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Power Quality of PV Multilevel Inverters in Residential Environment

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Abstract. The aim of the paper is to perform a comparative analysis of power quality for several PV multilevel inverters operating in residential environments. Two cases are presented, namely a diode-clamped multilevel inverter and a cascaded H bridge multilevel inverter which are compared with the situation of a pure sinusoidal supply regarding the voltage, the current and the instantaneous power waveform shapes. The waveforms are synthesized and uploaded in a programmable power source and are applied to a 40 W / 459 lx LED luminaire load. The harmonic limits check according to the standard IEC 61000-3-2:2018, Class C, regarding lighting equipment are also presented. The measurements revealed that a filter retrofitting method was needed in order to obtain compliance with the power quality standard requirements.

Key words. Photovoltaic systems, staircase inverters, harmonic limits, FFT harmonic spectrum.

1. Introduction

The European Union is committed to developing a sustainable, competitive, secure and decarbonized energy system. Directive (EU) 2018/2001 of the European Parliament and of the Council establishes a mandatory target regarding a share of at least 32% of energy from renewable sources in the Union by 2030.

The recommendation 2019/1019 of the European Commission issued in June 2019 regarding the modernization of buildings, highlights the importance of energy efficiency and the role of the building sector in achieving the Union's energy and climate goals and the transition to clean energy.

"On-site electricity generation systems" refer to systems designed to produce electricity, installed in the space where the building is located or in a confined space associated with it, and which are integrated to a certain extent within the electrical installations of the buildings.

Such systems include, in particular photovoltaic panels (e.g. roof-mounted photovoltaic panels), micro combined heat and power (CHP) installation and small-scale wind turbines [1].

Renewable energy sources have become essential for researchers mainly due to environmental problems, being considered as the main energy sources of the future. In this regard, the contribution of photovoltaic systems in single-phase systems in particular is unanimously acknowledged, due to their long-life service and high efficiency/cost ratio.

Inverters are an essential component of a photovoltaic power system. They have different topological structures, their main function being dc-ac conversion.

At the same time, a photovoltaic power supply system must meet several criteria of power quality. However, certain cost requirements, together with those of efficiency and reliability, have led to the development of inverter structures, from the simplest ones, with a small number of components, to more sophisticated multilevel structures, their stair case output voltages being more suitable for connecting photovoltaic energy source to AC loads since they emulate quite precisely a sinusoidal voltage waveform using DC ling voltages, compared with the simple voltage-source inverters.

Cascade converters are more often used in PV applications due to the modularity of their structure [2].

A large variety of such inverter topologies are found in the specific literature. They may be classified based on the number of power processing stages, the type of power decoupling, the types of interconnection between the stages, and the types of grid interface (Fig. 1.).

Speaking about photovoltaic applications are divided into four categories, namely:

- off grid domestic,
- off grid nondomestic,
- grid connected distributed,
- grid connected centralized [3].

The first two categories belong to standalone systems, while the last two ones represent grid connected systems.

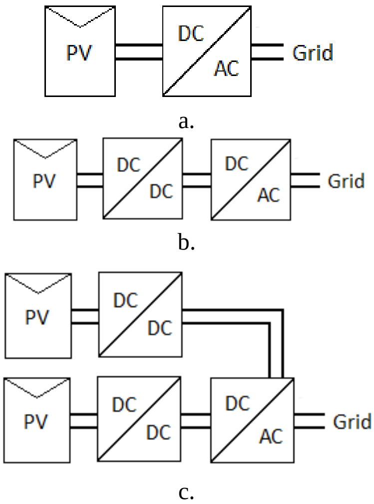


Fig. 1. Single (a) and dual (b) power processing inverter. Dual stage (c) inverter.

The development of applications with renewable sources, have led to the development of research in the field of multilevel converters, especially for photovoltaics and wind turbine applications.

