 1 mΩ and capacitance of 1 µF.

III. THE BATTERY MODEL

To assure the flexibility of the design, the battery model has to be compatible with several battery chemistries [11], [16], [17]. From the extensive array of batteries model available in the literature, only analytical ones are suitable for such a task. So after a careful analysis, the Shepherd model was chosen because it requires a limited number of parameters that can be obtained from the battery manufacturer data [7], [11], [17], [18].

The functional equations of the model are

- Discharge:

$$U_{out} = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + \mathcal{L}^{-1}\left(\frac{Exp(s)}{Sel(s)}\right)$$

- Charge:

$$U_{out} = E_0 - K \cdot \frac{Q}{Q + it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + \mathcal{L}^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s}\right)$$

where: Uout – output voltage, E0 – Open circuit voltage, Exp(s) – the voltage [1]–[3]at the end of the exponential zone (from the manufacturer discharge data), Sel(s) – has only two values -1 for discharge, 1 for charge, K – polarization constant (calculated from the manufacturer discharge characteristic), i* - discharge current at the end of the exponential zone, it – extracted capacity from the battery and Q – maximum capacity of the battery.

These equations are already part of the generic battery model from Matlab, so for their implementation, a discharge characteristic of a lead-acid battery was used – Fig 6. If another battery technology is needed, only the coordinates of the marked points from the nominal discharge characteristic have to be modified.

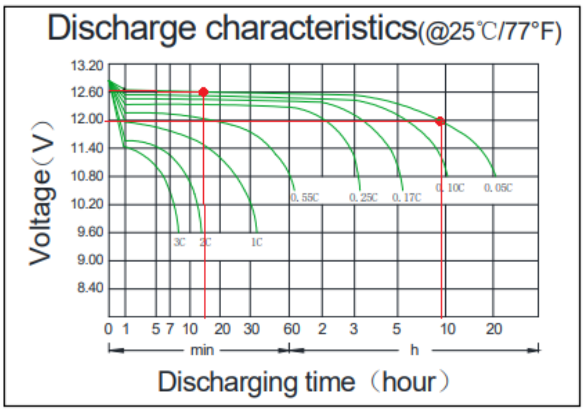

Figure 7. Lead-acid discharge characteristics

The presented algorithm based on extracting data from the battery manufacturer characteristics is generic and can be used for any battery technology and any size. After the data is introduced into the model – Fig. 7, different batteries can be tested easily to achieve the desired working parameters of the UPS.

IV. RESULTS AND DISCUSSIONS

The implementation of the UPS model was done in a sequence to verify the output of each component. Due to the simulation complexity for the case when the main line is down, two distinct scenarios were run: one to capture the transitory effects, which lasted 0.1 s and one to monitor de battery parameters which lasted 5 s. There were several attempts to extend the simulation time, but due to the limited computational resources, none could pass over 8 s, so several extrapolations were performed to approximate the UPS online time.

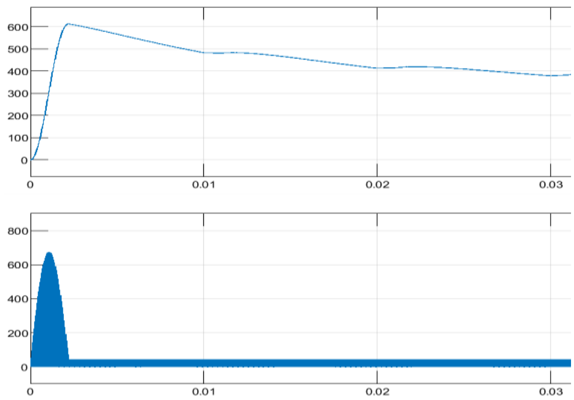

Figure 8. Boost converter output signals voltage (top), current (bottom)

When the UPS is online (no main power), the battery is in discharge mode, and the MOSFET switch from the boost converter is on, which leads to the total voltage from the battery dropping off on the converter's coil, causing an increase of the current to a peak value of 450 A and a decrease of the battery voltage to 45.9 V. This transitory effect lasted only 0.003 s. Also, during this time, there is an overshoot at the converter output of 150 V - Fig. 8.

After this transition period, the converter enters the nominal regime, supplying a 400 VDC output with a maximum 5 V ripple.

The inverter receives the VDC and converts it into an AC signal with an amplitude of 400 V.

The output voltage has a high harmonic content, with the third harmonic being the most significant one with an amplitude of 30% from the fundamental signal.

The passive L-C-L filter is introduced to smooth the signal and produce a sinusoidal-like output. The obtained sinusoidal-like signal – Fig. 9, presents the

