MASTER THESIS

Investigation of street lighting feeders

In partial fulfilment of the requirements for the degree

Diplom-Ingenieur(Dipl.-Ing.)

Committed by

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"We will make Electric Light so cheap that only the wealthy can afford to burn candles."

Thomas Alva Edison

Acknowledgment

This master thesis with the diploma examination are to accomplish my master studying and at this point I would like to acknowledge all who encourages and supports me during my studying.

At first I would like acknowledge Univ. Prof. Wolfgang Gawlik and Ass. Prof. Albana Ilo. Thanks so much Professor Wolfgang Gawlik, at the beginning of master study through the interesting lectures you encouraged me and gave me the idea about power energy. Thank you for providing the job position during the last years, it was very interesting and helpful. Grateful thank you, Professor Albana Ilo for interesting lecture about static load behaviour, and your encouragement in this work. I learned many lectures from you. Thank so much for the numerous meeting and your kindly supporting which make this master thesis possible.

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Zusammenfassung

Sowohl die Entwicklung von Straßenbeleuchtungen als auch der Ersatz konventioneller Lampen und der Übergang zur Verwendung von LEDs im letzten Jahrhundert bringen neue Herausforderungen. Es gibt eine Vielzahl an Studien, die sich mit dem Übergangsprozess beschäftigt haben. Straßenbeleuchtungen haben signifikante Einflüsse auf den Leistungsverbrauch und die harmonischen Oberwellen.

Das Ziel dieser Masterarbeit ist die Untersuchung des Einflusses mehrerer Beleuchtungskörper in Form einer Straßenbeleuchtung auf die elektrischen Eigenschaften in einem Netzabzweig und die technische Fragestellung, die sich bei Austausch konventioneller Lampen durch LEDs ergeben. Drei Arten von Lampen wurden untersucht: Leuchtstoff-, Entladungs- und LED-Lampen. Ein etwaiger Einfluss der Alterung wurde anhand von alten und neuen Lampen experimentell untersucht. Die Spannungsabhängigkeit einzelner Beleuchtungskörper und die Harmonische Oberwellen wurden durch Experimente untersucht, während das Verhalten eines ganzen Netzabzweigs simulationstechnisch untersucht wurde.

Die Experimente haben gezeigt, dass die Leuchtstofflampen konstantes Stromverhalten vorweisen, während LEDs konstanter Leistungsverbraucher sind.

Simulationstechnische Untersuchungen haben gezeigt, dass unabhängig von der Art der Lampen, eine Spannungserhöhung am Anfang des Abzweiges zu einer Erhöhung des Leistungsverbrauches führt.

Abstract

Development of street lighting in last century and substitution of traditional types to LEDs bring new challenges. There are a large number of studies that investigated this replacement. Street lighting has significant influence in power consummation and the total harmonic distortion.

The objective of this master thesis is the investigation of street lighting feeders and the technical issues that appears from the substitution of the traditional lamps with the LED ones. Three types of lamps are investigated: fluorescent, discharge and LED lamps. To study the aging effect new and old lamps are investigated experimentally. Load static behaviour and the total harmonic distortion are examined experimentally, while lightning feeder behaviour is investigated numerically.

Experimental results show that fluorescent lamps and discharge lamps have almost a mostly constant current behaviour. While LED lamps have almost mostly constant power behaviour. Numerical investigations have shown that the Energy consumption of lightning feeders increases with the increasing of supplying voltage at the beginning of feeder independent from the lamp type.

Content

1. Introduction

Street lighting is an important service provided by public authorities. Lighting ensures visibility in the dark and is essential for pedestrian and road safety. However, many street lighting facilities are obsolete and thus highly inefficient. This leads to high energy consumption and operation/maintenance costs.

1.1. Background

According to the European Commission, energy savings from more Effective Street and office lighting for the period 2009 - 2020 could be in the magnitude of 38 TWh. Mandating LED lighting for traffic signals and street lights could significantly contribute to the EU's 20-20-20 strategy [1]. An important aspect in this field was reported in EU Regulation No. 245/2009, to withdraw from market inefficient lighting technologies such Mercury vapor high pressure lamps and sodium vapor high pressure plug-in lamps [2].

1.2. Motivation

So far sodium high pressure lamps and metal halide high pressure lamps were applied in street lighting as standard. Today the number of LED technique in street lighting is increasing. The LEDs have following advantages:

- High flexibility and exact light guidance
- Long durability, at least 50.000 hours
- Colour temperature of white light is freely selectable
- Dynamic adjustment of light for the utilisation is possible(dimming)

The replacement of mercury vapour lamps by sodium vapour lamps brings about 15% of energy saving. The replacement by halogen metal vapour brings about 40% saving, while the replacement by LED lighting brings up to 70% saving. The replacement of the conventional lightning by the LED ones is in process.

This master thesis investigates the impact of the replacement of the conventional lightning by the LED ones on the electrical grid behaviour. [2].

1.3. Objectives

The objectives of this work are:

- the experimental investigation of
    - static load characteristic of different street lighting and
    - their harmonic distortion.
- numerical analyses of feeders with different lightning types

1.4. Scope

This thesis focuses on the five representative lightning types 1. Fluorescent lamps, 2. High pressure Sodium lamps, 3. LED-BRS419, 4. LEDWAY, 5. SPL60. All electrical parameters like current, active and reactive power and harmonics are measured experimentally. The ZIP model is derived for each lightning type. The behaviour of different lighting types on a 0.4 kV feeder is investigated numerically.

1.5. Thesis Structure

This thesis consists of 6 chapters as follows:

- Chapter 1: Introduction
  This chapter includes background, motivations, objectives and scope of the master thesis.

- Chapter 2: Technical background
  The subject of this chapter is the technical and theoretical aspect of street lighting. The first part begins with the technical description of different light types and their ballasts. The second part contains several approaches for load modelling and indicates on voltage depended static load models as major load modelling for the calculation of lighting feeders. Last part is devoted to theoretical principles of current harmonics.

- Chapter 3: Electrical behaviour of lighting
  This section begins with an overview of lighting electrical circuit, electrical data of lamps and ballasts, and measurement procedures. Further, there are presented experimental results on static load characteristic and harmonics.

- Chapter 4: Electrical behaviour of lighting feeder
  In this chapter are presented results of the numerical investigation of different feeders, which supplies different lightning types. Lightning itself is modelled based on experimental outcomes.

- Chapter 5: Appendix
  This chapter contains detailed measurement results for all types.

- Chapter 6: References

2. Technical background

The use of artificial light is the most natural thing for mankind of today He learned 790000 years ago to use the fire as light source. With the time it appeared the need of using smaller controllable flame. The first equipment for lighting purpose was an oil lamp. Their use in large scale dates some 70 000 years B.C. [3,4].

For the first time street lighting was used by middle of 17th century. Jan van der Heyden invented the oil streetlamp which was used for the first time in Amsterdam. In the following years similar oil street lamps or petroleum lamps were used in the most of European cities. In rural areas they are used until the end of 20th century. Figure 1. shows the development of street lighting from gas lamps to LED lamps.

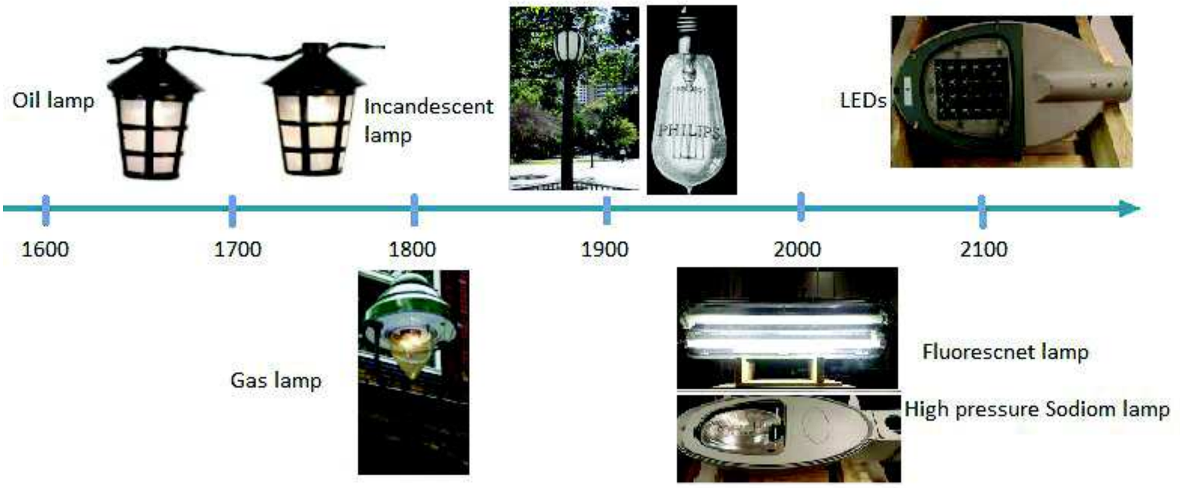

Figure 1. The development of street lighting from oil to LED lamps

The development of gas lighting is a typical product of industrial revolution of 19th century. The major importance of invention of them was the generation of a new lighting system to supply growing cities with sufficient light. In 1805 the gas lamps were installed first in London and then Paris (1817), Berlin (1829) and so on. Many inventors tried to optimise the technique of gas lighting. The most of experiments have been done by using solid materials which glowed in gas flame. Finally Carl Auer invented in 1887 the incandescent gas mantle which generates a bright white light. Further the arc lamps were invented by the Russian Pavel Yablochkov in 1875. This type of light uses alternating current, which realises an equal consume of both electrodes. This kind of light was firstly used in Paris in 1787. Arc lights had several disadvantages. The incandescent light bulbs were used at the end of the 19th century. They substituted the arc lights on the streets, but remained in industrial use longer. Incandescent lamps were primarily used for street lighting until the invention of high-intensity discharge lamps.

The investigation of gas discharge for lighting dates on the beginning of 20th century. High pressure sodium lamps, HPS, were developed and used for the first time in

USA. They are used in large scale for the street lightning. HPS lamps provide the greatest amount of photonic illumination for the least consumption of electricity.

But the newest street lighting technologies, such as LED or induction lights, emit a white light that provides high levels of scotopic lumens by a minimum energy consumption

This work is concentrated on three type's street lightning: Fluorescent; High pressure sodium lamps; LED

2.1. Technical description of different light types

There are three types of lamps, which will be discussed in this chapter: Thermal radiator, Discharge lamps and LEDs.Figure 2. shows the development of share in sales in percent of lamp in percent in 2010, 2016 and 2020. The new design LED with ballast (which makes the dimming possible and at the same time offers high power factor leads to high application of LEDs in residential, industrial and street lighting sections. It reduces total harmonic distortion and corrects power factor.

