# Study of a single-phase series active power filter with hysteresis control

Mihail Hr. Antchev,

Mariya P. Petkova,

Hristo M. Antchev

Department of Power Electronics
Technical University - Sofia
Sofia, Bulgaria
antchev@tu-sofia.bg

Vanjo T. Gourgoulitsov
Power Engineering and Electronics College
at the Technical University – Sofia, Bulgaria
vtg_otk@abv.bg

Stanimir S.Valtchev
Department of Electrical Engineering and UNINOVA
Research Center, Faculty of Science and Technology,
Universidade Nova de Lisboa, Portugal
ssv@fct.unl.pt

***Abstract*— This paper presents results from a study of an active single-phase series power filter with a control system based on modified hysteresis method. Waveforms from the computer simulation and waveforms from the carried out tests of the filter are presented, comparing the operation at limited and unlimited maximum switching frequency of the power switches.**

***Keywords-series active power filter; hysteresis control; frequency limitation***

## I. Introduction

Active power filters (APF) are perspective means to improve the quality of the electrical energy [1,2]. Series active power filters are applied meanly to remove disturbances in the quality of the voltage of AC distribution network [3,4,5,6]. The most widely used topology of the single-phase filters power circuit is the full-bridge shown in Fig.1. The control of APF is carried out in such a way that in each moment the voltage $U_F$ is added to the voltage of the grid $U_S$ and produces the voltage that supplies the load $U_L$ which has a waveform much closer to the sine wave. The filter $L_F, C_F$ eliminates the harmonics in the filter voltage due to the high frequency switching. The transformer ratio of $Tr$ depends on the value of the DC supply voltage. The control implementations may be different: pulse-width modulation, predictive control, sliding mode control, etc. [7,8,9]. Some control systems implementations have a constant switching frequency [10], some are based on hysteresis control with limitation of the maximum switching frequency. This last method shown in [11] allows optimizing the active power losses in the switches, and optimizing the design of the filter $L_F, C_F$, thus improving the electromagnetic compatibility of the converter as well.

The aim of the authors is to investigate the operation of the series APF shown in Fig.1 when its control system is implemented using hysteresis control with and without limitation of the maximum switching frequency of the power devices.

## II. Operational Basis

The control system of this APF is based on the comparison of the instantaneous values of a reference sine wave $U_{REF}$ synthesized in phase with the grid voltage $U_S$ to the load voltage $U_L$. The comparison is performed with a defined hysteresis voltage interval $H$. If the instantaneous value of the load voltage is lower than that of the reference sine wave, the transistors $VS1, VS3$ turn on, in case it is higher, then $VS2, VS4$ turn on. The reference sinusoid is generated through observing the voltage of the point of common coupling (PCC) $U_S$. If the reference sinusoid value is kept equal to that of the first harmonic of the $U_S$ then only a filtering is carried out. If the reference sinusoid is maintained at constant amplitude then in addition to the filtering, a stabilizing of the voltage $U_L$ is performed.

### A. *Hysteresis control without limitation of the maximum frequency*

Fig.2 illustrates the concept of the implementation of the hysteresis control with no limitation of the maximum switching frequency. The turning on of the power switches happens when the above mentioned difference between $U_S$ and $U_L$ reaches values: $U_{REF} - H$ for $VS1, VS3$ and $U_{REF} + H$ for $VS2, VS4$.

The switching frequency of the power switches varies during the time of each half-period of the reference voltage and the maximum value of that frequency is theoretically unlimited. This value is possible to be changed by changing the hysteresis value $H$.