With the development of smart buildings and the near zero energy buildings, photovoltaic panels will become a "sine qua non" component in residential and commercial and tertiary buildings.

In DC coupled systems the batteries are connected via a charge regulator between the DC link and the PV inverter (Fig. 2) [3].

In the AC-coupled systems the batteries are connected to the photovoltaic system, which consists of the PV generator and inverter, via a charging regulator and an inverter (Fig. 3) [3].

Due to the modular structure of the photovoltaic systems, several configurations of inverters' connection are developed (central inverter, string inverter, multistring inverter and ac/cell module) [3].

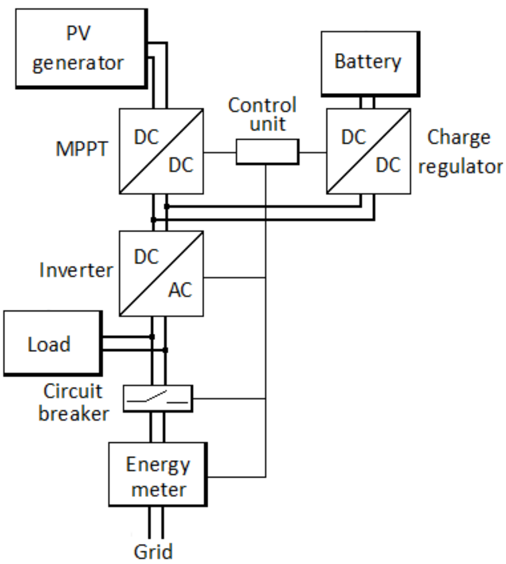


Fig. 2 DC coupled residential PV system

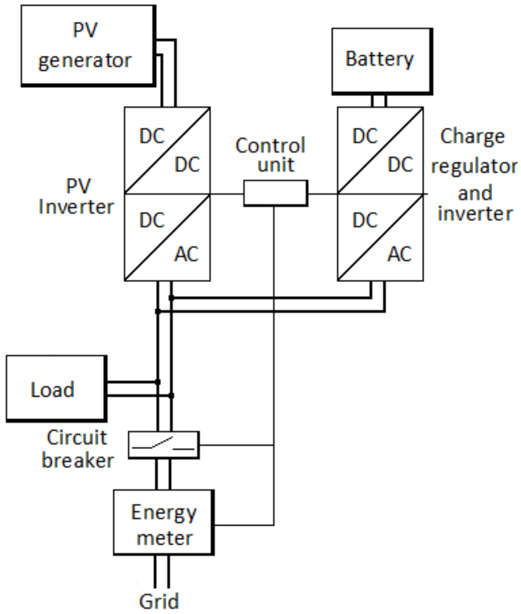


Fig. 3 AC coupled residential PV system

2. Inverters in PV systems

The simplest structure of inverter is the voltage source inverter, for which the input is a voltage stored in the DC link capacitor. This inverter chops the input DC voltage and generates an AC voltage of a desired magnitude and frequency.

Fig. 4 shows the schematic diagram of this type of inverters, with two legs. Unlike the simple structure presented in Fig. 4, multilevel converters, or staircase inverters, have several advantages, the stepped output voltage leading to a lower harmonic content of the voltage and current. Power quality improves with the increasing of the number of voltage steps, the shape of the waveform becoming closer to a sinusoidal one.

The most popular topologies of such inverters are single source inverters (flying capacitor and diode clamped multilevel inverters) and multilevel source inverters (cascaded H-bridge, which can be cascaded, hybrid multilevel or new hybrid multilevel inverters) [4-7].

Fig. 5 presents the schematic diagram of a single-phase four level diode-clamped multilevel inverter while Fig. 6 presents the corresponding waveform of the output voltage.