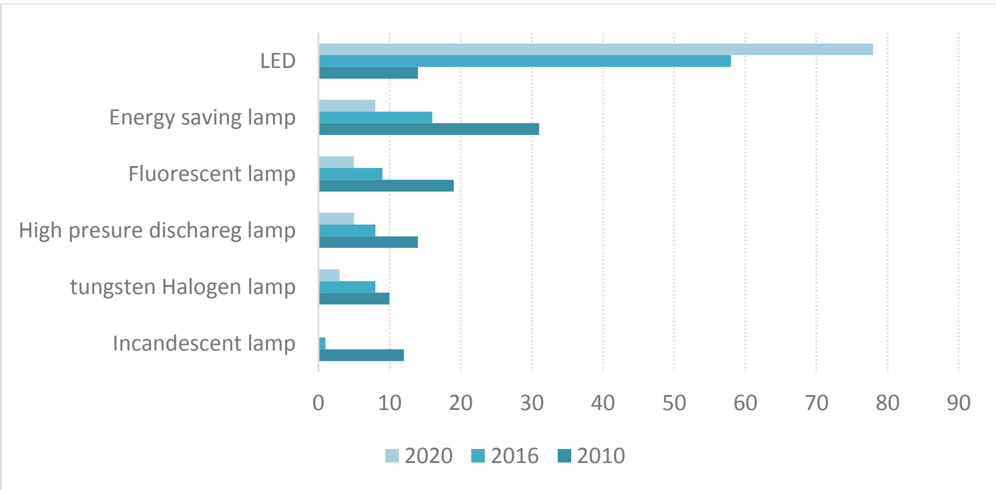

Figure 2. Development of share in sale in percent of lamps in 2010, 2016 and 2020 [5]

2.1.1. Ballast

According to [4, 6] ballast stabilises the current through the electrical load. Ballasts are applied when an electrical circuit shows a minus resistance coefficient to the voltage source. Connection of this circuit to the main power system result a high amount of power consummation until the circuit will be damaged. To prevent this event, the ballast is connected in series with the load so that it shows a positive resistance koefficient or a reactance. A connection of ballast to the discharge lamps is required to reach the durability of the lamp.

The power factor is defined as relationship between apparent and active power and is not exactly equal to cosine of phase angles between RMS voltage and RMS current because the power factor includes all harmonics and cos(ρ) just fundamental.

$$\lambda = \frac{P}{S} \tag{2.1}$$

$$\lambda = \varepsilon \,.\cos\rho \tag{2.2}$$

The power factor is the same as cos(ρ) for sinusoid wave form and shall be near to one. Deviating from this value means street lighting disturbs the networks. The power factor of inductive ballast is lower than 0.5 and it must be compensated by connecting a capacitor in series or parallel. Figure 3. shows the voltage and current profile of a fluorescent lamp without capacitor. It can be seen that the low value of power factor causes an inductive behaviour.

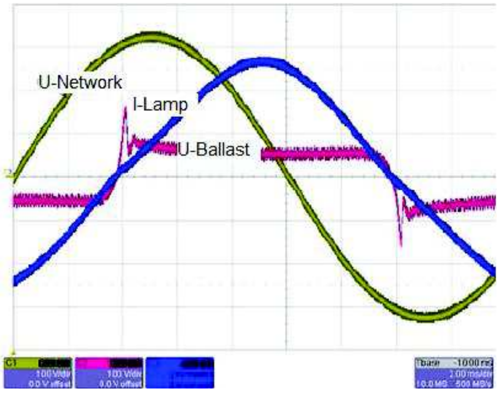

Figure 3. The voltage and current profile of a fluorescent lamp without compensation capacitor [6]

Figure 4. shows the voltage and current profile of a fluorescent lamp connected to a compensation capacitor. The lamp shows a capacitive behaviour which I-Network is leading the U-Network.

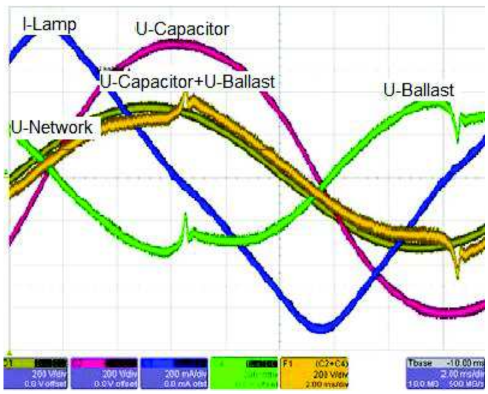

Figure 4. The voltage and current profile of fluorescent lamp connected to a compensation capacitor [6]

2.1.2. Thermal radiator

This type of lamp emits high percentage of infrared radiation and just small percentage of visible part of spectrum. Electric current flows through the filament wire, which heats the illuminate. The heating result is an infrared radiation. By this type of lamps, the luminous efficiency is very low. For instance, incandescence light bulb is thermal radiator and the luminous efficiency is between 9 -19 lm/W. An increase of luminous efficiency is reached through the increase of temperature of illuminate. The thermal radiation lamps include following sorts:

– Incandescent lamps
– Tungsten halogen lamps

- Incandescent lamp: Incandescent lamp luminous efficiency at nominal voltage 225 V is between 9 to 19 lm / W. An increase of luminous efficiency is just through an increase of temperature possible. An increase of temperature accelerates evaporation of tungsten atoms which reduces the durability. 1% luminous variation results almost 7% durability variation. The incandescent lamps with 40 Watt are filled with a gas to reduce tungsten evaporation.

The average value of durability is 1000 h. For some application there is a design execution for incandescent lamp at 225 V with durability of 2500 h that where the current flux is 15% lower than the lamps with durability of 1000 h.

The incandescent lamps are produced for nominal voltage between 225 to 240 V and for electrical power 40 to 500 Watt. The operation values of incandescent lamps are strongly voltage depending. An overvoltage of 5% results 20% increase of light flux and 50% decrease if durability. Figure 5. Shows the impact of voltage variation on electrical parameters of gas filled incandescent lamp [4].

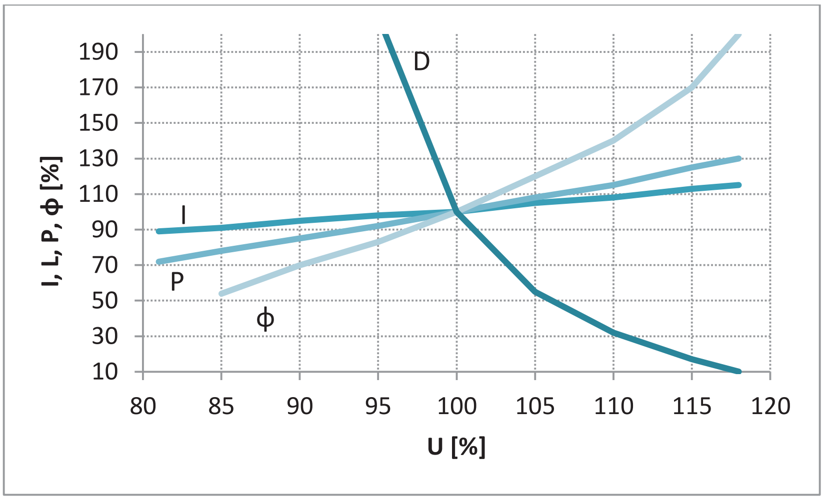

Figure 5. The dependence of electrical parameters of incandescent lamp to the voltage

- Tungsten halogen lamps: Adding halogen to the filling gas causes the chemical reaction between tungsten and halogen. Through this reaction, tungsten begins to evaporating from filament and simultaneously diffuses towards the bulb wall. On a temperature between 2350C and 3150 the halogen and the tungsten will be combined in the zone between the filament and the bulb wall. The combined molecules diffuse to the filament, where the halogen is available for the next chemical reaction and the tungsten is deposited again to the filament. Figure 6. shows the component of tungsten halogen lamps [7,8].

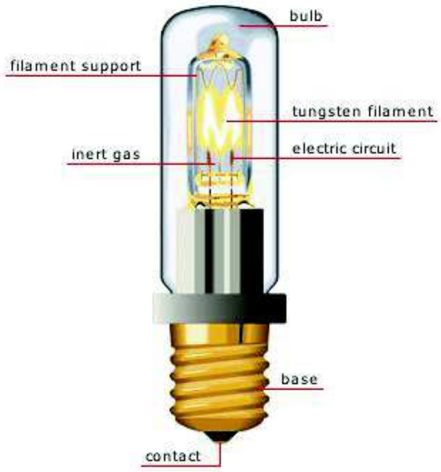

Figure 6. The component of tungsten halogen lamps [8]

2.1.3. Discharge lamps

By discharge lamps, electrical current flows through discharge tubes, which include gas or metal vapour. The effect of the atom excitation in the discharge tube is radiation. The radiation depends on type of gas, metal vapour and respectively pressure ratio in the discharge tube.

These lamps have negative current-voltage characteristics; it means voltage decreases with an increase of current so that the lamps will destroyed by a high amount of current without current limitation. Therefore, discharge process must be stabilised through ballast(2.1.1). The discharge lamps include following sorts:

- Fluorescent lamps
- High pressure sodium lamps
- Low pressure sodium lamps
- Metal halide high pressure lamps

- Fluorescent lamp: The principle of fluorescent lamp is like a low pressure gas discharge. Figure 7. shows the construction of fluorescent lamp. It consists of a glass tube (discharge tube) which is evacuated from air and filled with appropriate gas such as argon, neon or mixed gas and saturated mercury vapour at a low pressure. The discharge process radiates ultraviolet rays by generating electrical field between two electrodes at high efficiency and flicker free. The phosphor layer on the inside of glass tube converts the ultraviolet rays to the visible light.

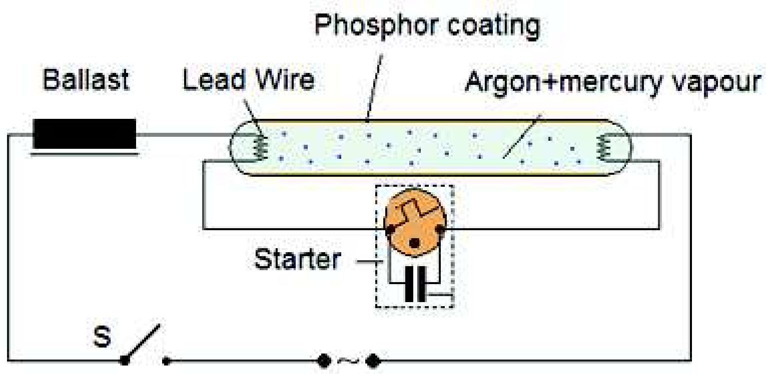

Figure 7. The construction of fluorescent lamp[9]

This process is temperature depended. Figure 8. shows the current flux of fluorescent as a function of temperature. The light flux reaches its maximum value at 25^0C. At higher temperature the light flux is reduced, therefore a cold spot is utilized in fluorescent lamps, which moves this value to the right [6,10].

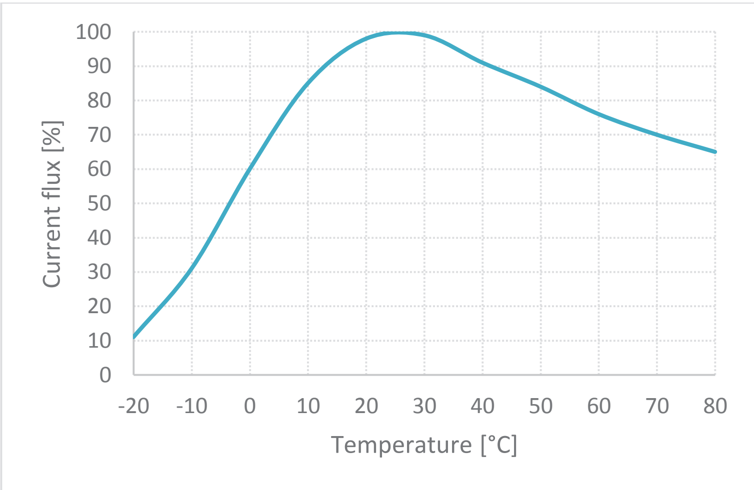

Figure 8. Current flux as a function of temperature [4]

The application of parallel electronic starter is to ascertain optimal preheat time, ignition time, ignition voltage and to prevent the high voltage for the beginning of discharge process. At the beginning of this process the current flows through the thyristor and at the same time the starter heats the electrode and produces ignition pulses- 0.9 kVs to 1.3 kVs-. The heated electrodes release electrons which cause the ionization of gas. These electrodes produced by tungsten coating with alkaline earth metal carbonate as emitter. Their heating converts the alkaline earth metal carbonate to alkaline earth oxide and at this time process begins.