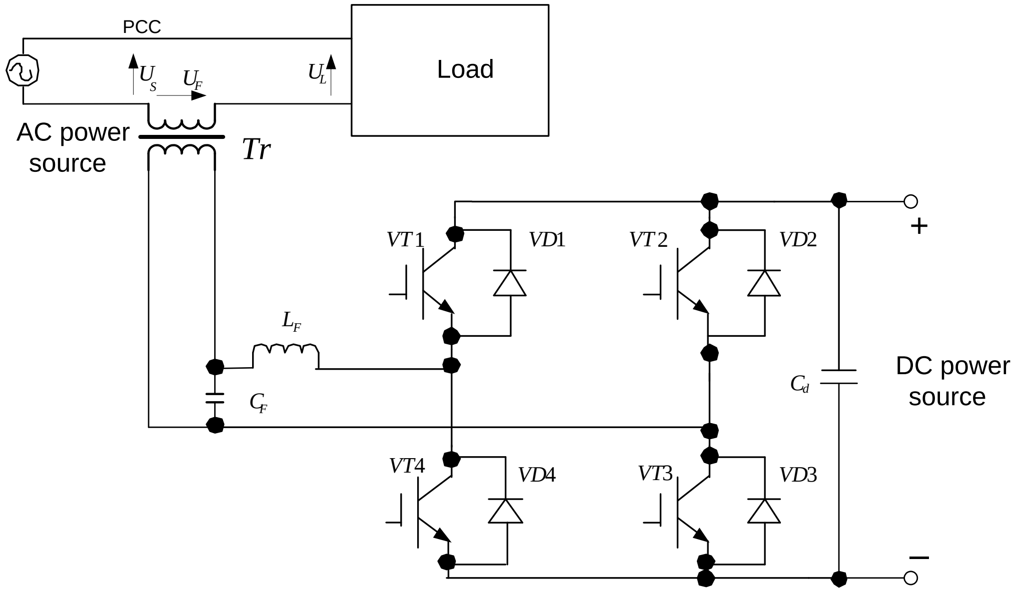


Figure 1. Power stage of a single-phase full-bridge series active power filter

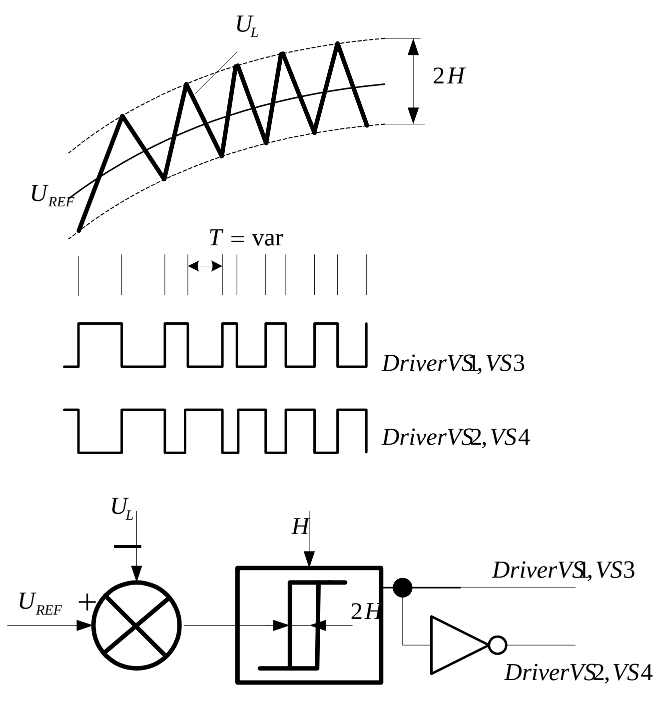


Figure 2. Building blocks and time diagrams illustrating the tracking down of the reference curve at a not limited maximum switching frequency