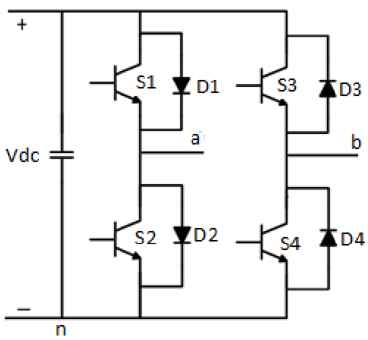


Fig. 4 Single-phase voltage source inverter

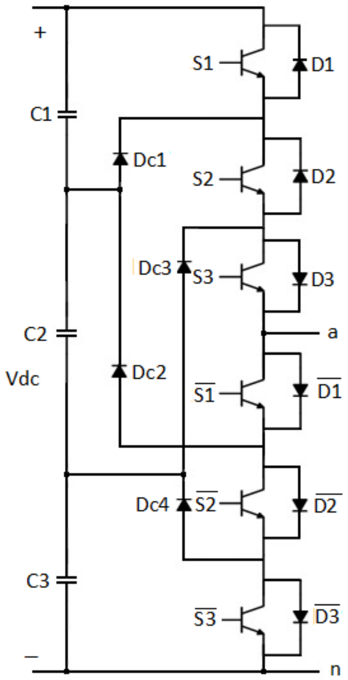


Fig. 5 Single-phase four level diode-clamped multilevel inverter

Fig. 7 depicts the stepped output voltage corresponding to a cascaded H bridge multilevel inverter [8].

These waveforms were synthesized and uploaded in a programmable AC source, capable to provide any waveform at a desired magnitude and frequency. Their shapes are intended to emulate multilevel inverters.

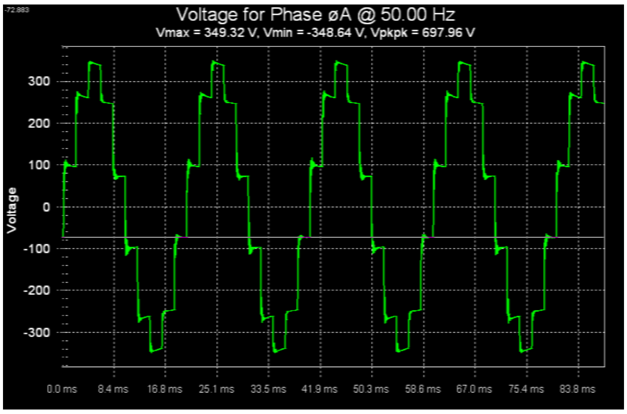


Fig. 6. Synthesized output voltage of four level diode-clamped multilevel inverter

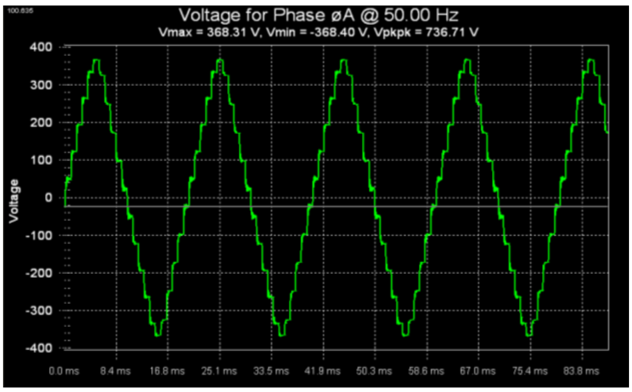


Fig. 7. Synthesized stepped output voltage of a cascaded H bridge multilevel inverter

3. Measurements and Comment


Fig. 8 Power quality measurements of the luminaire

Measurements were performed using a California Instruments CTS Series 3.2 system, which represents a compliance test system for EN IEC 1000-3-2 (Harmonics) including A14, EN IEC 1000-3-3 (Flicker) and various EN IEC 1000-4 AC immunity tests. Consisting of an AC power source, a power analysis conditioning system (PACS) and a PC based data acquisition system, the CTS provides a complete turn-key solution for IEC testing (Fig. 8).