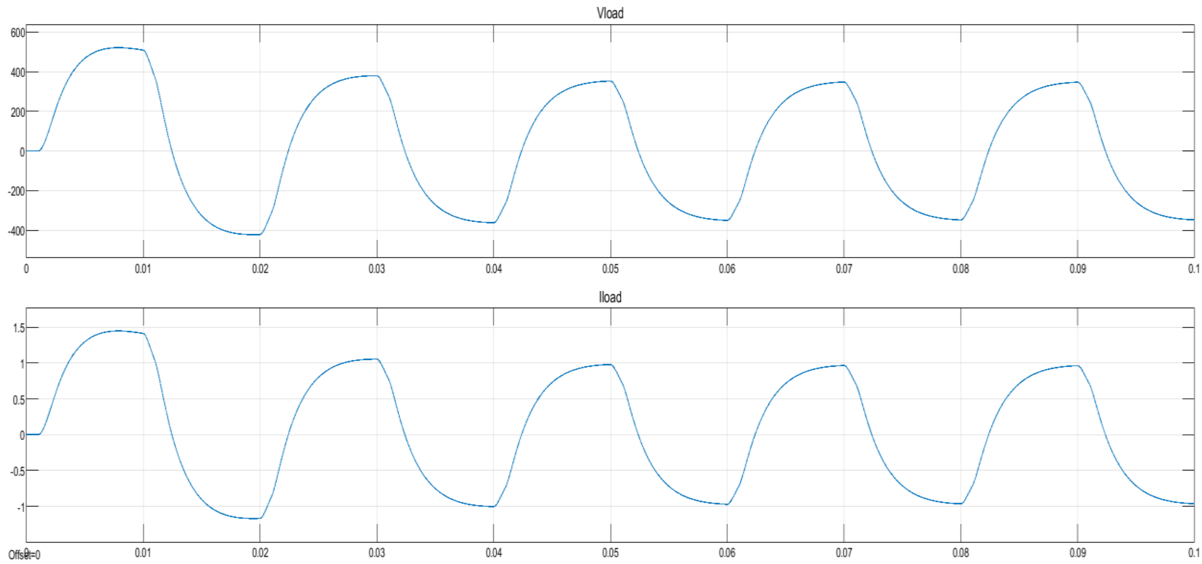

Figure 9. UPS output signals voltage (top), current (bottom)

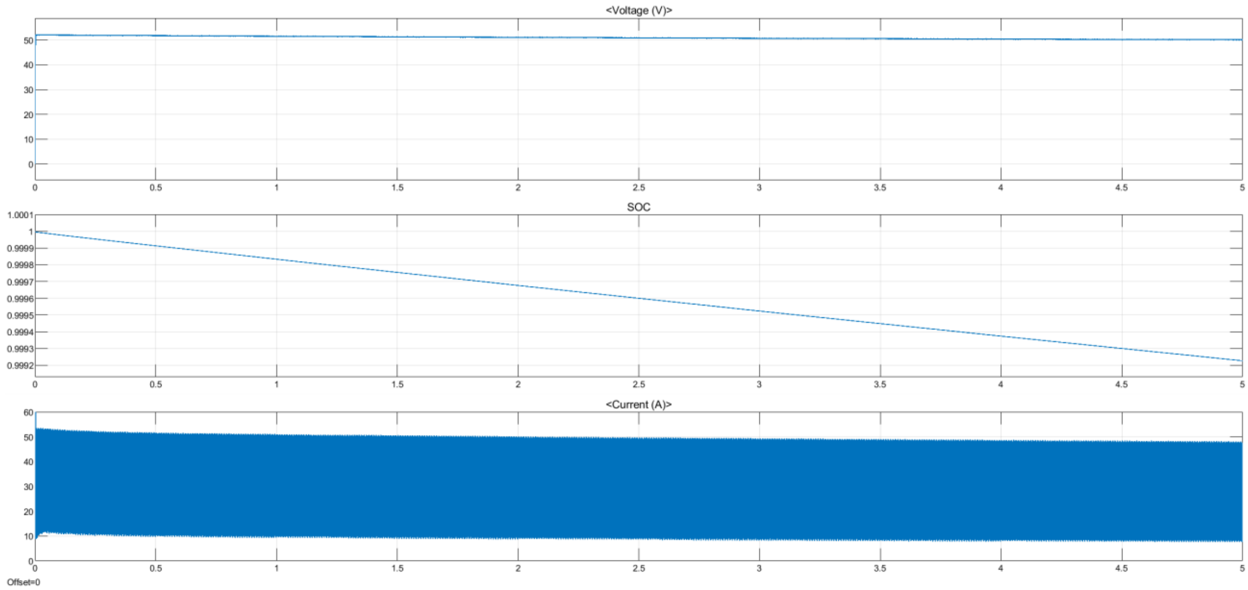

Figure 10. Battery parameters voltage (top), state of charge (middle), current (bottom)

0,03 s period of transitory effects, but after this enters a stable regime. The cutting frequency of the filter was chosen to be half of the command frequency of the inverter [14].

The UPS load was considered an 800 Ω resistive one, producing an output current similar to the one recorded. The output voltage has an amplitude of 340 V (240 V RMS) and a THD of 0.74%, which concurs with the power quality standards.

To determine the battery's performance, a second simulation was run for 5 s while the UPS powered the same 800 Ω load – Fig. 10. During the simulation time of 5 s, the battery voltage dropped from 52.3 V to 49.8 V. The average current is 35.5 A, and this causes a drop in the state of charge from 100 % to 99.92 %. Based on this, the drop rate was computed to be 0.96%/min. Considering that the working condition for a lead-acid battery is between 100% to 80%, the working time of the battery that powers the UPS is 20' 48". This time concurs with the record values for a 400 W load.

CONCLUSION

In this paper, the development of an online UPS model is presented. The model is based on commercially available UPS and the datasheets and service manuals provided by the manufacturer. The model was constructed to be as general as possible and can be easily extended to different output powers.

The developed model was validated based on power recordings from an actual UPS and can be used to determine the battery technology and size for a specific application.

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