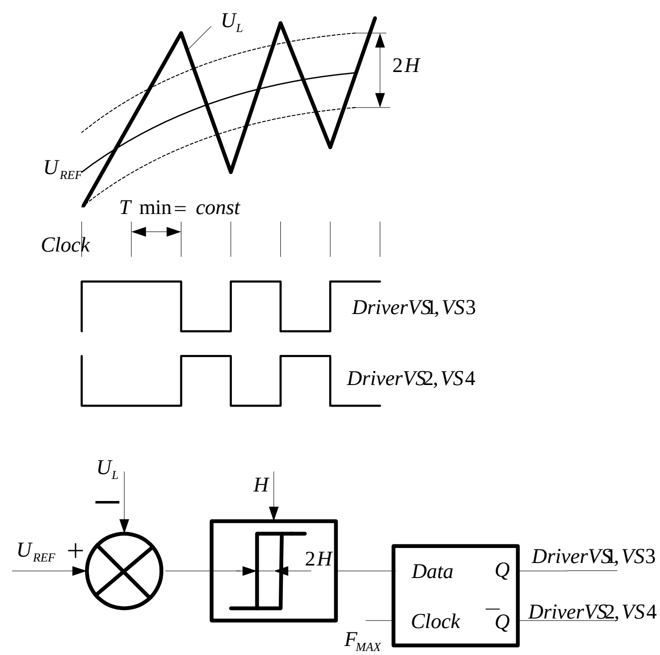


Figure 3. Blocks and time diagrams illustrating the tracking down of the reference curve at a limited maximum of the switching frequency

## *B. Hysteresis control at limited maximum switching frequency*

Fig.3 illustrates the concept of the implementation of the hysteresis control with an imposed limitation of the maximum switching frequency. The turning on of the power switches does not happen immediately at reaching the value $U_{REF} - H$ for $VS1, VS3$ and the value $U_{REF} + H$ for $VS2, VS4$. The turning on is performed after arriving at the corresponding values and delayed synchronously by the length of a clock signal. The frequency $F_{MAX}$ of that signal will limit the maximum switching frequency of the power switches.

Using this control, a certain distortion of the sine wave is expected to be observed, instead of the ideal reference, but the positive result is the convenient more efficient operation of the power switches at this limited switching frequency.

## III. Computer Simulation

The simulation software applied was PSIM and the performed the computer simulation is relayed in the next figures.

### *A. Results from computer simulation without limitation of the maximum frequency*

The operation of the single-phase APF is studied at a trapezoidal waveform of the grid AC voltage $U_S$. The considered here waveform is similar to that of a source with limited power, loaded with a non-linear load – uncontrolled full wave rectifier with active-capacitive type of load without applying of power factor correction (PFC). Fig.4 displays the simulated (idealized) circuit for the computer simulation. The results of the simulation are shown in Fig.5, Fig.6 and Fig.7. The total harmonic content of the source voltage is estimated as high as 20%. The height (amplitude value) of the trapezoid is 300V. The values of the load resistance and load inductance are 400Ω and 2.4H, respectively.