The ballast is necessary for the stable and continuous operation of lamp. It works as a regulator of AC current to limit normal current. Electrical circuit with negative resistance drains big amount of power from supply network until it will be destroyed. To prevent this event, the ballast will be connected in series to the load which has positive resistance or reactance and limits the current to a suitable level. There are two kinds of ballast; conventional ballasts and electronic ballasts.

a. Conventional ballast

Figure 9. shows different types of ballasts for fluorescent lamp. The current is depicted in red and the voltage is depicted in blue. Figure 9a. shows the resistor ballast. This type of conventional ballast has a power factor near to one but it produces high amount of power loss. The resistor causes high current waveform distortion because of delay in re-ignition[6,7].

Figure 9b. shows the choke or inductor ballast which generates phase displacement smaller than 0.5. It offers lower distortion by current waveform and lower power loss and therefore a stable operation in comparison with resistor ballast. The low power loss provides a circuit efficiency of 80% to 90%. The power loss arises because of coil resistance and copper winding and increases with an increase of temperature and hysterias in the iron coil. Design of choke ballast depends on voltage and current rating. For instance, large sizes of chokes are required for an operation at high current.

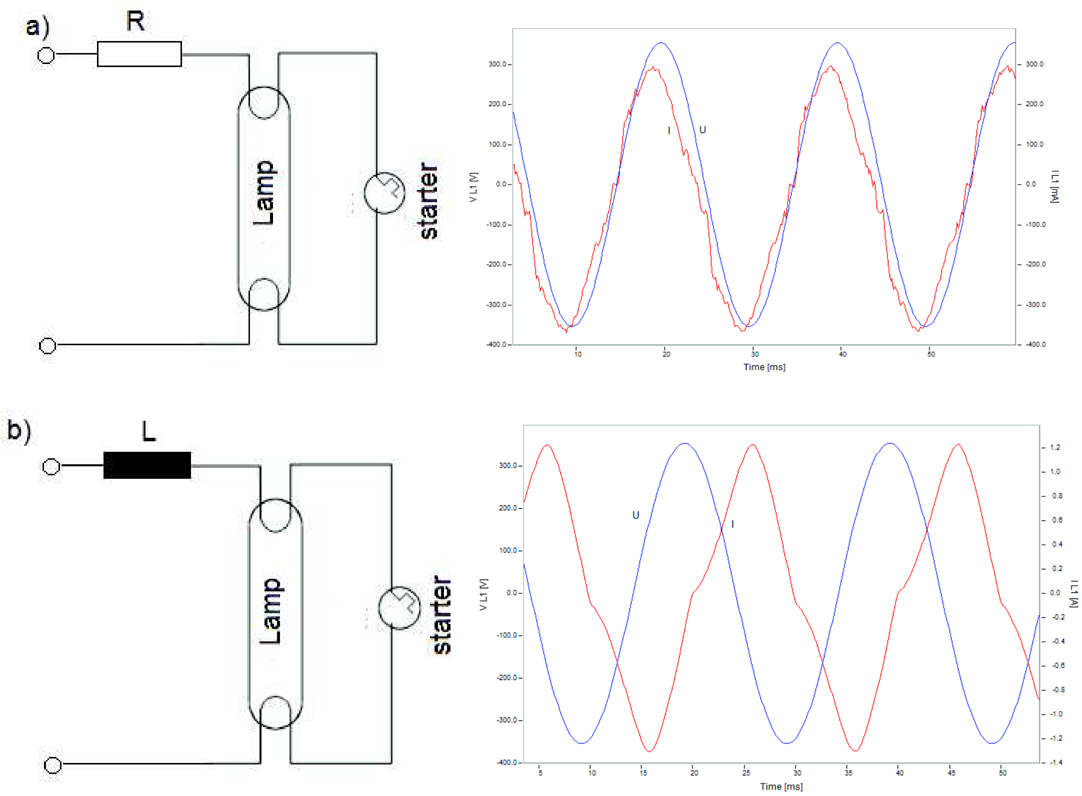

Figure 9. Different types of ballasts for fluorescent lamps: a) Resistor ballast; b) Choke ballast

Figure 10. shows an overview of choke capacitor ballast construction. The disadvantage of low power factor must be compensated through the capacitor. These types of ballast are called choke capacitor ballast. The disadvantage of in series connected capacity is a high power loss, which causes stroboscopic effect in conventional lamps with two light sources (Fluorescent lamp double switch). Parallel connected capacity to supply voltage has no influence on the magnetic ballast. [6,7]

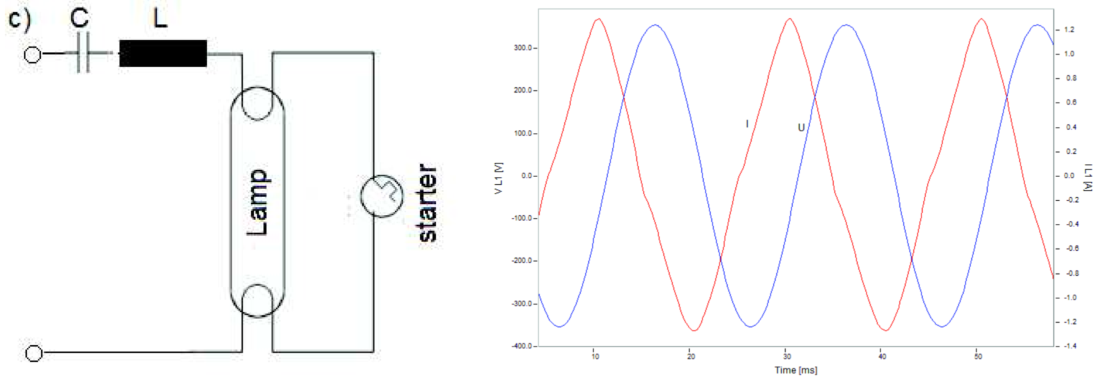

Figure 10. Overview of Choke and capacitor ballast construction

b. Electronic ballasts

Electronic ballast are required to prevent the indicated stroboscopic effect, to improve luminous efficiency, to correct the power factor, and to reduce current TDH by high power factor The electronic ballasts are defined for fixed voltage and frequency with a voltage tolerance of $\pm 10\%$. The operating time of lamp decreases if the ballast operates with network voltage near to the upper value of ballasted voltage.

As indicated in [11,12] there are different types of topology for electronic ballasts which correct the power factor and control steady state for better wave shape. Figure 11. shows a ballast topology for fluorescent lamp. The load is defined as resistance load. The circuit consists of a rectification to convert AC voltage to DC voltage and boost converter to generate discontinuously pulse current waveform the same as input voltage. Resonant power inverter operates at high frequency.

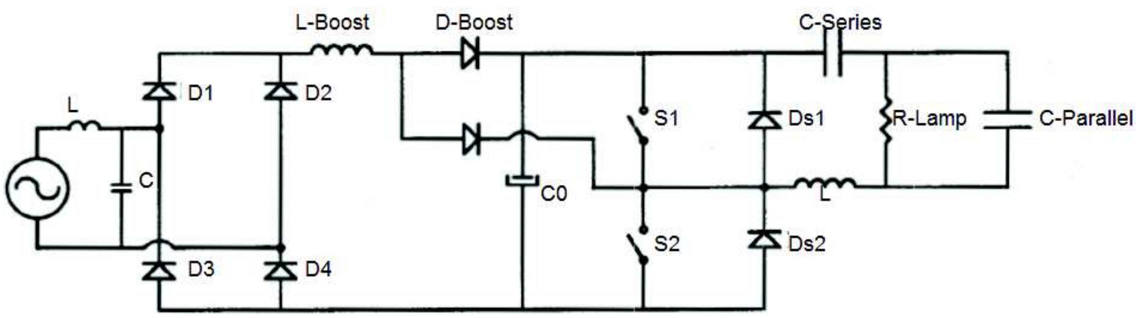

Figure 11. Topology of ballast for fluorescent lamp [11]

Figure 12. shows equivalent circuit of inverter. The parameters in the equivalent circuit are defined as following:

$$C_{series} = 15 \frac{U_{lamp}}{U_{input}} \frac{1}{R_{lamp} * \omega_S} \qquad 2.3$$

$$C_{parallel} = \frac{C_{series}}{15} \qquad 2.4$$

$$L = \frac{16}{C_{series} * \omega_S{}^2} \qquad 2.5$$

where C_{series} is the in series connected capacity, $C_{paralle}$ is in parallel connected capacity and L is the inductance in resonant operation. Boost inductivity depends on input voltage, switching frequency and duty cycle[11].

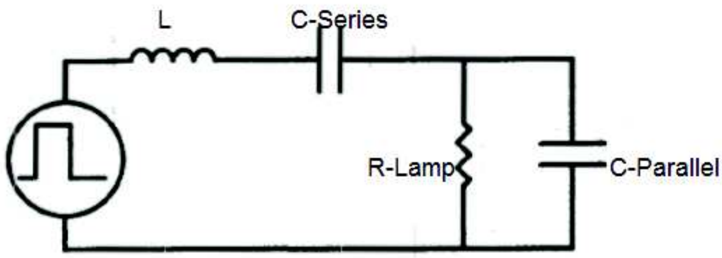

Figure 12. Equivalent circuit of the inverter [11]

At the beginning of the process switching frequency and resonant frequency are equal:

$$\omega_{\text{switching frequency}} = \omega_{\text{resonant frequency}} = \frac{1}{\sqrt{L\left(\frac{C_{series}*C_{parallel}}{C_{series}+C_{parallel}}\right)}} \qquad 2.6$$

The following formula presents the resonant frequency in the stable operation:

$$\omega_{\text{resonant frequency,Stable}} = \frac{1}{\sqrt{L * C_{series}}} \qquad 2.7$$

The main parts of conventional ballast are steel (86%) and copper wire (10 %) but the main parts of electronic ballast are steel (59%), transformer (21%), capacitor (10%) and last 10% inductor, diodes, fuses and wires [12]. An increase of electronic component causes higher TDH. The most important difference of the magnetic and electronic ballast is the TDH. Figure 13. Shows the voltage and current profile of fluorescent lamp with magnetic ballast. The current by magnetic ballast is high but TDH is 9.55%.