The load used in the measurements was a LED 37 W luminaire, having the following catalog main data: the installed nominal power 37 W, the power factor PF= 0.91, the average illumination level 459 lx, the lighting installed power density 1.68 W/sq·m/100lx

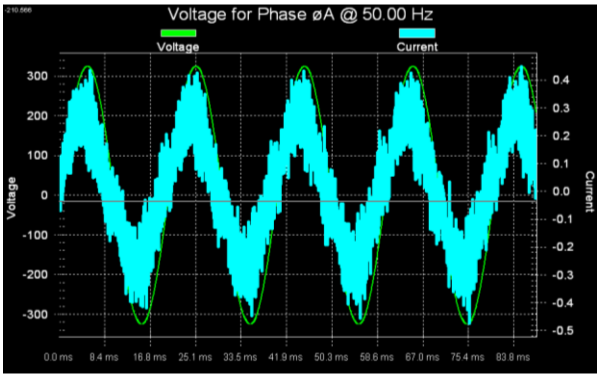
The measurements carried out, are accompanied by several consideration, constituting a brief comparative power quality analysis between the currents drawn by the two staircase voltages in relation with the pure sinusoidal supply voltage. The analysis took into consideration mainly the harmonic content of the current drawn by the load and the power factor.

A. *Sinusoidal supply voltage*

Fig. 9 depicts the waveforms of the voltage and of the current drawn by the load in pure sinusoidal supply conditions. The measured active power was: P = 40 W and the power factor PF = 0.899, the voltage and the current drawn by the load being almost in phase. However, one can observe a slight difference between the measured quantities and the catalog data.

Even if the supply voltage delivered by the programmable power source was perfectly sinusoidal, the current drawn is not sinusoidal. Fig. 10 depicts a detailed filtered waveform of this current. At the same time Fig. 11 presents the low level of its harmonic content.

Fig. 12 presents the instantaneous power drawn by the load. One can see that the almost sinusoidal waveform is almost above the abscise axis, which is an indication of the high value of the power factor. However, a large ripple is present in the shapes of the current and instantaneous power waveforms.



Fig, 9. Voltage and current waveforms (pure sinusoidal supply)