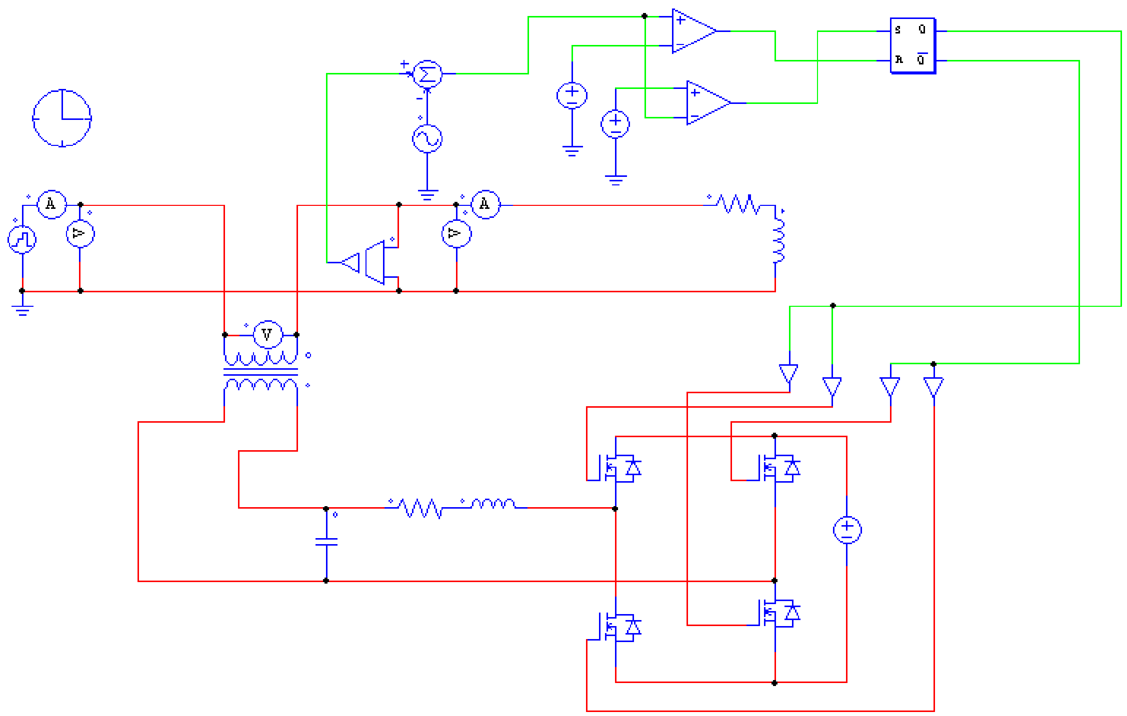

Figure 4. Idealized power stage and control circuits used for the computer simulation of the single-phase APF, when no limitation on the maximum switching frequency is applied and the load is complex, resistive and inductive (series connection)

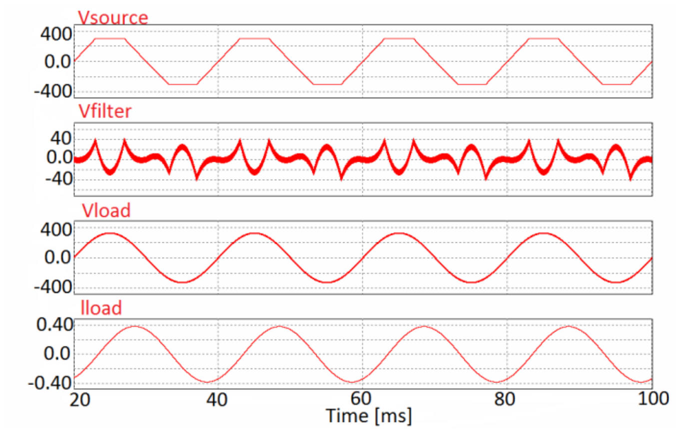


Figure 5. Results from the simulation of the circuit shown in Fig.4. From top to bottom: the grid voltage, filter voltage, load voltage and grid current, respectivelly. The time span is 80 ms

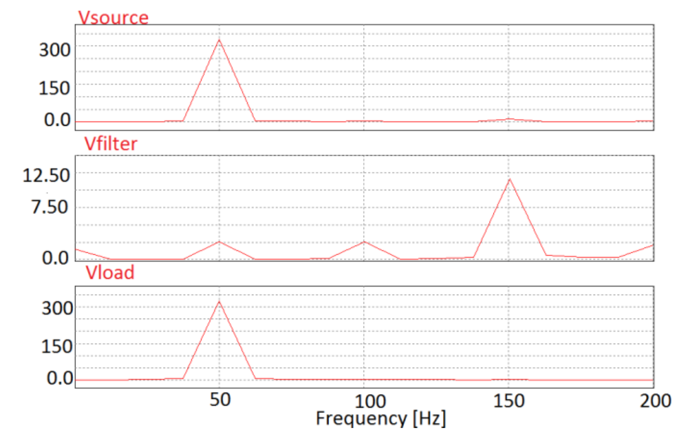


Figure 6. Harmonic spectrum from top to bottom :the grid voltage, filter voltage, load voltage, respectively. The range of X-axis is [0, 200 Hz]

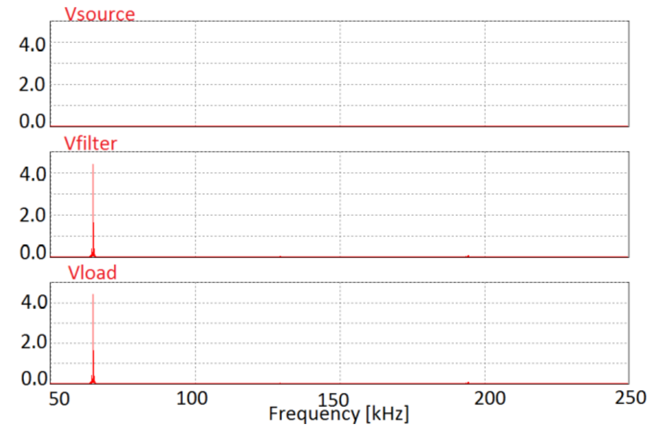


Figure 7. Harmonic spectrum from top to bottom: the source (grid) voltage, filter voltage, load voltage, respectively. The frequency span of the horizontal axis is from 50 kHz to 250kHz