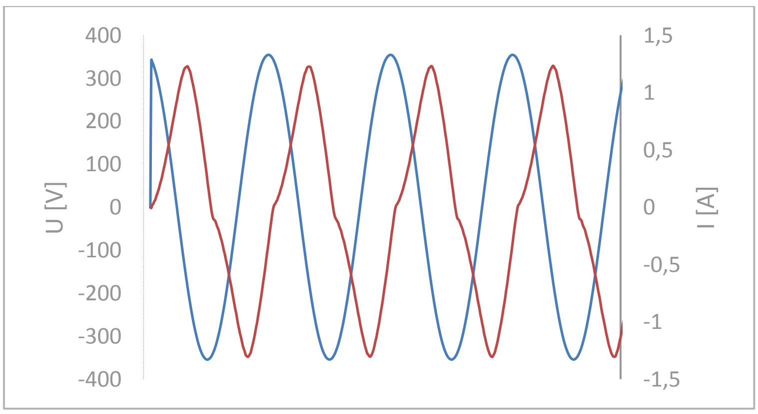

Figure 13. The Voltage and current profile of fluorescent lamp connected to magnetic ballast

Figure 14. shows the voltage and current profile of fluorescent lamp connected to the electronic ballast. As shown this lamp has lower current and higher TDH (10.1%) in compare to the magnetic ballast [14].

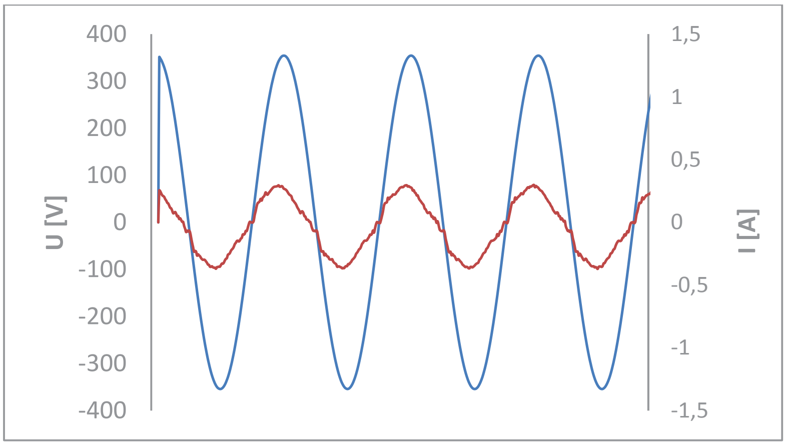

Figure 14. Voltage and current profile of fluorescent lamp connected to electronic ballast

- High pressure discharge lamps: High pressure discharge lamps in compare to fluorescent lamps are filled with gas at higher pressure and have higher ignition voltage. Figure 15. shows a ballast design for these lamps. The ballast circuit contains a half bridge inverter supplied with 400V bus, where $C_{seriesis}$ and L_{series} control the current flows through the lamp (R_{lamp}).

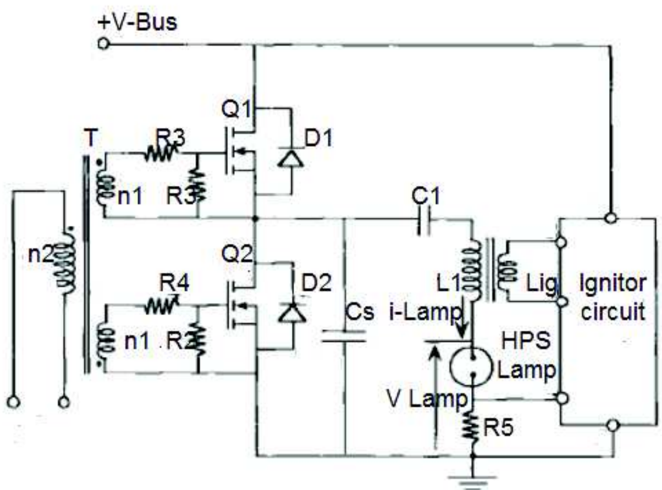

Figure 15. Topology of ballast for high pressure lamp [12]

Figure 16. shows ignitor structure. Ignitor generates and delivers high voltage through L_{ig} in the lamp so long as the thyristor is turned on. Ignition of lamp generates current which is detected through diode and disconnect the pulser to produce high voltage. This ballast has an application for OSRAM and NAVRAN 150W [12].

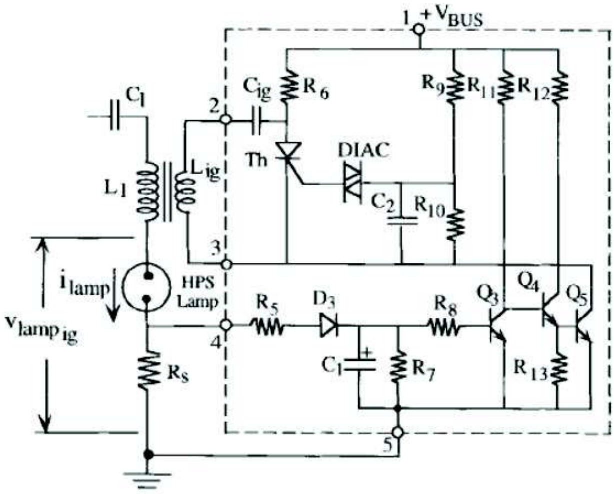

Figure 16. Ignitor circuit [12]

Figure 17. Shows the start-up time of discharge high pressure lamp on 230 V at room temperature. This NARVA manufactured light source has 150 W. It can be seen that the stat-up time is almost 4-5 minutes.

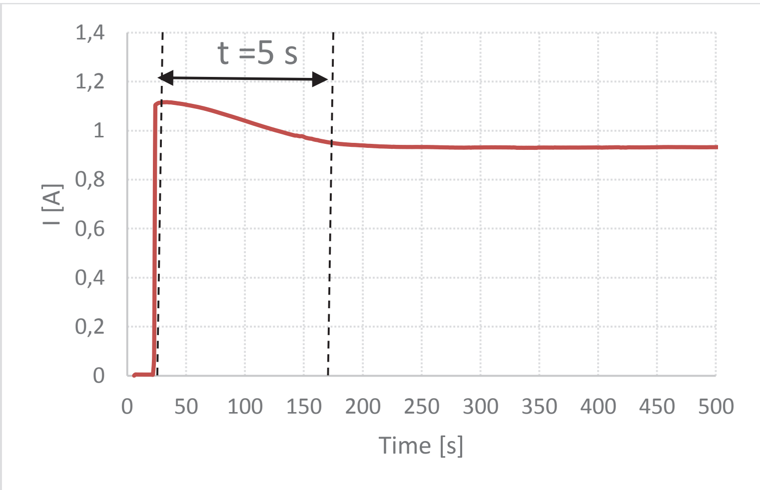

Figure 17. The start-up time of discharge high pressure lamp

- Metal halide lamps: The lamps are applied in the light technique because of high luminous efficiency and high colour rendition. Additionally to mercury the evaluated tube shape or clear glass outer bulb is filled with sodium, thallium, indium and lithium to improve the colour rendition of the lamp. Electronic ballast is the same as high pressure sodium lamps. The difference of metal halide lamps to the sodium high pressure is the start-up time. Figure 18. shows the stat-up time. It can be seen that the start-up time is shorter than in the case of sodium high pressure lamps. The lamps are in steady state after 2-3 minutes [4].

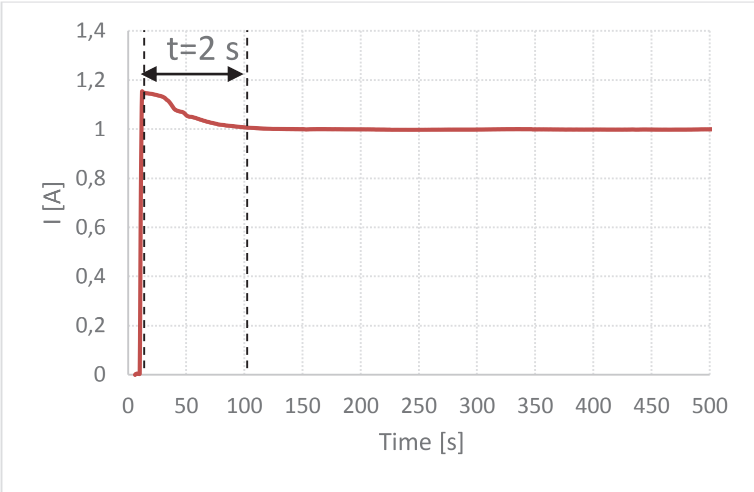

Figure 18. The start-up time of metal halide lamp

-Sodium vapor low pressure lamps: The lamps have with183 lm /W the highest luminous efficiency. The luminous efficiency of this type of lamp depends on a certain discharge temperature. The light is monochromatic yellow so that color vision is not possible [4]. A character of this lamp type is that the discharge occurs at low pressure almost by 0.1 Pa and at the temperature of 260 °C [7].

2.1.4. Light emitting diodes

Electrical current flows through the semiconductor and the interaction of electrical field with the solid emits light by this type of lamp. Electroluminescence panel and light emitting diodes belong to this category. Electroluminescence panel is developed through the microcrystalline powder phosphors based II_VI compounds, such as zinc sulphide. Electroluminescence panels are suitable for high voltage and low current density but light emitting diodes and high current density devices operate at low voltage.

Considering on high efficiency and high power factor, LEDs will be more applied in future. Figure 19. shows a schematic overview of high power LED. For better beam shaping the LEDs are in the reflecting cavity and are coated with total internal reflection lenses. The main component for high luminous efficiency and high performance is micro lens array plate [15, 16].

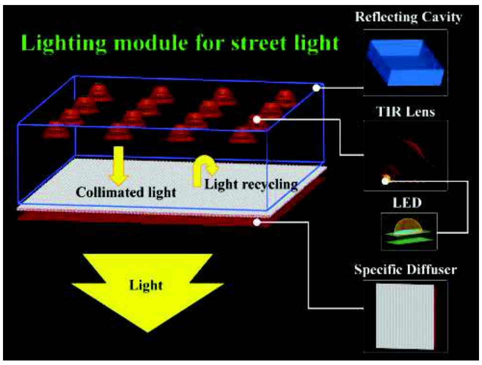

Figure 19. Schematic overview of LED lamp [15]

The electronic ballast for LEDs generates high percentage of current TDH. Figure 20. shows the Buck-Boost PFC with voltage mode regulator a This type of ballast reduces the harmonic pollution and offers higher power factor and lower active power. Buck-Boost PFC regulates the boosted voltage V_{Bus} and simultaneously regulates also the load current I_{Bus}[16].

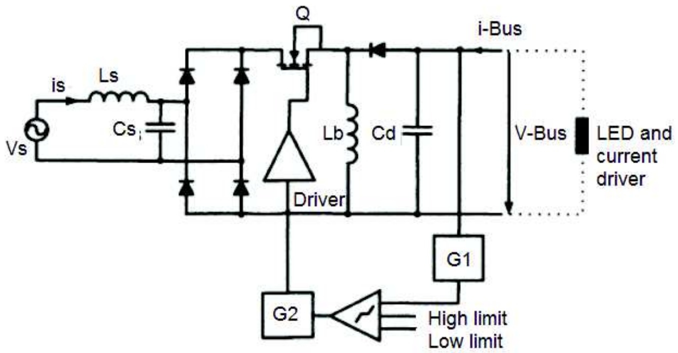

Figure 20. Buck-Boost PFC with voltage mode regulator [16]

2.2. Light model

Seen from grid point of view light act as a load.