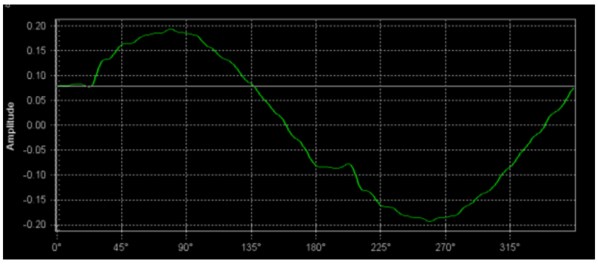


Fig. 10. Waveform of the current drawn by the load

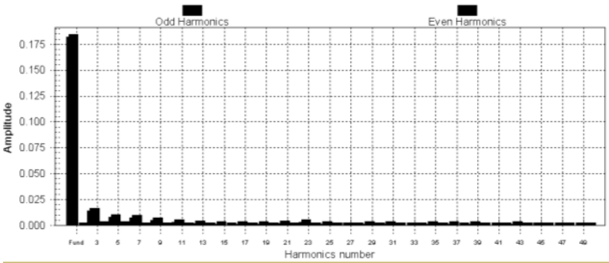


Fig. 11. FFT of harmonic current drawn by the load

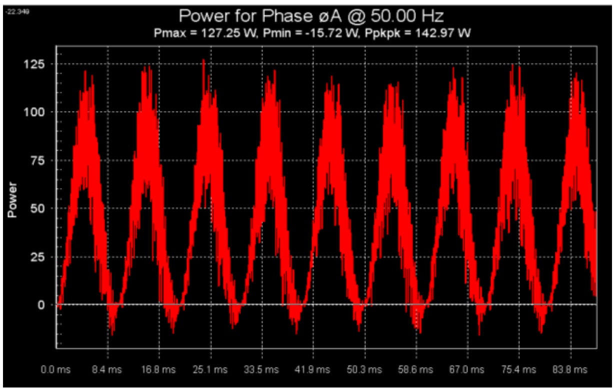


Fig. 12. Instantaneous power for sinusoidal voltage supply

B. Four level diode-clamped multilevel inverter supply

Fig. 13 depicts both the voltage and the current drawn in the case of a diode-clamped multilevel inverter supply. In contrast to the pure sinusoidal, the THD_V is 16.81%, the current drawn is I = 0.329 A while in the sinusoidal case the RMS current was I_{sine} = 0.202 A, greater with 63% at the same active power drawn from the grid and a poor power factor of only 0.532. It means that the difference of 0.127 A is destinated to cover the reactive and mostly the harmonic distortion power. Moreover, the current waveform shape presents a multitude of peaks, being obviously far from a sinusoidal one.

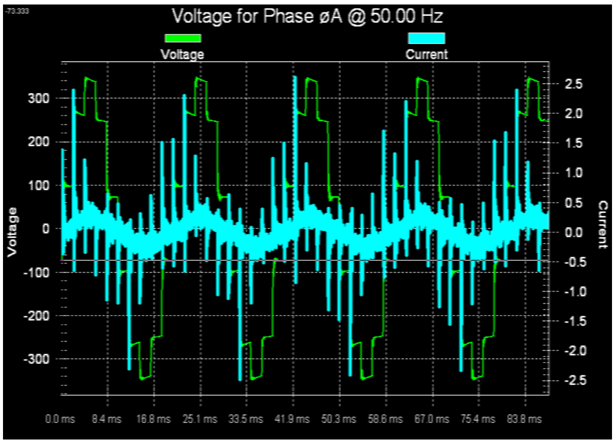


Fig. 13. Voltage and current waveforms (diode-clamped multilevel inverter supply)

The crest factor of the current in this situation is 7.942, in comparison with the pure sinusoidal situation where the crest factor was only of 2.353. Recall that the crest factor is the ratio between the instantaneous peak current required by the load and the RMS current. Most common electrical appliances exhibit a crest factor of 1.4.

Table I presents the harmonic limits for the four-level diode-clamped multilevel inverter supply, according to the standard IEC 61000-3-2:2018 which deals with the limitation of harmonic currents injected into the public supply system [9].

For the purpose of harmonic current limitation, equipment is classified as follows:

1) *Class A* (balanced three-phase equipment, household appliances, excluding equipment identified as Class D), tools, excluding portable tools, dimmers for incandescent lamps, audio equipment).

Obs. Equipment not specified in one of the three other classes shall be considered as Class A equipment.

2) *Class B* (portable tools, arc welding equipment which is not professional equipment).
3) *Class C* (lighting equipment).
4) *Class D* (equipment having a specified power less than or equal to 600 W, of the following types: personal computers and personal computer monitors, television receivers, refrigerators and freezers having one or more variable-speed drives to control compressor motor(s)).

Obs. Class D limits are reserved for equipment that can be shown to have a pronounced effect on the public electricity supply system.

Luminaires belong to class C equipment. For lighting equipment having an active input power greater than 25 W, the harmonic currents shall not exceed the relative limits given in Table I [9].

Table II presents the harmonic limits of the current drawn by the load in the case of the diode-clamped multilevel inverter supply. One can observe the high harmonic content, lasting from the seventh to the fortieth harmonic order, only with short gaps.

Table I. - Limits for Class C equipment (according to the standard IEC 61000-3-2:2018)

Harmonic order n	Maximum permissible harmonic current expressed as a percentage of the input current at the fundamental frequency %
2	2
3	30·λ
5	10
7	7
9	5
11≤n≤ 39 odd harmonics only	3
λ is the circuit power factor	

Fig. 14 presents the FFT chart of the harmonic limits content. From Table II and Fig. 14 one can see that there are several groups of four odd harmonics exceeding the standard limits, forming a shape similar to parabolas. Their maxima are situated between 700–900 % of limit.

