ARCHIVES OF ELECTRICAL ENGINEERING VOL. 68(4), pp. 787–802 (2019)

DOI 10.24425/aee.2019.130683

Single phase UPS systems loaded with nonlinear circuits: analysis of topology in the context of electric power quality

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(Received: 26.03.2019, revised: 04.06.2019)

Abstract: Along with the increase in the use of nonlinear electronic devices, e.g. personal computers, power tools and other electrical appliances, the requirements for uninterruptible power supplies are constantly growing. This paper proposes a method and deep analysis of results viable for checking how single-phase uninterruptible power supplies (UPSs) cope with nonlinear circuits under varying power loads in terms of electric energy quality. Various classes of single-phase UPS systems with different topologies were tested, for instance line-interactive and double conversion (online) single-phase UPS devices. Furthermore, measurements were carried out in view of a power source – loads were supplied both from a power grid and UPS built-in battery. Juxtaposition of the obtained results such as a THD_U, THD_I (Total Harmonic Distortion) percentage ratio of input/output voltage and current, a power factor and crest factor volume etc. of the tested UPS systems indicated major differences in their performance during laboratory tests.

Key words: electrical measurements, harmonic distortion, nonlinear circuits, uninterruptible power supply

1. Introduction

Uninterruptible power supply systems are utilized to provide reliable and high quality electricity as backup power supply solutions. Such systems nowadays find a wide range of applications in supplying and securing local electric power networks. UPS devices are typically used to protect or backup hardware, e.g. personal computers, data hubs, telecommunication and electrical equipment. The primary role of this family of devices is to provide high quality power when a main input power source fails [1, 2].

The most basic parameters of uninterruptible power supply (UPS) systems are power (active and apparent power) and battery backup time. Although this data is rarely enough to choose a suitable UPS, it is critical for the initial match between the offered solution and the application requirements. Most of the data provided by manufacturers concerns linear loads. It is a major challenge to select a proper UPS solution for the application where highly nonlinear and time varying load characteristics are involved [3].

In this paper an important question is posed, whether to choose high-end UPS systems with advanced topologies implemented in respect of achieving electric power quality standards over the simpler solutions – UPS systems with standard topologies that produce energy of lower quality and are seemingly sufficient for powering most linear circuits. A major problem arises when nonlinear loads are taken into consideration.

Battery backup time depends on the power amount required for feeding connected devices and apparently it's not changing linearly. Therefore this parameter ought to be presented by manufacturers in form of tabular data or charts [4].

In this case rated power is the maximal apparent power delivered continuously by the inverter of the UPS. An output power factor defines the ratio of maximal active power to maximal apparent power delivered by the inverter. However, it does not indicate the actual power ratio at the output of the power supply. It depends directly on fed circuits [5]. Bearing in mind both the active power P_{UPS} and the apparent power S_{UPS}, the UPS should be selected so that the aggregated rated load characteristics of powered devices do not exceed one of them. It has been specified by the fallowing equations:

$$S_{\text{UPS}} \geq k \cdot \sum_{i=1}^{n} \frac{P_i}{\cos\varphi_i}\,, \tag{1}$$

$$P_{\text{UPS}} \geq k \cdot \sum_{i=1}^{n} P_i\,, \tag{2}$$

where P_i is active power of a fed circuit, k is the coincidence factor and $\cos\varphi_i$ is the fed circuit power factor. UPS efficiency is not constant and changes nonlinearly with respect to a load. Efficiency achieves the highest value after exceeding 50% of the power load.

Significant are parameters related to power quality delivered by the UPS and their impact on the energy grid. The most important is the Total Harmonic Distortion ratio of input/output voltage (THD_u) and current (THD_i). In power systems, lower THD means reduction in peak currents, heating, emissions, and core loss in electric motors [6]. The range of voltage values and frequencies at which the UPS will not switch to battery power and the range of programmable output voltage parameters (value and frequency) are also determined. A crest factor specifies the acceptable ratio of the peak output current to the effective output current without causing voltage distortion. Further it determines the ability of the UPS to supply nonlinear loads. If the UPS is feeding a load close in value to rated, exceeding the crest factor by the current can cause the output voltage to be distorted and the UPS can read this as an overload.

It is recommended to choose the topology of the UPS in accordance to the desired voltage parameters at its output. The VFD (Voltage and Frequency Dependent) topology called offline topology is recommended for devices which require protection against the effects of overvoltage and transient voltage losses. It is worth mentioning the line-interactive topology which is an improvement to the offline topology. Line-interactive UPSs can cope with continuous undervoltages, brownouts and overvoltage surges without consuming the limited reserve battery power. It is achieved by selecting automatically different power taps on the built-in autotransformer [7, 8]. VFI (Voltage and Frequency Independent) called online topology is meant for devices requiring protection against frequency distortions, noise and harmonic distortion. This solution provides an impenetrable barrier between the incoming power from a grid and sensitive electronic equipment. It is also called a double-conversion UPS due to the rectifier directly driving the inverter, even when powered from the standard AC current [8, 9, 11, 12]. Moreover, UPSs in the double conversion topology are equipped with a static bypass that can increase UPS efficiency. If the input voltage parameters are within acceptable limits in terms of power quality, the UPS transfers the power to the bypass path, so that its efficiency grows to almost 99% in the entire load range. In the case when a user manually blocks the ecological mode of the power supply, it can provide the highest quality energy at the expense of efficiency. The efficiency of a properly loaded device does not fall below 90%. However, power supplies with a load smaller than 50% significantly lose their efficiency (Fig. 1).