According to [17] load is defined as:

"The term load can have several meanings in power system engineering:

a. A device, connected to a power system, that consumes power,

b. The total power (active and/or reactive) consumed by all devices connected to a power system,

c. A portion of the system that is not explicitly represented in a system model, but rather is treated as if it were a single power consuming device connected to a bus in the system model.

d. The power output of a generator or generating plant."

Load model represents mathematical relationship between voltage and frequency to active and reactive power in the power system. It shows how voltage variation affects active and reactive power demand [24]. Studies indicate that the simulation for voltage stability studies are strongly influenced by load model [18].

Generally there are three types of analysis for load modelling [18, 19]:

- Measurement dependent analysis
- Component based analysis
- Voltage depended analysis

- **Measurement dependent analysis** represents the response of active and reactive power over the time (day, week or month), when power system voltage and frequency are varied. The disadvantage of this analysis are the costs of equipment's and monitoring of all system nodes for variations of different factors and over the time in specific time of year (winter or summer) or day. For accurate analysis the measurement must be repeated. The advantage of this analysis is testing of voltage sensitivity and direct monitoring.

- **Component based analysis** required the information about load characteristics, load composition and class mixed data Figure 21. Shows the overview of component based analysis. It can be seen that component based analysis consists on following parameters [17]:
  - **Load characteristics** describes the electrical characteristics such as power factor and active and reactive power deviation over the time.
  - **Load composition** describes generally percentage of load composition. It consists induction motor, lighting, resistive loads, heating, etc. Load composition data base are depending on time of day, week or year.
  - **Load class mix** indicates on consumer class such as residential, commercial, industrial or street lighting class. The class mix data base depends on location or region. The main components in street lighting class are discharge lamps which have mostly constant current characteristics. Although in some places there are more LEDs with mostly constant power characteristics.

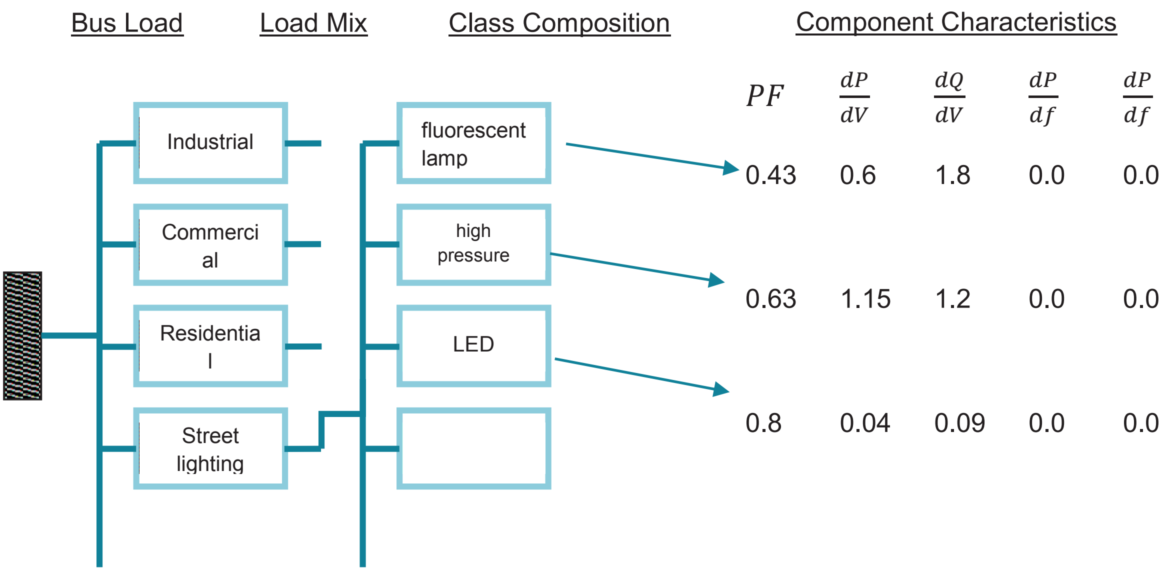

Figure 21. The overview of component based analysis

The advantage of this approach in compare to the measurement depended approach is the abundance measurement. In this analysis characterisation of all compositions and devices at the bus feeder are required and for modelling based on load classes the composition characteristic must be re-examined.

- **Voltage dependent analysis** represents response of load to the voltage variation and frequency. The analysis divided to dynamic and static analysis where dynamic load analysis is time dependent and is applied for nonlinear system Static load characteristics represent active and reactive power through combination of power, current and impedance components.

Considering the voltage dependent analysis, the following model methods are described to analyse street lighting characteristics.

2.2.1. ZIP load model

According to [19] load is presented by polynomial model as follows:

$$P = P_{\mathrm{n}}\left[\mathrm{K}_2^{\mathrm{p}}\left(\frac{V}{V_{\mathrm{n}}}\right)^2 + \mathrm{K}_1^{\mathrm{p}}\left(\frac{V}{V_{\mathrm{n}}}\right) + \mathrm{K}_0^{\mathrm{p}}\right] * (1 + K_P \Delta f) \quad 2.8$$

$$Q = Q_n\left[\mathrm{K}_2^{\mathrm{q}}\left(\frac{V}{V_n}\right)^2 + \mathrm{K}_1^{\mathrm{q}}\left(\frac{V}{V_n}\right) + \mathrm{K}_0^{\mathrm{q}}\right] * (1 + K_Q \Delta f) \quad 2.9$$

Where $\mathrm{K}_0^{\mathrm{p}}, \ \mathrm{K}_1^{\mathrm{p}}, \mathrm{K}_2^{\mathrm{p}}, \mathrm{K}_0^{\mathrm{q}}, \mathrm{K}_1^{\mathrm{q}} \text{ and } \mathrm{K}_2^{\mathrm{q}}$ are polynomial load model coefficients, $\mathrm{P_n}$ and $\mathrm{Q_n}$ are values of active and reactive power on nominal voltage $\mathrm{V_n}$. $K_P \text{ and } K_Q$ describe the load dependence from frequency. This work concentrates on the load to voltage dependences. The frequency dependence is not treated.

Equations 2.8 and 2.9 describe three different load types:

- Mostly constant impedance load where $\mathrm{K}_2^{\mathrm{p}} > \ \mathrm{K}_1^{\mathrm{p}} + \mathrm{K}_0^{\mathrm{p}}$. In this case active power modifies with square of voltage.
- Mostly constant current load where $\mathrm{K}_1^{\mathrm{p}} > \ \mathrm{K}_0^{\mathrm{p}} + \mathrm{K}_2^{\mathrm{p}}$. In this load active power modifies voltage.
- Mostly constant power load where$\mathrm{K}_0^{\mathrm{p}} > \ \mathrm{K}_2^{\mathrm{p}} + \mathrm{K}_1^{\mathrm{p}}$. In this model modification of voltage doesn't impact active power.

The combination of these three types of load in polynomial formula is called ZIP model where $\mathrm{K}_0^{\mathrm{p}} + \mathrm{K}_1^{\mathrm{p}} + \mathrm{K}_2^{\mathrm{p}} = 1$ and $\mathrm{K}_0^{\mathrm{q}} + \mathrm{K}_1^{\mathrm{q}} + \mathrm{K}_2^{\mathrm{q}} = 1$ is provided [17, 20].

According to [21] the polynomial model is described through the following:

$$P = a_1 V^2 + b_1 V + c_1 \quad 2.10$$

$$Q = a_2 V^2 + b_2 V + c_2 \quad 2.11$$

Where a_1 and a_2 are mostly constant impedance load, b_1 and b_2 are mostly constant current load and a_1 and a_2 are mostly constant power load.

In compare to equation it can be seen the original values are given and offer the opportunity to see active and reactive power derivation over voltage.

2.2.2. Exponential load model

The exponential model is defined as follows:

$$P = P_n \left(\frac{V}{V_n}\right)^{n_P} * (1 + K_P \Delta f) \qquad 2.12$$

$$Q = Q_n \left(\frac{V}{V_n}\right)^{n_Q} * \left(1 + K_Q \Delta f\right) \qquad 2.13$$

Where $\mathrm{n_P}$ and $\mathrm{n_Q}$present the relationship of active and reactive power to the voltage and, $\mathrm{K_P and\, K_Q}$ describe the frequency dependence of load. In this work the frequency dependence is ignored Three different kinds of load can be described through this formula:

- <u>Constant impedance load</u> where $n_Q = 2, n_P = 2.$
- <u>Constant current load</u> where $n_Q = 1, n_P = 1.$
- <u>Constant power load</u> where $n_Q = 0, n_P = 0[13]$

2.2.3. ZIP-exponential load model

This model is combination of the last two methods and described through the following formulas [22]:

$$\frac{P}{P_n} = \left(1 - \left(K_{pi} + K_{pc} + K_{p1} + K_{p2}\right)\right)\left(\frac{V}{V_n}\right)^2 + K_{pi}\left(\frac{V}{V_n}\right) + K_{pc} + K_{p1}\left(\frac{V}{V_n}\right)^{npv1} \times \left(1 + K_{pf1}\Delta f\right) + K_{p2}\left(\frac{V}{V_n}\right)^{npv2} \left(1 + K_{pf2}\Delta f\right) \qquad 2.14$$

$$\frac{Q}{Q_n} = \left(1 - \left(K_{qi} + K_{qc} + K_{q1} + K_{q2}\right)\right)\left(\frac{V}{V_n}\right)^2 + K_{qi}\left(\frac{V}{V_n}\right) + K_{qc} + K_{q1}\left(\frac{V}{V_n}\right)^{nqv1} \times \left(1 + K_{qf1}\Delta f\right) + K_{q2}\left(\frac{V}{V_n}\right)^{nqv2} \left(1 + K_{qf2}\Delta f\right) \qquad 2.15$$

$P_n, Q_n, and\ V_n$; The nominal values,

$K_{p1}, K_{p2}, K_{q1}, K_{q2}, K_{pf1}, K_{pf2}, K_{qf1}, K_{qf1}, npv1, npv2, nqv1$ and $nqv2$; The coefficients of exponential part of total load,

K_{pi} and K_{qi}; The coefficients of constant current part of total load,

$K_{pc}$and K_{qc}; The coefficients of constant power parts of total load.

2.3. Current harmonics

As indicated in pervious chapter the new technology street lamps are connected to electronic ballasts which reduce power consummation. In some street lamps there is a discharge device. These power electronic devices which convert voltage (DC to DC, DC to AC, AC to AC or AC to DC) are useful but they generate at the same time nonlinear behaviour in power system. They change the sinusoidal process system and generate current harmonic in AC power. The second disadvantage of the devices is resonant occurrence by reactive power compensation. For compensation these devices are connected in capacitors which improve power factor but can also generate resonance effect and lead to current or voltage distortion [23].

2.3.1. Harmonics generation

There are different types of devices which generate harmonics in power system such as: converter, arc Furnaces, Static VAR compensator, Inverter for dispersed generation, single phase or three phase inverters, electronic phase control, pulse width modulated drive (PWM). The following section is concentrated on the current harmonics that are generates from converters and AC lines.