Table II. - Harmonic Limits Check for four level diode-clamped multilevel inverter supply

Harmonic order	Frequency	% of Limit	Compare
2	100	85.227	Pass
3	150	92.735	Pass
5	250	45.455	Pass
7	350	178.571	Fail
9	450	488.636	Fail
11	550	928.030	Fail
13	650	151.515	Fail
15	750	18.939	Pass
17	850	284.091	Fail
19	950	681.818	Fail
21	1050	776.515	Fail
23	1150	246.212	Fail
25	1250	75.758	Pass
27	1350	265.152	Fail
29	1450	606.061	Fail
31	1550	681.818	Fail
33	1650	227.273	Fail
35	1750	94.679	Pass
37	1850	265.152	Fail
39	1950	549.242	Fail

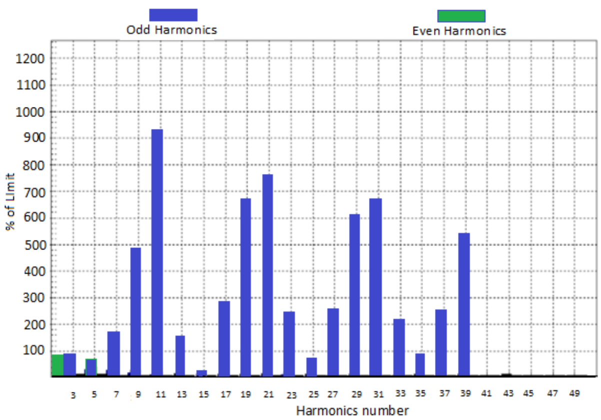


Fig. 14 Harmonic limits in compliance with IEC 61000-3-2

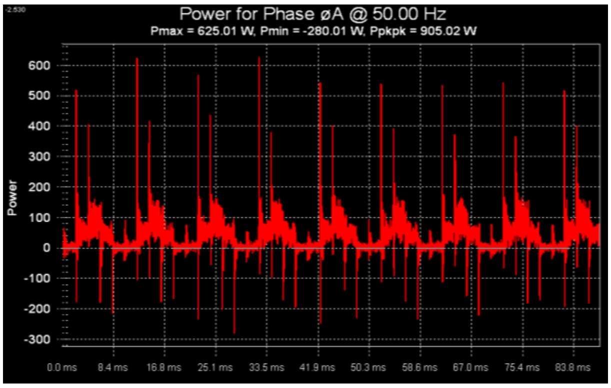
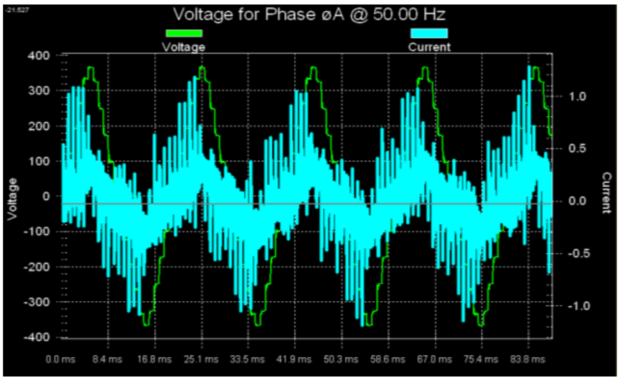


Fig. 15. Instantaneous power for four level diode-clamped multilevel inverter supply

The peaks of the current waveform generate a similar form for the instantaneous power displayed in Fig. 15, the peak to peak power being of 905.02 W.

A. Cascaded H bridge multilevel inverter supply

The same measurements were performed in the case of cascaded H bridge multilevel inverter supply.