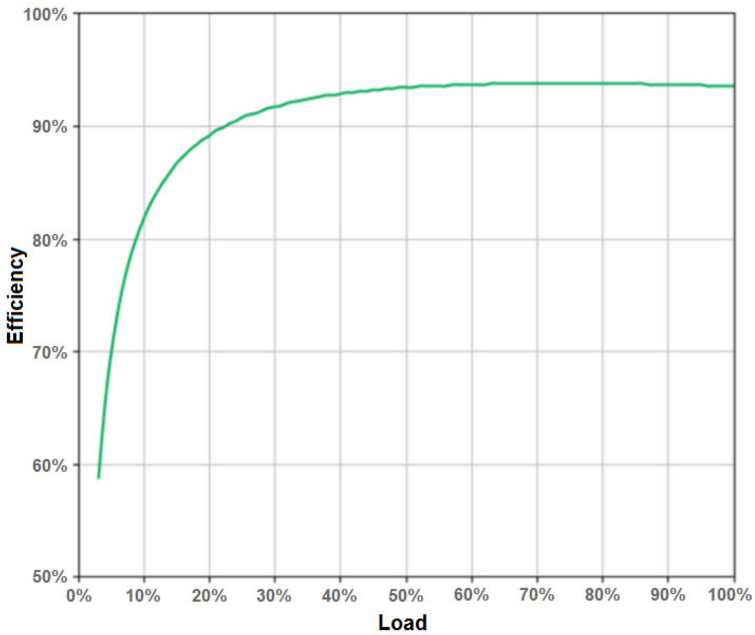
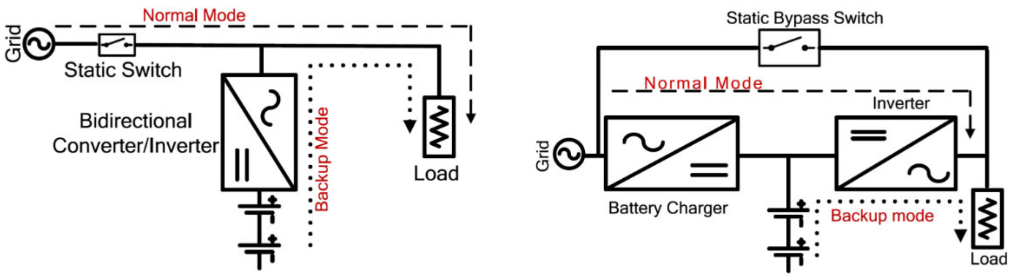


Fig. 1. Efficiency graph for 300 kVA online UPS [10]

The line-interactive and online topology used for tests were shown in Fig. 2. Due to the research of specific UPS systems, the topology diagrams were analyzed. The expected and actual results of current and voltage measurements were referred to the topologies indicated in literature.



(a) (b)

Fig. 2. Topology used for tests [1]: (a) line-interactive topology; (b) online topology

Planned tests and measurements of three different UPSs were conducted to prove that:

– Mostly Double-conversion but also line-interactive UPSs tend to improve power quality by filtrating harmonics even when their loads are strongly nonlinear,
– Double-conversion and line-interactive UPSs are able to approximate or recreate sine waveforms of voltage and current even when their loads are strongly nonlinear,
– High-end UPSs with double conversion topology indicate optimal efficiency when their loads range from at least 30% to 50% of the nominal output.

2. Measurement system and equipment

The catalog data of the power supplies contain information regarding parameters for powering linear loads, which do not fully illustrate the possibility of using the power supply in practice. The purpose of the experiments carried out in the laboratory was to check how UPSs work when supplying nonlinear loads, both when connected to a grid, as well as feeding loads from a battery.

The Rogowski coil with a CWT 15R integrator has been used to measure currents. Its output voltage was 2 mV and was corresponding to a 1 A current flowing in the tested conductor. The classic voltage divider was used to measure the voltage. Along with the voltage measuring probes, it gave ratio of 1:100. The measurements were observed using the Tektronix TPS 2024 four-channel digital oscilloscope. Fig. 3 shows the configuration of the proposed measurement system. Two devices were used as nonlinear loads. First of them was a standard personal computer equipped with a 200 W power supply and a 17-inch CRT monitor equipped with a 150 W power supply. It was mainly used to test line-interactive UPSs with smaller value of rated power. The second load was a heat gun of a rated power equal to 1500 W, fed directly by a 2.5 kVA autotransformer. The autotransformer was used to adjust the load value. The heat gun acted as a highly nonlinear load.

During the laboratory tests, UPS systems of different topology were examined: line-interactive and online (double conversion). Specific data on the tested UPS systems were shown in Table 1.

Device **A** is a line-interactive UPS – a far more advanced device than its predecessor which is a standard offline UPS. It has a built-in display, basic measurement functions and is available in the power range from 0.5 kVA to 1.5 kVA.

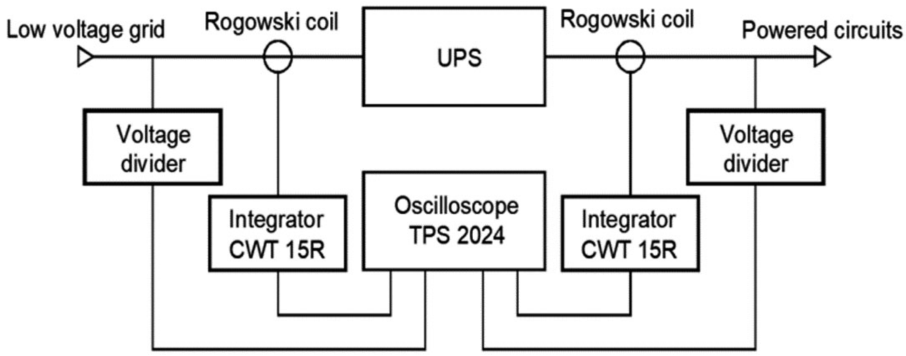


Fig. 3. Block scheme of proposed measurement system

Table 1. Basic parameters of tested UPS devices

UPS label	Apparent power [VA]	Active power [W]	cos φ	Topology	Wave from type
A	550	330	0.6	Line-interactive	Step approximation
B	1 000	700	0.7	Line-interactive	Sine wave
C	3 000	2 700	0.9	Online (Double Conversion)	Sine wave

Line-interactive UPS **B** thanks to a full sinusoidal projection is used to power individual devices or rack cabinets with server equipment. It is available in a free-standing version, as well as for mounting in a rack cabinet and has an SNMP card slot in order to communicate with the LAN network. The power range of this family of devices varies from 750 VA to 3 kVA. Online UPS **C** belongs to the UPS family designed to power high-end IT equipment. This is one of the most advanced devices in its class. UPSs which belong to that class are available in the power range from 2.2 kVA to 10 kVA.