-Converter are the main part of ballast which generates harmonics. An ideal current and voltage wave shape assume that there is no ripple respectively no inductive load connected to the circuit. In this circuit type the voltage transfers from one phase to the other one at a certain time. Commutation phenomena occur when inductance is present. In the real commutation there is an overlap will be occurred because of conduction between two devices where in this period current does not transfers from one phase to other one. In reality there is a short circuit during this overlap [23]. Figure 22 shows M3 line-commutated power converters circuit. As depicted a three-phase power supplies system M3 circuit. The circuit contains; 1. Real thyristors, 2. LR load with $L \rightarrow \infty$, 3. Connected grid side inductance L_S [24].

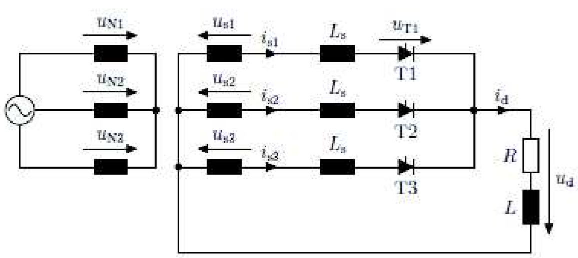

Figure 22. M3 line-commutated power converters circuit[24]

Figure 23. shows current and voltage curves by the M3 circuit considering on commutation for ignition angle $\alpha = 120°$. The gray surface indicated the overlap during the conduction of two thyristors.

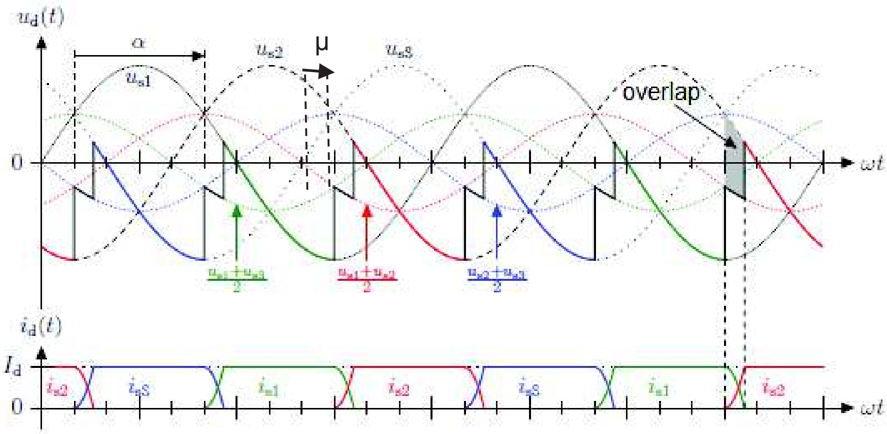

Figure 23. Current and voltage curves by M3 circuit considering on commutation for ignition angle $\alpha = 120°$[24]

The harmonic current in converter is defined:

$$I_h = I_{dc}\left\{\sqrt{\frac{6}{\pi}}.\frac{\sqrt{C_0^2 + C_1^2 - 2C_0^2C_1^2\cos(2\alpha+\mu)}}{h[\cos\alpha - \cos(\alpha+\mu)]}\right\} \tag{2.16}$$

Where α is ignition angels, μ is commutation overlap angel. $C_0^2$and $C_1^2$are defined as following:

$$C_0^2 = \frac{\sin\left[(h-1).\frac{\mu}{2}\right]}{(h-1)} \quad and \quad C_1^2 = \frac{\sin\left[(h+1).\frac{\mu}{2}\right]}{(h-1)} \tag{2.17}$$

-AC line harmonics: The current harmonics which are generated from AC line is defined as following

$$\mathrm{I_h} = \mathrm{I_c}\frac{2\sqrt{2}}{\pi}\left[\frac{\sin\left(\frac{h\pi}{3}\right)\sin h\frac{\mu}{2}}{h^2\frac{\mu}{2}} + \frac{r_C G_h\cos\left(\frac{h\pi}{6}\right)}{1-\sin\left(\frac{\pi}{3}+\frac{\mu}{2}\right)}\right] \tag{2.18}$$

$$G_{h=}\frac{\sin\left[(h+1).(\frac{\pi}{6}-\frac{\mu}{2})\right]}{(h+1)} + \frac{\sin\left[(h-1).(\frac{\pi}{6}-\frac{\mu}{2})\right]}{(h-1)} - \frac{2\sin\left[h(\frac{\pi}{6}-\frac{\mu}{2}).sin(\frac{\pi}{3}+\frac{\mu}{2})\right]}{h} \tag{2.19}$$

Where $\mathrm{I_c}$ is DC current at the end of commutation and $\mathrm{r_C}$ is Δi related to $\mathrm{I_c}$. Figure 24. shows the definition of values in equation 2.18.

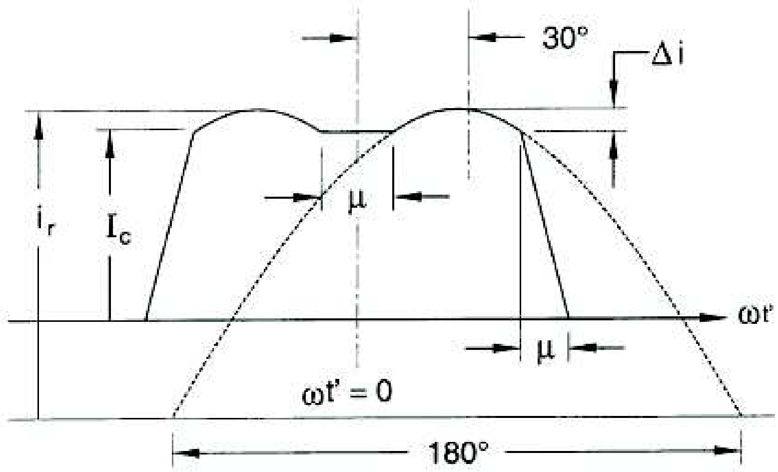

Figure 24. Definition of values in equation 2.18 [23]

2.3.2. System response characteristics

According to [23] the generated harmonics current from devices which are indicated in the previous chapter influence directly system frequency response characteristics. There are many factors which can impact, such as; System short circuit capacity, capacitor banks and insulated cable, load characteristics, balanced and unbalanced system condition, resonant condition, normal flow of harmonic current and system characteristics. This section is concentrated on the major importance of load characteristics which can affect system frequency response.

Load has two impacts on the system frequency response characteristics:

The first impact is through the resistive component of load. The importance of the resistive portion is at system resonance. Figure 25. the system response with varying load level for a system with parallel resonance near the forth harmonic.

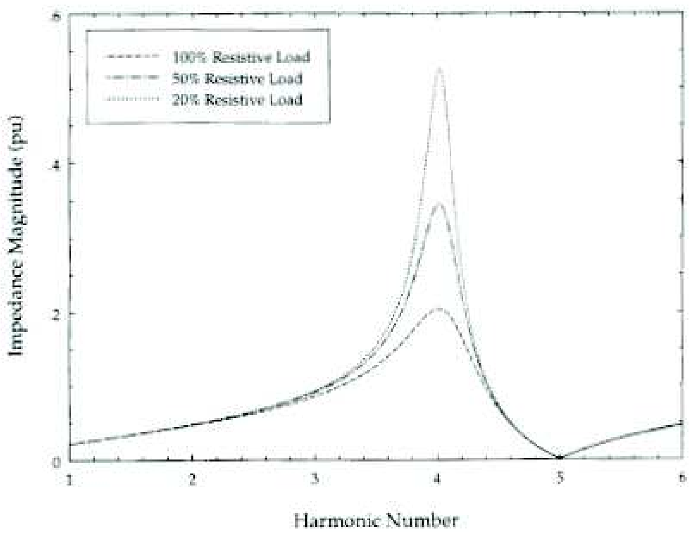

Figure 25. The effect of system resistive load on parallel resonance [23]

The second impact is through the dynamic load such as motors which applied in industrial system and commercial and residential systems. These types of loads can shift the frequencies where resonance occurs.

2.3.3. Total distortion harmonics in street lighting

Total harmonic distortion according IEEE 1035:1989 is defined as following:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}}.100\% \qquad 2.20$$

Figure 26. shows the relationship between the THD in percent and the voltage per unit for a fluorescent lamp. It can be seen that the THD is almost 4% at 220 volt. The fluorescent lamp was connected with conventional ballast and compensation capacitor.

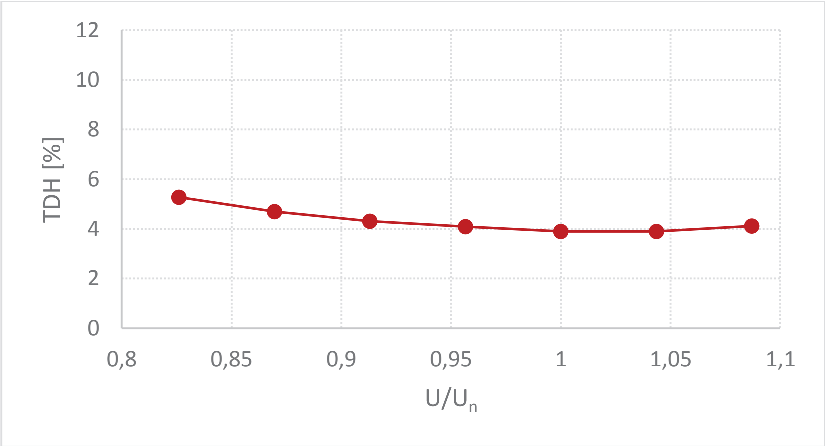

Figure 26. Relationship between THD in percent and the voltage for a fluorescent lamp

Figure 27. shows the relationship between the THD in percent and the voltage per unit for a new design LED which is connected to programmable ballast. The TDH is almost 10 % at the nominal voltage. The electronic devices and converters in this type of ballast cause the higher value of TDH in compare to the fluorescent lamps.

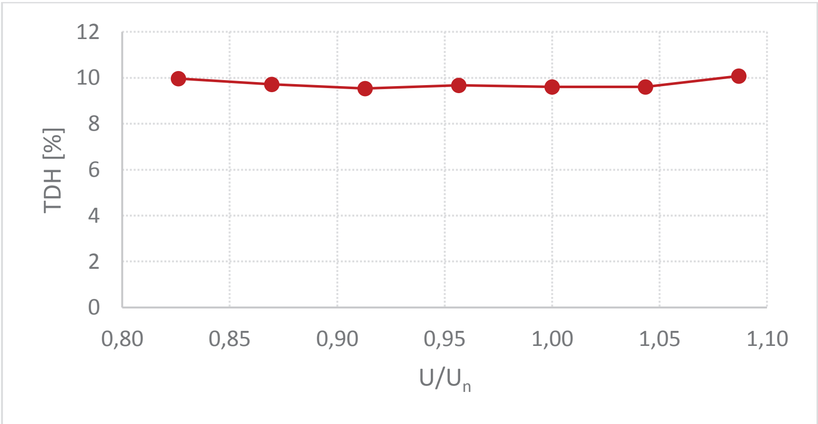

Figure 27 Relationship between THD in percent and the voltage for a LED

Figure 28. shows the harmonic current spectrum of lighting in the past, present and in future. It can be seen that the fluorescent lamps in the past shows lower current harmonics but in future the current harmonic will be higher through the replacement of LEDs [26].