Fig, 16. Voltage and current waveforms (Cascaded H bridge multilevel inverter supply)

Table III. - Harmonic Limits Check for H bridge multilevel inverter supply

Harmonic order	Frequency	% of Limit	Compare
2	100	28.090	Pass
3	150	131.205	Fail
5	250	28.090	Pass
7	350	56.180	Pass
9	450	11.236	Pass
11	550	56.180	Pass
13	650	0.000	Pass
15	750	131.086	Fail
17	850	56.180	Pass
19	950	374.532	Fail
21	1050	674.157	Fail
23	1150	842.697	Fail
25	1250	299.626	Fail
27	1350	74.906	Pass
29	1450	18.727	Pass
31	1550	18.727	Pass
33	1650	18.727	Pass
35	1750	18.727	Pass
37	1850	149.813	Fail
39	1950	56.180	Pass

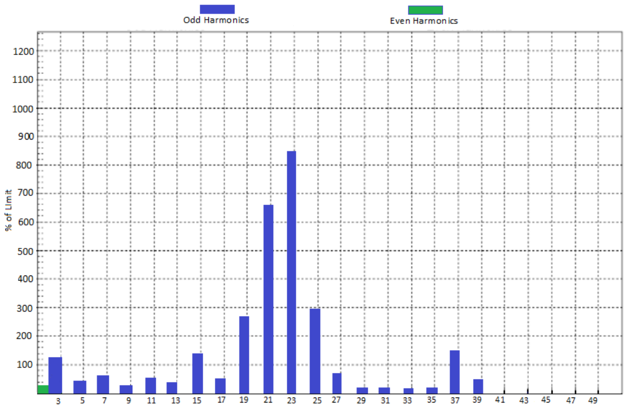


Fig. 17 Harmonic limits in compliance with IEC 61000-3-2

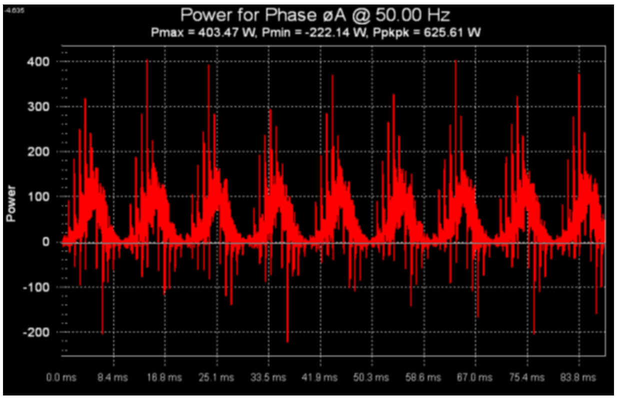


Fig. 18. Instantaneous power for cascaded H bridge multilevel inverter supply

One can easily see that the results are far better than in the previous case. From Table III and Fig. 17 one can see that there is only one group of four odd harmonics exceeding the standard limits, situated between the 19^{th} and 25^{th} harmonics order.

At the same time, for a THD_V of only 11.72, the rms current is only of Irms = 0.280 A, exceeding with 39% the rms current drawn in the case of the pure sinusoidal supply. The power factor is also improved, being 0.620. Only a difference of 0.078 A is meant to support the reactive and the harmonic distortion power. The measured crest factor was in this situation only of 4.562. The instantaneous power has a shape similar to the previous case.

4. Conclusions

The above analysis revealed that in terms of efficiency the inverters waveforms were obviously far from the pure sinusoidal supply but considering that the approach considered only residential green energy systems not connected to a distribution grid, power efficiency and the harmonic content of the voltage and current waveforms don't represent capital issues.

However, if one intends to inject power into a low voltage power distribution grid, some cautions are needed. Among them the retrofitting of a filtering system is compulsory. At the level of domestic systems, a passive filtering method would be enough. Obviously, for more powerful PV systems, other filtering methods presented in the literature would be necessary [10 – 14].

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