*B. Results from the computer simulations when the maximum switching frequency was limited*

Fig.8 displays the computer simulation (idealized) circuit. The results of the simulation are shown in Fig.9, Fig.10 and Fig.11. The waveform of the AC (grid) source as well as the character and complex value of the load remain the same as in the previous case (unlimited switching frequency).

Comparing the results shown in Fig.7 and Fig.11, the main disadvantage of the operation at limited switching frequency is observed in the presence of some (not so many) higher order harmonics in the waveform of the load voltage with a broad spectrum.

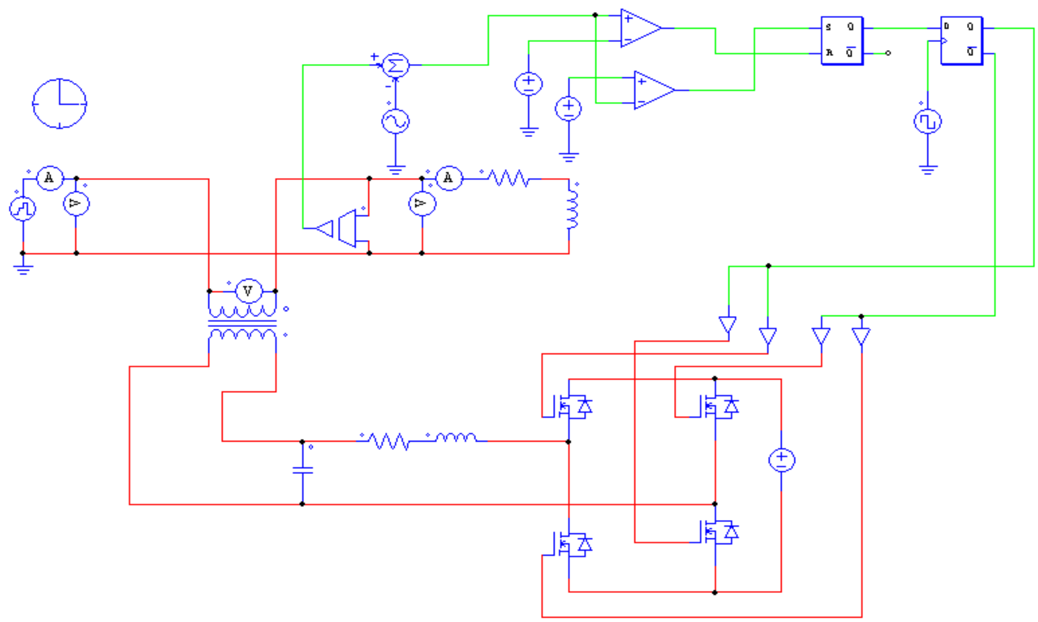

Figure 8. Idealized power stage and control circuits used for the computer simulation of the single-phase APF, when the limitation on the maximum switching frequency is applied and the load is complex, resistive and inductive (series connection)

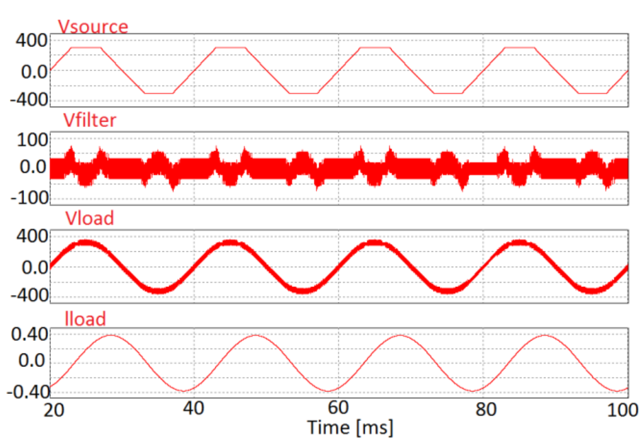


Figure 9. Results from the simulation of the circuit shown in Fig.8 when the switching frequency is limited to $f = 200kHz$. From top to bottom: the grid voltage, filter voltage, load voltage and source current