3. Results and analysis of measurements

For every UPS type three to five series of measurements were carried out. During the first series, UPSs were powering the described PC. The second series concerned powering of a heat gun. In the third series, the heat gun was also powered by the chosen UPS but in overload conditions (highly nonlinear load). In the fourth series, the PC or heat gun were powered by a UPS battery. For a higher grade UPS, (**C**), additional series were carried out.

A. UPS A – Results and analysis

During the first series of tests (A.1), power supply A was feeding a desktop computer. The UPS improved slightly the power factor (cos φ_{in}) at the input of the power supply. However, this was not due to the compensating properties. The improvement of the power factor should be associated with very low UPS efficiency (η).

The power supply during the test run was recharging the batteries, so that it took an additional amount of active power and passed it to the battery.

Table 2. Detailed results concerning UPS model A

UPS Model	**Series number**	U_{in} **[V]**	U_{out} **[V]**		I_{in} **[A]**	I_{out} **[A]**	**Crest factor**
	A.1	239.86	236.24		3.29	1.09	3.72
	A.2	236.92	232.28		7.47	5.86	3.38
	A.3	–	242.20		–	0.59	3.61
	–	P_{in} **[W]**	P_{out} **[W]**	P_{bat} **[W]**	S_{in} **[VA]**	S_{out} **[VA]**	η **[%]**
	A.1	764.21	188.20	56.70	788.09	253.83	25
A	A.2	1393	826.27	254.30	1769.3	1361.3	59
	A.3	–	129.13	–	–	142.19	–
	–	$\cos\varphi_{\mathrm{in}}/\cos\varphi_{\mathrm{out}}$	$\mathrm{THD}_{I_{\mathrm{in}}}\%$		$\mathrm{THD}_{I_{\mathrm{out}}}\%$	$\mathrm{THD}_{U_{\mathrm{in}}}\%$	$\mathrm{THD}_{U_{\mathrm{out}}}\%$
	A.1	0.79/0.61	52		71	11	11
	A.2	0.97/0.74	22		56	9	10
	A.3	–/0.91	–		31	–	31

This improved slightly the input power factor ($\cos\varphi_{\mathrm{in}}$) and increased uptake of the basic harmonic current for battery charging. That positively affected the relative value of the subsequent harmonics of the current. The observed distribution of harmonics is characteristic for all devices powered by a switched-mode power supply.

During the second series of the tests, (A.2) the heat gun was powered by the UPS at overload conditions. The impact on improving the input parameters while the UPS battery was charging, was satisfying (input power factor) and slightly better than in series A.1. The current pulses weren't clean. It is worth noting that the UPS during this test worked with over 50% overload. The UPS signaled that it was overloaded. However a few minutes of work with such power load did not burn internal fuses. The graphical results of energy quality parameters, as well as current and voltage waveforms were presented in Fig. 4.

Despite the fact that a heat gun renders less of higher harmonics than a PC – a large ratio of even harmonics occurred in graphs (Fig. 4).

The third series (A.3) concerned a PC powered by a UPS built-in, fully charged battery. Powering the computer from the battery via the inverter did not cause any disruptions in its functioning. The output power factor ($\cos\varphi_{\mathrm{out}}$) turned out to be the best of all three series. Series A.1 presents lower values of $\cos\varphi_{\mathrm{out}}$ in comparison to series A.3, despite the receiver was identical. It is a result of feeding a strongly non-linear receiver (negative influence on the input from network). It is also caused by a simple construction of UPS A, the low ability to correct