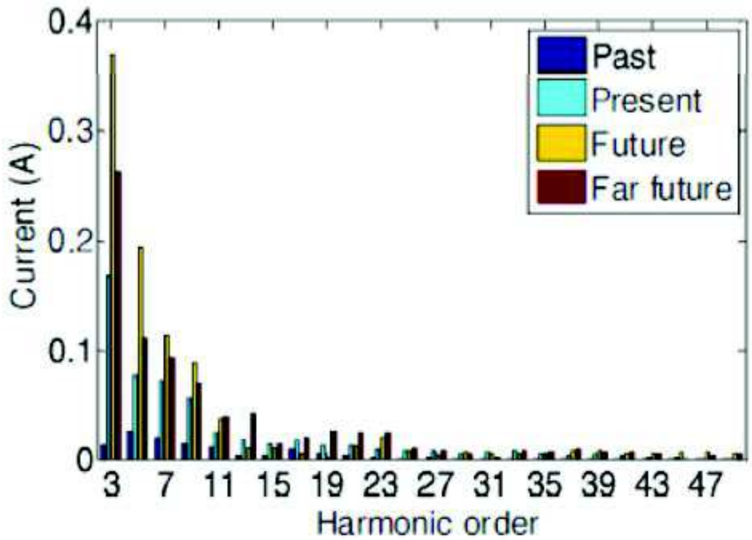

Figure 28. The harmonic current spectrum of lighting [26]

3. Electrical behaviour of lighting

Different light technologies have diverse electric behaviours. Therefore, their impact on the grid is unequal. This chapter is dedicated on the investigation of the most usable lightning types.

3.1. Lighting types

Four types of lamp with different number of light sources and altering effects are investigated experimentally:

- Fluorescent lamps
- High pressure sodium lamps
- Metal halide lamps and
- Light emitting diodes

Figure 29. shows an overview of the construction of NARVA manufactured **fluorescent lamps T8/T12 36 W** connected to the conventional magnetic ballasted TRIDONICACTO-ETAWATT 36 in series with capacitors as depicted in Figure. NARVA electronic starter includes thyristor connected parallel to capacitor.

For optimal light flux the distance between light sources is 32mm. The old types are connected with conventional magnetic ballast AUSTRIA-EMAIL.

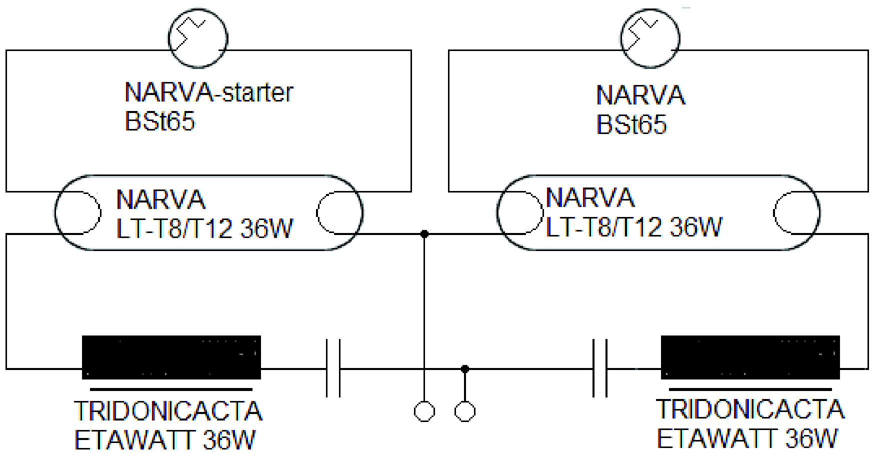

Figure 29. Construction of NARVA manufactured fluorescent lamps connected to the conventional magnetic ballasted

Figure 30. shows an overview of the construction of NARVA manufactured **high pressure sodium lamp** that is connected with electronic ballast TRIDONIC and Ignitor. Start- up time is almost 6 minutes. The same circuit is offered for OSRAM manufactured **halide lamp**.

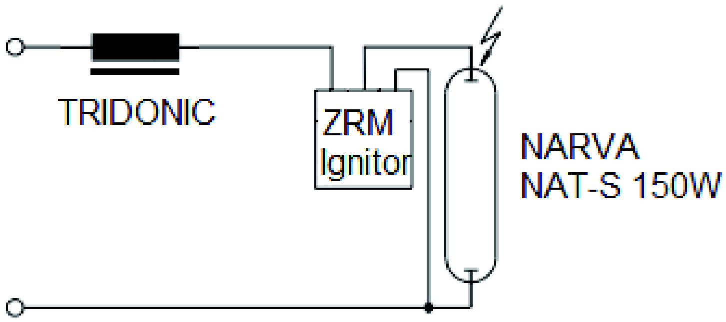

Figure 30. Construction of NARVA manufactured high pressure sodium lamp connected to electronic ballast and Ignitor

Three types of LEDs were measured:

LEDWAY: The LED array contains 100 diodes which provide 100 Watt. **SPL-60**: The LED array contains 60 diodes and provides 70 Watt. **BRS419 PHILIPS**: It contains 24 diodes and provides 17 Watt. The LED is connected to the electronic ballast-Xitanium electronic drivers- as is depicted in following. Figure 31. shows construction of BRS419. The LED drivers offer programming and dimming.

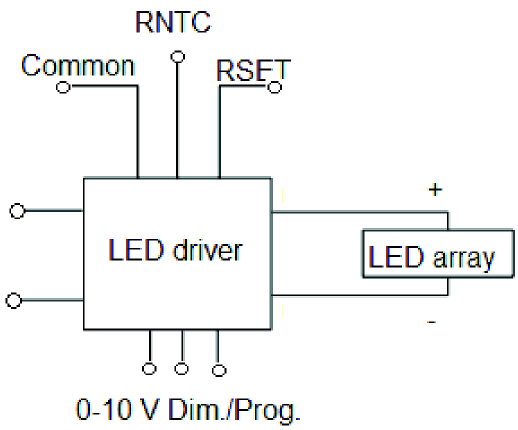

Figure 31. Construction of BRS 419 [27]

3.2. Measurement procedure

Figure 32. represents an overview of measurement scheme used to investigate the electrical behaviour of different light types. Measurement where performed in the electrical laboratory of ESEA, TU Wien.

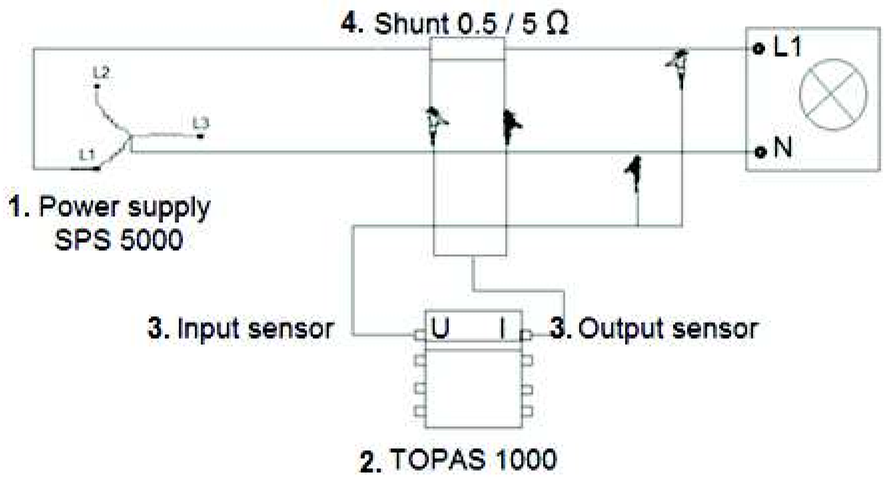

Figure 32. Overview of measurement scheme

The main elements of the measurement scheme are:

- **Power Supply- SPS-5000:**. This power supply fulfils the source requirements (Voltage and frequency stability, low total harmonic distortion and ideal internal resistance) according to the IEC/EN 61000-3-2. Table 1. shows an overview of technical data of power source supply SPS-5000.

SPS technical data	
Voltage accuracy (45Hz-450Hz)	$\pm 0.5\ \%$
Current accuracy (45Hz-450Hz)	$\pm 0.8\ \%$
Power accuracy (P; Q; S) (45Hz-450Hz) For measurement with shunt	$\pm 1\ \%$
Power factor accuracy (45Hz-450Hz)	$\pm 0.1\ \%$
Frequency accuracy for f= 50Hz	$\pm 0.1\ \%$
Internal impedance	real ; 0.00…4 Ω
	Inductive; 0.00…6.40 mH
Internal impedance accuracy	$\pm 2\ \%$
TDH	$\pm 0.3\ \%$

Table 1. Technical data of power source SPS-5000

- **Power network analyser TOPAS 1000:** Power network analyser TOPAS 1000 is used to measure electrical parameters (current, voltage, active power, reactive power, apparent power and power factor) and harmonics.

- **Sensors:** The input sensor is 600 V CATIII for voltage test 400 V AC/DC to measure the voltage. Output sensor is connected to the 0.5 Ω/ 5Ω shunt to measure the current.

- **Shunt:** To detect and measure low current in Light emitting diodes and to reduce the TDH, the output sensor is connected to the shunt with 0.5 Ω/ 5Ω

All measurements are performed in room temperature $22℃ \pm 1℃$. The fluorescent and LEDs are measured for 15 minutes because the electrical parameter values are stable after one minute. The values of high pressure Sodium lamps due to reigniting and run-up- time are stable after 7 minutes and these lamps are measured for 30 minutes.

3.3. Lighting load behaviour

In this chapter are shown measurement results. Active power, reactive power and power factor are measured for different voltage values, from 0.83 to 1.09 p.u.. The objective of these measurements was to define the coefficients for the ZIP model of the light-load.

- **Fluorescent lamps**

Two types of fluorescent lamps are investigated: with one and two light sources. Normally from evening to 11:00 pm are switched on two lamp sources, meanwhile after 11:00 pm is switched on only one source. To determine the aging effect old and new exemplars were measured. The lamp itself has a resistive behaviour but connected to the ballast indicates inductive character

$$0.31 \leq \cos\rho \leq 0.43 \ \ for\ V_n \approx 230\ V_{RMS}$$

Table 2. shows the electrical parameters of fluorescent lamp on the nominal voltage.

Status	new		old	
Light source	1X	2X	1X	2X
Voltage	230.2 V	230.04 V	230.3 V	230.06 V
Active power	64 W	83.48 W	65.97 W	89.56 W
Reactive power	162.49 var	172.04 var	212 var	270.43 var
Power factor	0.35	0.43	0.29	0.31

Table 2. Electrical parameters of fluorescent lamp on the nominal voltage

Figure 33. shows the static load behaviour of the new fluorescent lamp with one light source in the case of active and reactive power. Figure 33a. shows active power behaviour of new fluorescent lamp with one light sources where $K_2^P = -0.12, K_1^P = 1.95$ and $K_0^P = -0.82$ and Figure 33b. shows reactive power of new fluorescent lamp with one light source where $K_2^Q = 1.29, K_1^Q = 0.25$ and $K_0^Q = -0.04$. Considering on polynomial model based on nominal values it can be seen that the fluorescent lamps have a high current coefficient and can be described through the mostly constant current model.