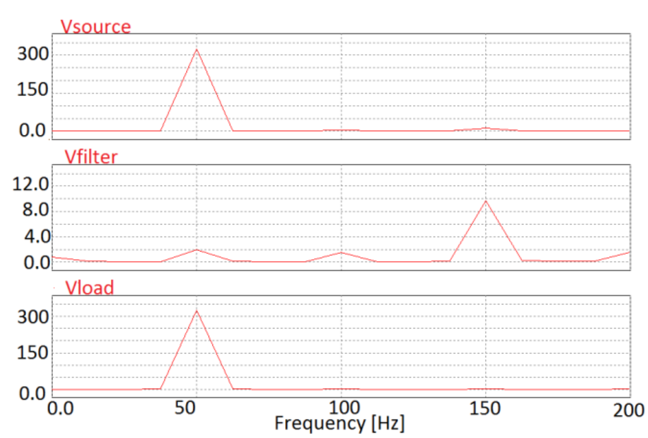


Figure 10. Harmonic spectrum from top to bottom: the grid voltage, filter voltage, load voltage, respectively. The horizontal axis range is from 0 to 200 Hz

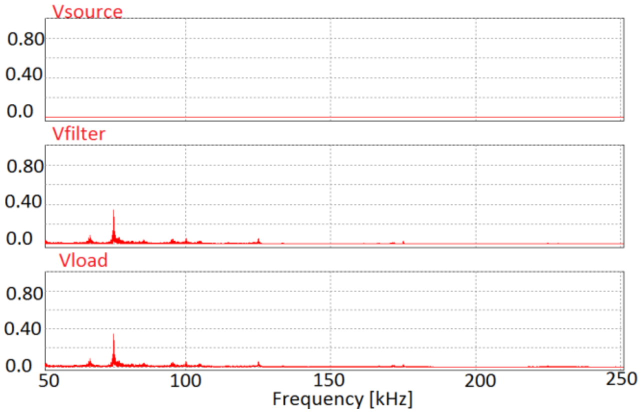


Figure 11. Harmonic spectrum from top to bottom: the grid voltage, filter voltage, load voltage, respectively. The X-axis range is 50 kHz to 250kHz