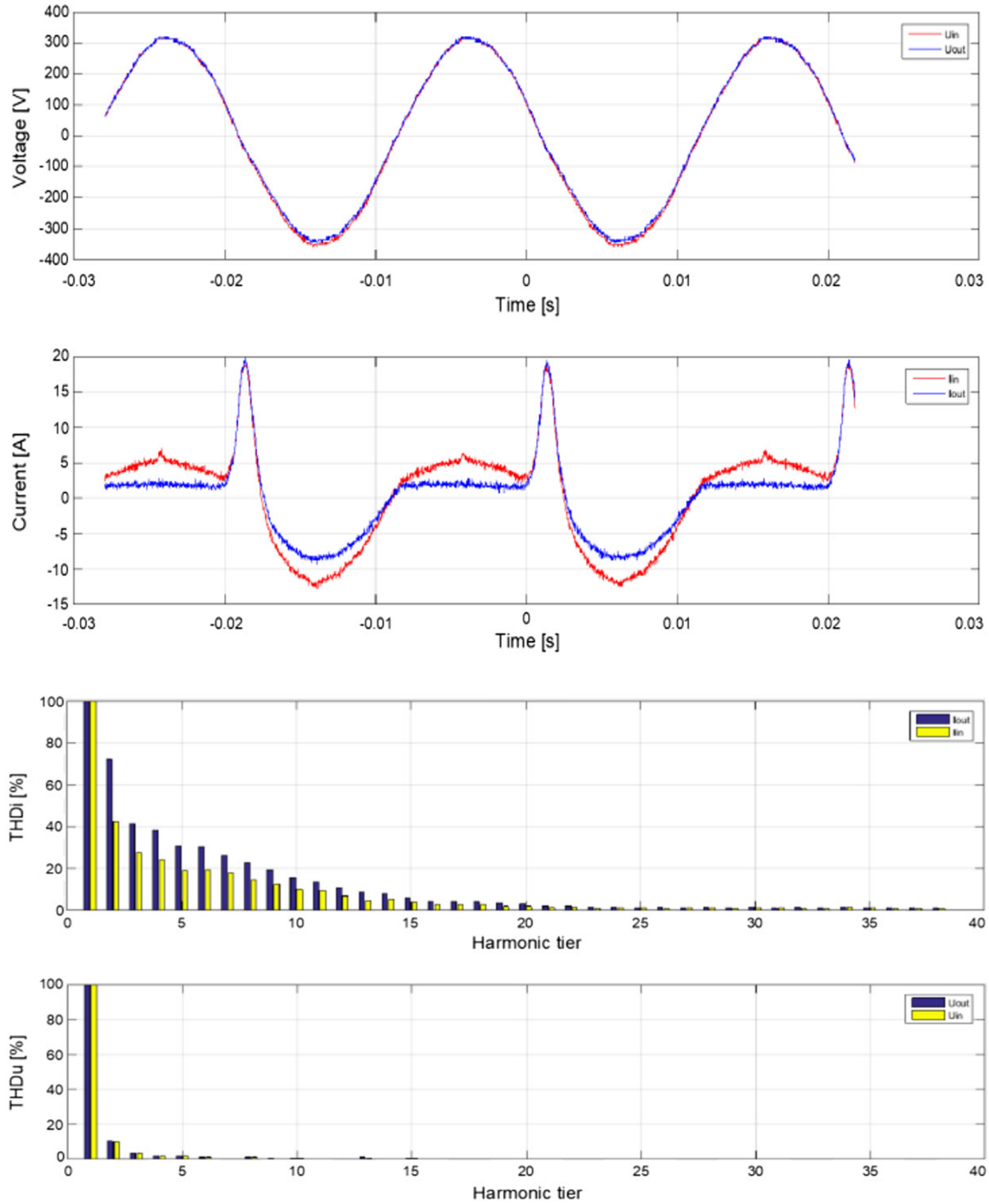


Fig. 4. Graphical results of energy quality parameters and presentation of voltage/current waveforms for series A.2

the power factor and the fact that the battery was not fully charged. Series A.3 tends to present better values of an output power factor. The difference was caused by the fact that the battery was fully charged during the measurements and there was no negative non-linear disruptions from the network (the receiver was powered only from the battery). The active power value delivered by the power supply was decreased by 30%. This proves that the step approximation of the sine wave works very well while powering the switched-mode power supplies. There is no need to use power supplies with a full sine waveform.

B. UPS B – Results and analysis

Table 3. Detailed results concerning UPS model B

UPS Model	Series number	U_{in} [V]	U_{out} [V]		I_{in} [A]	I_{out} [A]	Crest factor
	B.1	236.97	232.67		5.05	2.97	2.5
	B.2	235.93	230.41		8.55	6.86	3.12
	B.3	–	237.07		–	4.77	2.88
	–	P_{in} [W]	P_{out} [W]	P_{bat} [W]	S_{in} [VA]	S_{out} [VA]	η [%]
	B.1	1100.7	523.9	136.20	1195.6	690.07	48
B	B.2	1595.2	1031.2	324.60	2017.5	1579.7	65
	B.3	–	641.6	–	–	1131.7	–
	–	$\cos\varphi_{in}/\cos\varphi_{out}$	$THD_{I_{in}}$%		$THD_{I_{out}}$%	$THD_{U_{in}}$%	$THD_{U_{out}}$%
	B.1	0.92/0.76	28		54	11	11
	B.2	0.79/0.65	51		67	11	12
	B.3	–/0.57	–		61	–	11

During the first series (B.1) of the tests, power supply B was feeding a heat gun. A higher grade line-interactive UPS was better at filtering higher harmonics in comparison to the previous UPS model. In conjunction with the energy consumed, needed for charging the battery, it well reflected the shape of the sine wave of the input current while feeding a nonlinear load. The output power factor was slightly better comparing to a similar series in subsection A (Fig. 5).

During the tests with a heat gun in the overload conditions (series B.2), the UPS performed worse with harmonic filtration and power factor correction but still better than UPS A (Fig. 6).

Series B.3 showed that the tested UPS copes well with mimicking the sine wave pattern during battery backup time. An active power load close to the nominal value greatly deformed the UPS voltage waveform.

Furthermore, a voltage dip occurred right at a current pulse (peak). When the current passed through zero, the inverter recovered the corresponding value of voltage. However, it couldn't cope with mapping a full waveform of the sinusoid in the next wave. The upper peak of the wave is reconstituted much better. The crest factor value is low because the voltage dip is limiting the peak current value. Despite large distortions.

The UPS maintains the effective voltage value. Fig. 7 shows waveforms of voltage and current while feeding the heat gun from the UPS battery.