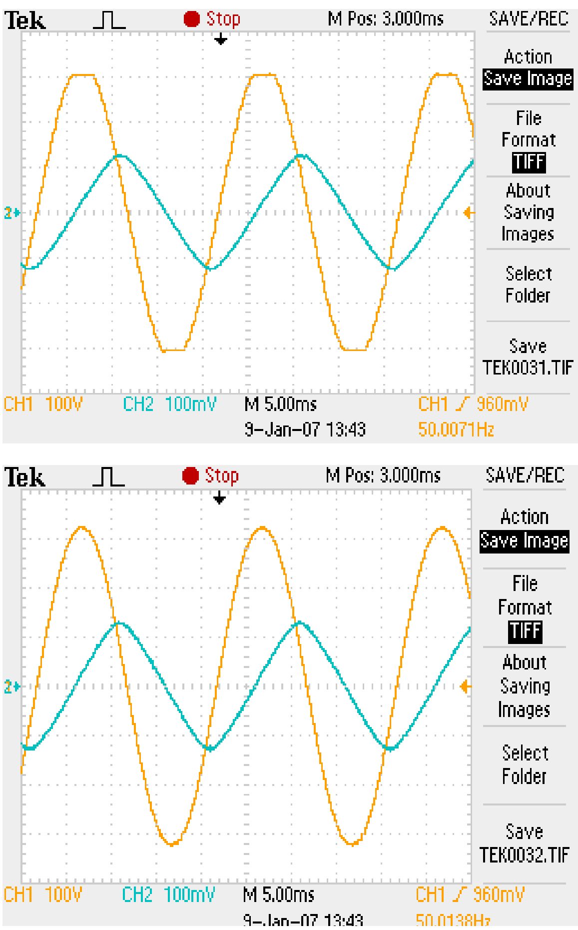


Figure 12. Experimental results of the operation of the single-phase series APF with active-inductive load CH1 – load voltage and CH2 – load current. Top – APF is off, Bottom – APF is on (no frequency limitation)

## IV. EXPERIMENTAL RESULTS

Fig.12 displays the experimental results of the load voltage and current when the APF is off and on. The values of the load elements are the same as those used in the computer simulation. The APF is controlled using hysteresis control without frequency limitation.

Fig.13 and fig.14 displays parameters of the load voltage, especially the harmonic spectrum and total harmonic distortion (THD) in both cases: with and without active power filtering (APF). In the case of the applied APF, the THD is reduced to 1.6%.

## V. CONCLUSION

The hysteresis control methods studied (limited and unlimited switching frequency) of the single-phase active power filter are both performing well to achieve the general purpose: to eliminate the low order harmonics of the source (grid) voltage. A slight disadvantage of the limited maximum switching frequency is the presence of high order harmonics with a broad spectrum in the waveform of the load voltage.

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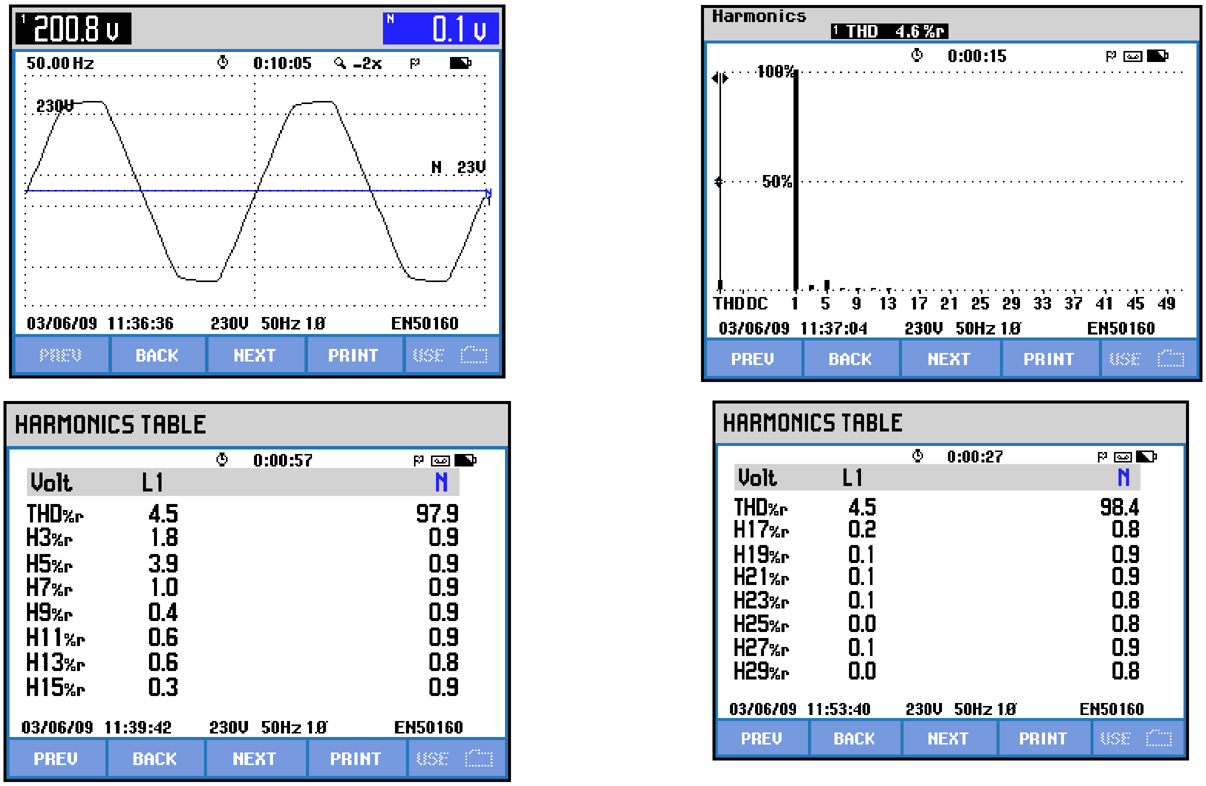


Figure 13. Parameters of load voltage when APF does not operate

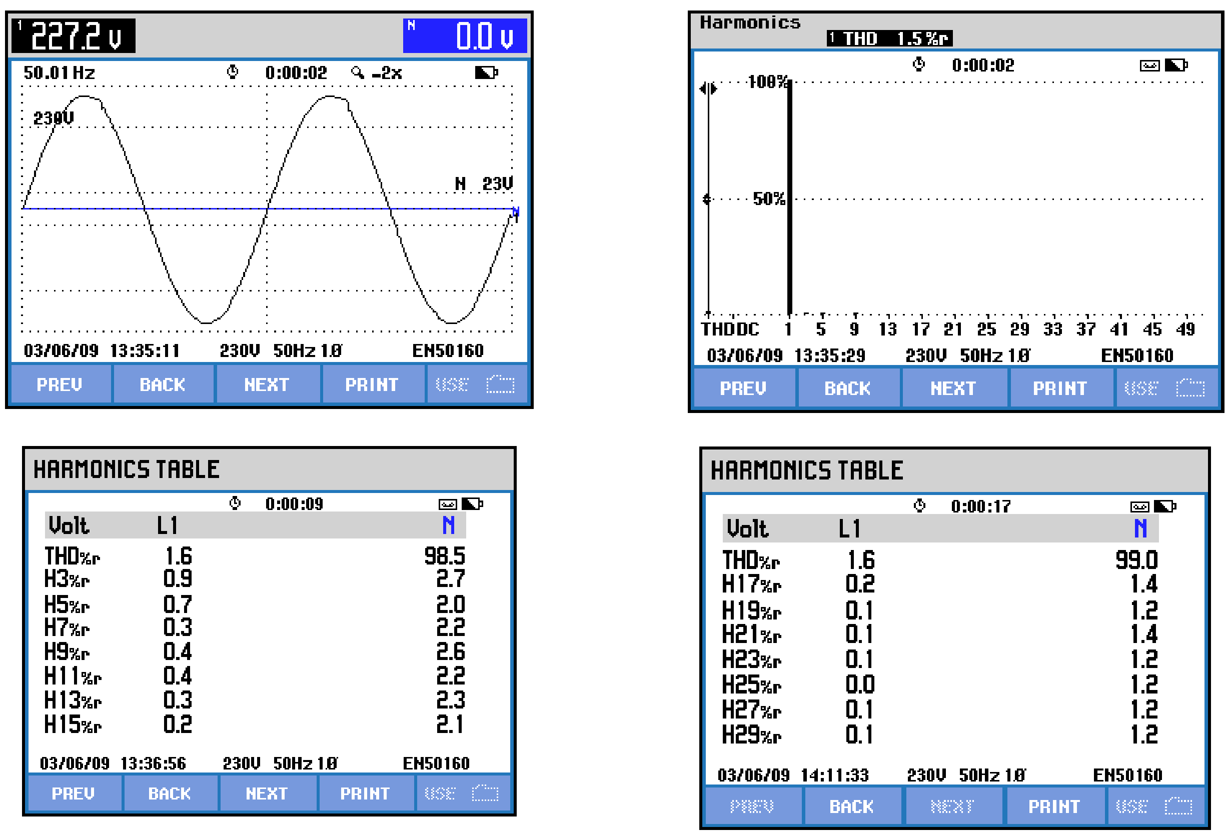


Figure 14. Parameters of load voltage when APF operates