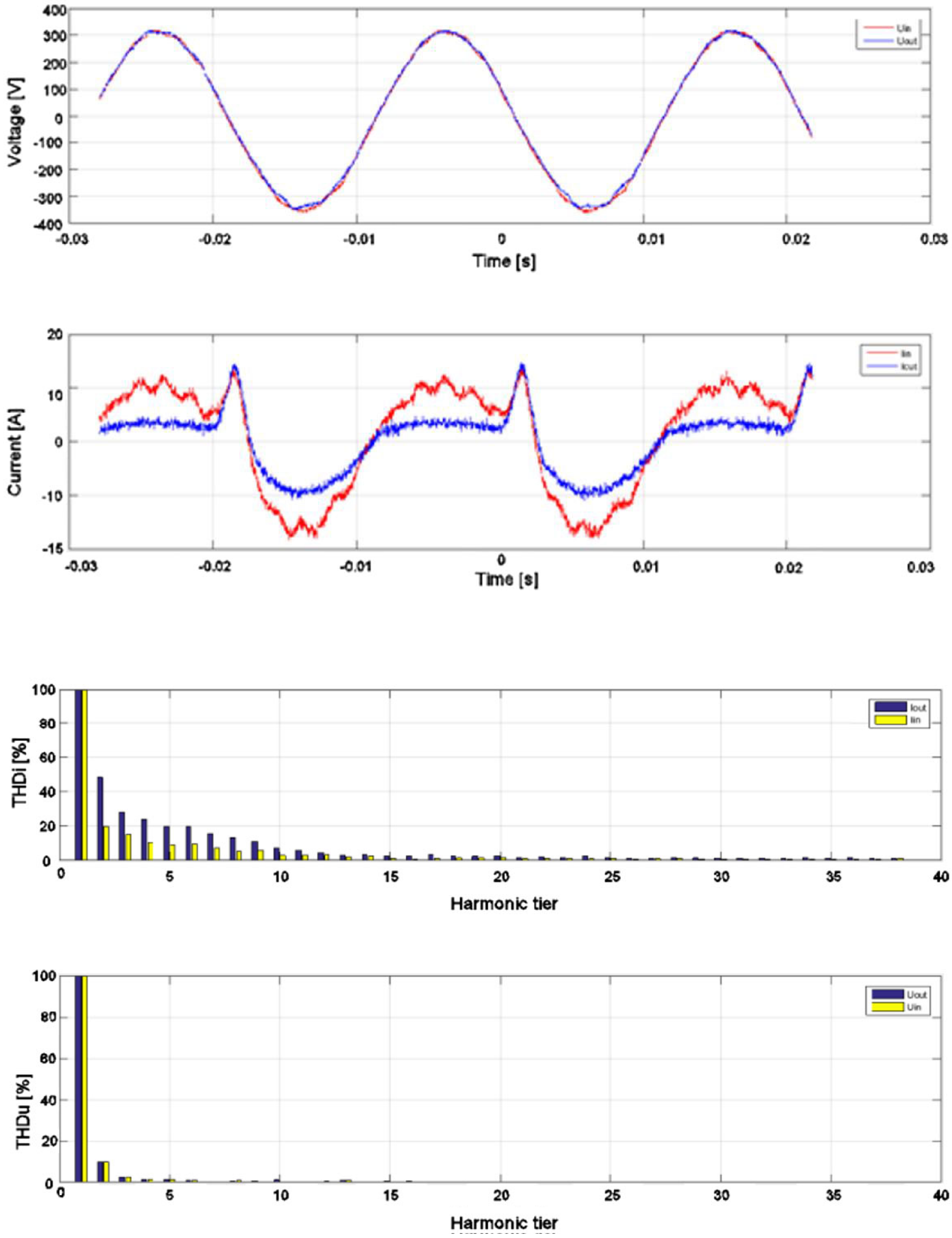


Fig. 5. Graphical results of energy quality parameters and presentation of voltage/current waveforms for series B.1

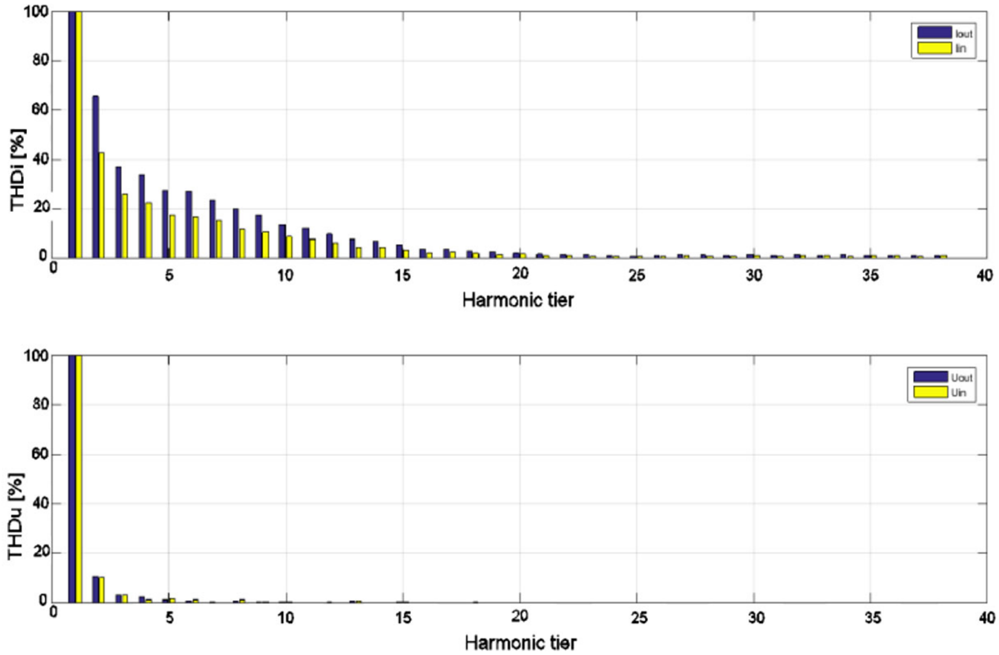


Fig. 6. Graphical results of energy quality parameters for series B.2

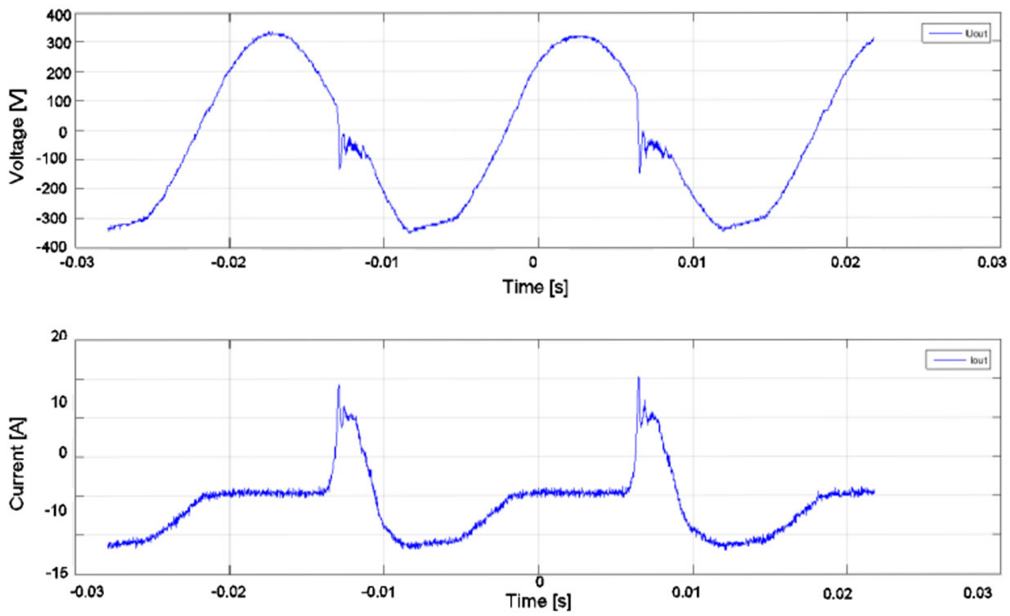


Fig. 7. Shape of voltage and current waveforms while powering load from UPS battery. Series B.3

C. UPS C – Results and analysis

UPS C has implemented double conversion topology. All series were conducted with the usage of a heat gun as a nonlinear load.

Table 4. Detailed results concerning UPS model C

UPS Model	Series number	U_{in} [V]	U_{out} [V]		I_{in} [A]	I_{out} [A]	Crest factor
	C.1	238.08	238.32		2.14	2.77	2.02
	C.2	237.11	238.28		4.86	5.45	1.55
	C.3	233.00	237.80		16.19	16.98	1.44
	C.4	–	238.40		–	3.90	5.12
	C.5	–	237.61		–	11.75	1.45
	–	P_{in} [W]	P_{out} [W]	P_{bat} [W]	S_{in} [VA]	S_{out} [VA]	η [%]
	C.1	343.25	283.87	59.38	509.49	660.15	82.70
	C.2	1102.00	959.84	229.5	1152.35	1298.60	87.10
C	C.3	3686.60	3399.05	398.15	3772.27	4037.84	92.20
	C.4	–	560.64	–	–	930.65	–
	C.5	–	2792.80	–	–	2810.45	–
	–	$\cos\varphi_{in}/\cos\varphi_{out}$	$THD_{I_{in}}$%		$THD_{I_{out}}$%	$THD_{U_{in}}$%	$THD_{U_{out}}$%
	C.1	0.67/0.83	57		44	10	10
	C.2	0.96/1.00	10		10	10	10
	C.3	0.96/1.00	9		10	10	10
	C.4	–/0.60	–		59	–	10
	C.5	–/1.00	–		10	–	10

During the first series of measurements (series C.1) it was confirmed by the fact that the current waveforms did not overlap each other. The input current impulse was probably caused by the charging of input capacitors, which are responsible for covering energy needs while sudden jumps of output current occurred. The UPS power load was around 10% in this series. According to the catalog data, at this load level, the efficiency of the UPS should be less than 90%. This means that the UPS had to use the energy stored in the battery to maintain the proper value of the nonlinear load voltage. Unlike the previous UPSs, model **C** did not filter the harmonics rendered by the loads. It also did not improve the input power factor for conditions set in series C.1 (Fig. 8).

In series C.2 power loads close to half of the nominal power value were applied. UPS C performance improved significantly. Levels of higher harmonics returned to the grid decreased several times (showed in Fig. 9). The input power factor exceeded a value of 0.96 and the output

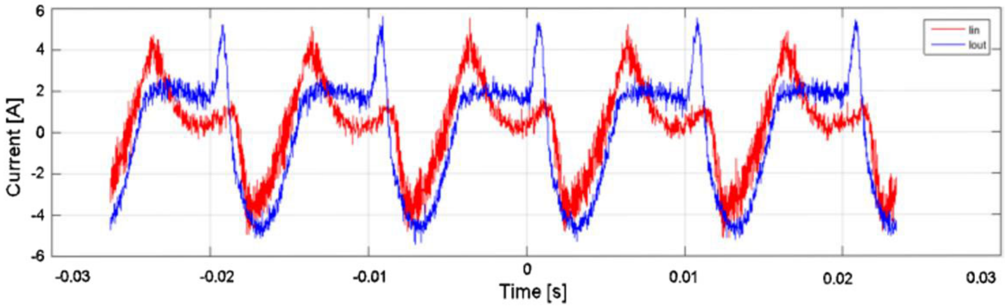
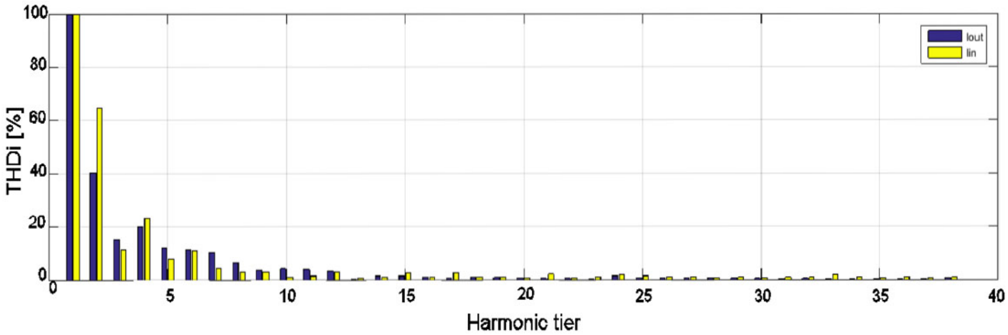
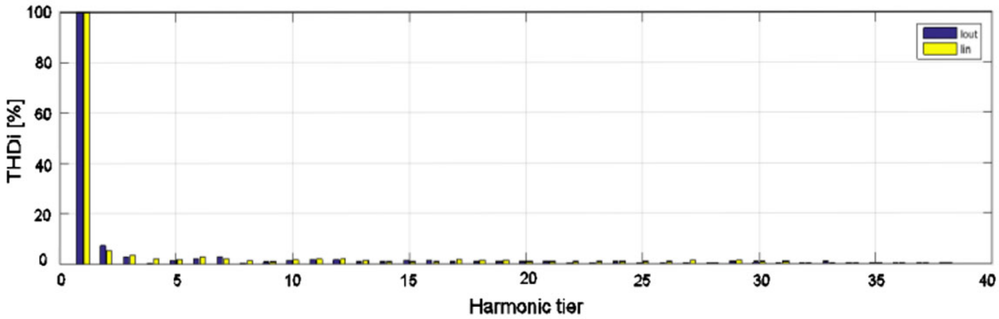


Fig. 8. Shapes of current input/output waveforms characteristic for double conversion UPSs. Series C.1



(a) Series C.1



(b) Series C.2

Fig. 9. Comparison of THD_i ratios in series C.1 and C.2

power factor was equal to one. The crest factor has dropped to 1.55 which was slightly a higher value than $\sqrt{2}$ – the crest factor for the ideal sine wave.

The main goal of series C.3. was to overload the tested UPS online. In order to achieve that, a 1000 W incandescent bar was used as an additional load.

After loading the UPS, the efficiency was 92.20%, so the tested power supply used the battery to a small extent. The crest factor value was 1.44, which means that the output current was almost in a shape of a sine wave. The power supply was overloaded by 20% of the rated active power, but the overload wasn't indicated by the device. This means that UPS **C** can be overloaded permanently by 15% to 20% of the nominal rated power.

Series C.4 and C.5 concerned feeding loads from a UPS battery. The output power factor in series C.4 was much lower. The harmonic levels were higher in the output current.

The higher harmonics caught on the chart showed that the values of even harmonics (2nd and 4th) are greater than the odd ones (3th). This indicated that the heat gun renders much more even harmonics than the average electronic device.

Furthermore, a very high crest factor is caused by strong voltage spikes that did not appear in every period. The pulses are smaller in certain periods. It may be caused by DC capacitors that were charging. In series C.5, UPS C fed the power load close to the nominal power output of the device.

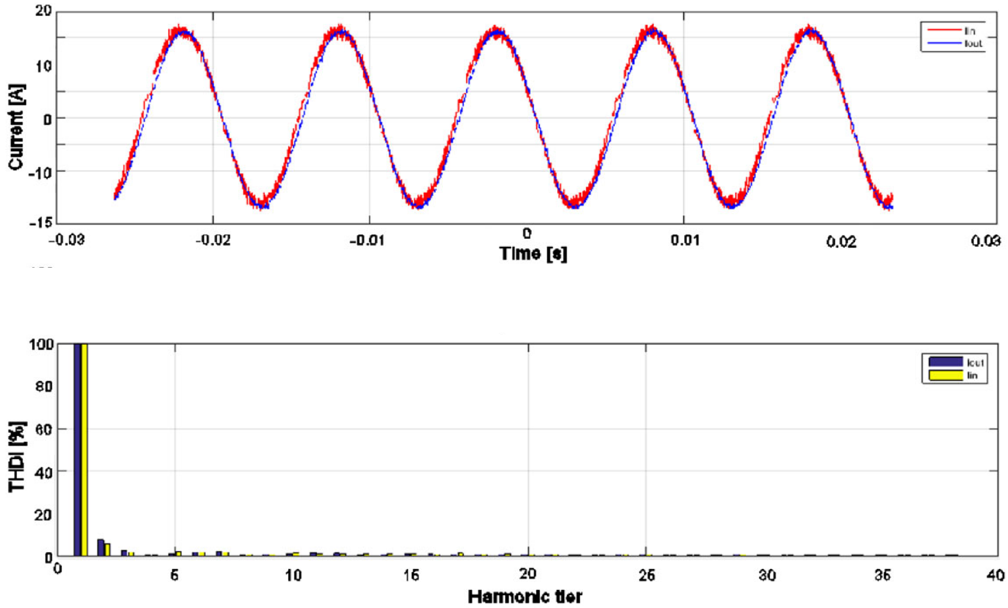


Fig. 10. Shapes of current input/output waveforms and THD_i ratio for series C.3

When loads where switched onto feeding from the battery, it did not affect the work of connected circuits (the heat gun and incandescent bar). The power supply was able to take the load after a cold start – without power from the grid. However, it was not possible to set full rated power output, due to the magnetizing currents of the autotransformer.

When the UPS was powered from the grid, it was able to handle a step load even when a magnetizing current occurred.

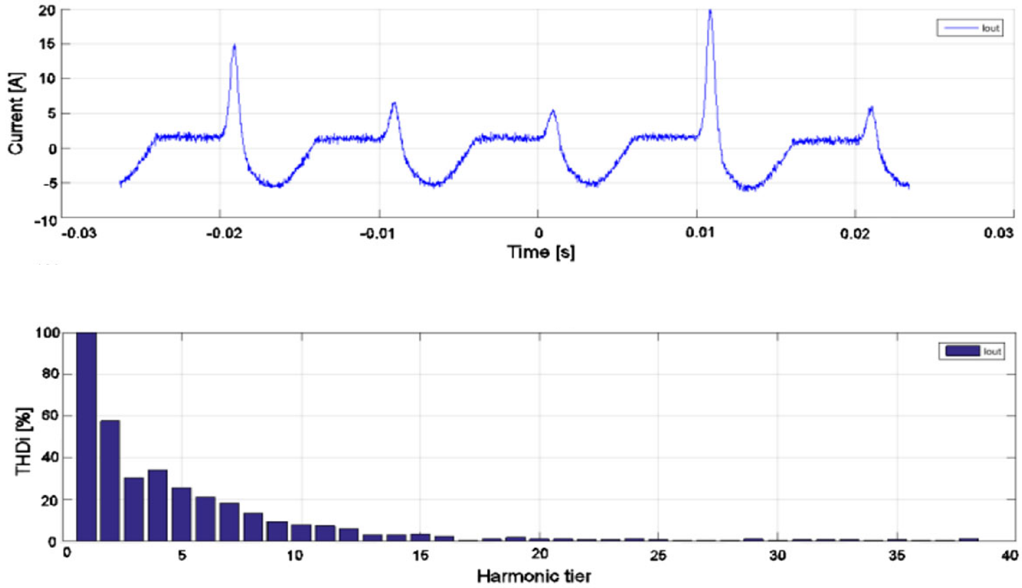


Fig. 11. Shape of current output waveform and THD_i ratio for series C.4

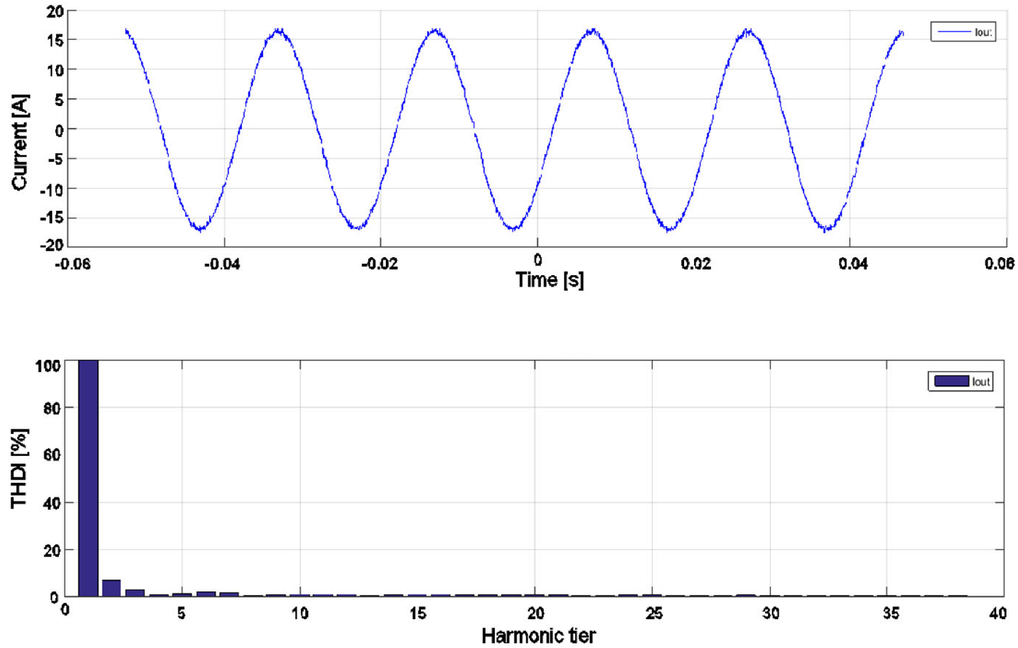


Fig. 12. Shape of current output waveform and THD_i ratio for series C.5

4. Conclusion

This paper shows that high-end UPSs topology can be recommended for powering nonlinear loads in terms of achieving good quality of electric energy. Various key parameters, which were presented in this work, such as voltage and current waveforms, ratios of Total Harmonic Distortion, etc. are indisputable proof of that. The UPS **C** tests, results confirmed the thesis that the UPSs of online topology achieve proper operating parameters with power load in the range from 30% to 100% (at least from 30% to 50% of the nominal output) of the nominal output. The test results of UPS **B** and **C** confirmed the thesis that the presented double-conversion line-interactive topology copes well with filtering the interferences (Total Harmonic Distortion ratios) from the strongly nonlinear loads, but only in the load range not exceeding the rated power of the device. The conducted research confirms that high-end UPSs with double-conversion topology are able to effectively limit the passing of disturbances caused by the loads with nonlinear characteristics. The exception was when the loads were fed from the UPSs battery. UPS **B** performed worse with the harmonics filtering during battery back-up time. Moreover, the results showed that UPSs, **B** and **C**, coped very well with sine wave shape approximation (almost ideal shape of sine). Exception was when the nonlinear loads were powered from the UPS battery – the waveforms tended to be slightly deformed as described in the results (UPS **A** and **B** mostly). UPS **A** has shown worse results according to harmonics filtering and sine wave approximation. Although it coped well while powering the switch-mode power supply (Personal Computer) which was not as strongly nonlinear as the heat gun. The conclusion is that the step approximation is sufficient for smaller nonlinear loads.

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