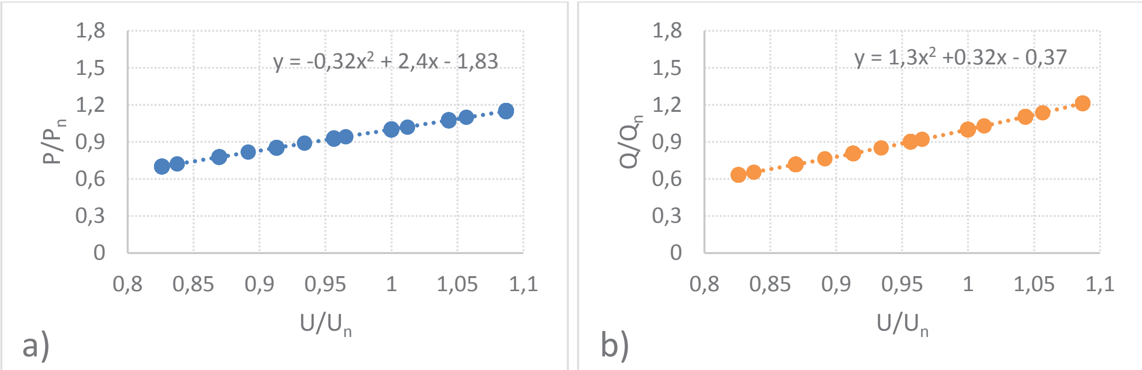

Figure 33. Static load behavior of the new fluorescent lamp with one light source a) Active power; b) Reactive power

Figure 34. shows the power factor as a function of voltage for new fluorescent lamp with one light source. Power factor decreases with the voltage increase.

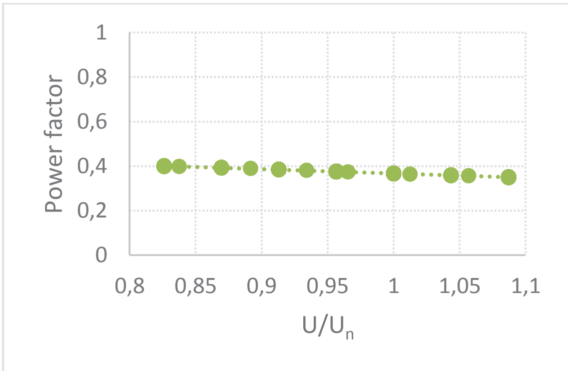

Figure 34. Power factor versus voltage for new Fluorescent lamp with one light source

Figure 35. shows the static load behaviour of the new fluorescent lamp with two light sources in the case of active and reactive power .Figure 35a. shows active power behaviour of new fluorescent lamp with two light sources where $K_2^P = -0.04, K_1^P = 1.75$ and $K_0^P = -0.71$ and Figure 35b shows reactive power of new fluorescent lamp with two light sources where $K_2^Q = 1.45, K_1^Q = -0.38$ and $K_0^Q = -0.08$.

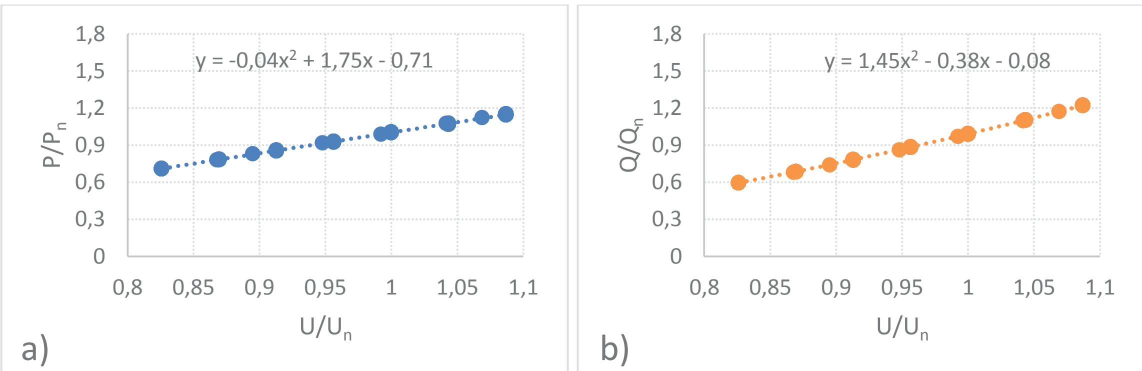

Figure 35. Static load behavior of the new fluorescent lamp with two light source : a) Active power; b) Reactive power

Figure 36. shows the power factor as a function of voltage for new fluorescent lamp with two light sources. Power factor decreases with the voltage decrease.

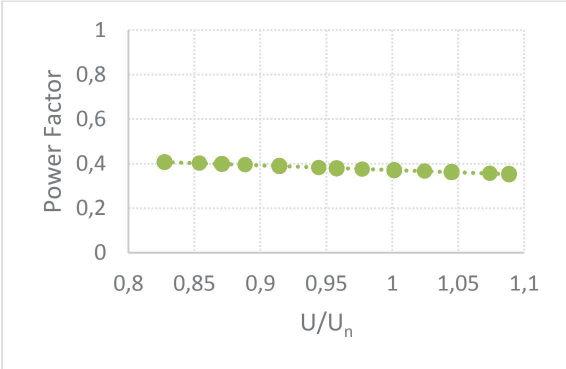

Figure 36. Power factor versus voltage for new Fluorescent lamp with two light sources

Figure 37. shows the light load as a function of voltage for new fluorescent lamp with one light source. Figure 37a. shows active power as a function of voltage for new fluorescent lamp with one light source, where $\frac{dP}{dV}$ is approximately 0.5 W/V. Figure 37b. shows real reactive power as a function of voltage for the new fluorescent lamp with one light source where $\frac{dQ}{dV}$ is approximately 1.5 vars/V.

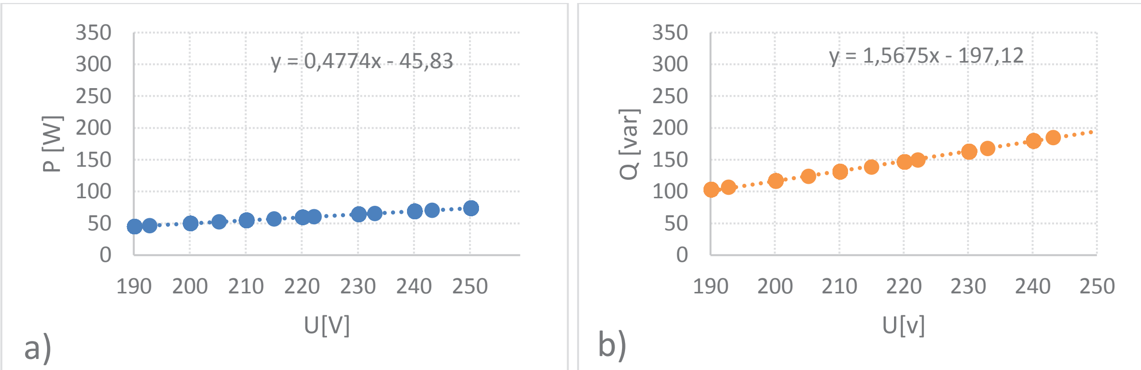

Figure 37. Light load as a function of voltage for new fluorescent lamp with one light source: a) Active power; b) Reactive power

Figure 38. shows the light load as a function of voltage for new fluorescent lamp with two light sources. Figure 38a. shows the active power as a function of voltage, where $\frac{dP}{dV}$ is 0.6 W/V. Figure 38b. shows the reactive power as a function of voltage, where $\frac{dQ}{dV}$ is1.8 var/V.

It can be seen the impedance load component is almost zero and the behaviour is almost linear. High increasing of reactive power $\frac{dQ}{dV} = 1.8\ var/V$ for two light sources and $\frac{dQ}{dV} = 1.5\ var/V$ for one light source is because of decreasing power factor and loss of capacity in circuit.

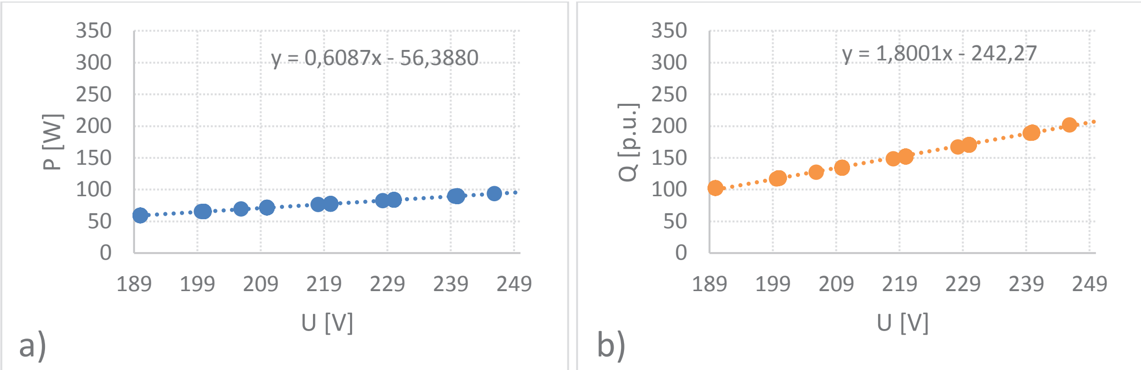

Figure 38. Light load as a function of voltage for new fluorescent lamp with two light sources: a) Active power; b) Reactive power

Figure 39. shows the static load behaviour of the old fluorescent lamp with one light source in the case of active and reactive power. Figure 39a. shows active power behaviour of old fluorescent lamp with one light source where $K_2^P = 0.45, K_1^P = 0.83$ and $K_0^P = -0.28$ and Figure 39b. shows reactive power of old fluorescent lamp with one light source where $K_2^Q = 1.53, K_1^Q = -0.72$ and $K_0^Q = 0.19$. It can be seen that mostly constant current component is high like as the new types.

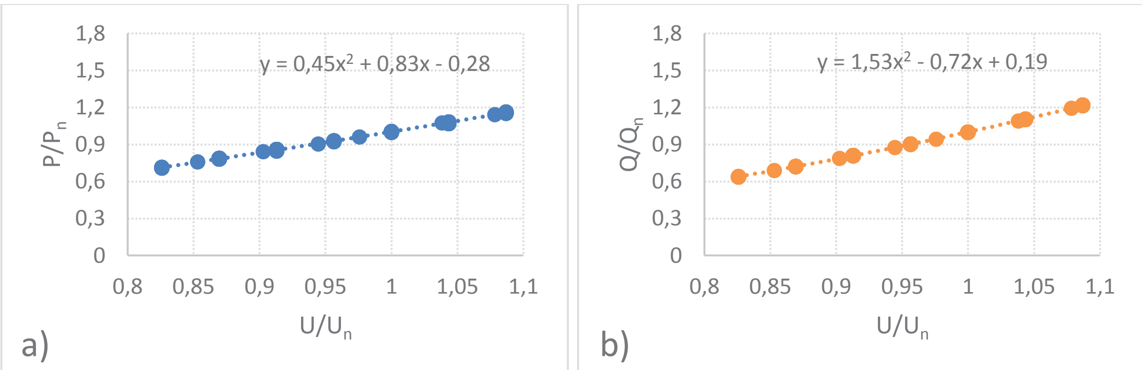

Figure 39. Static load behavior of the old fluorescent lamp with one light source: a) Active power; b) Reactive power

Figure 40. show the power factor as a function of voltage for old fluorescent lamp with one light source. The power factor profile is linear as same as the new type.

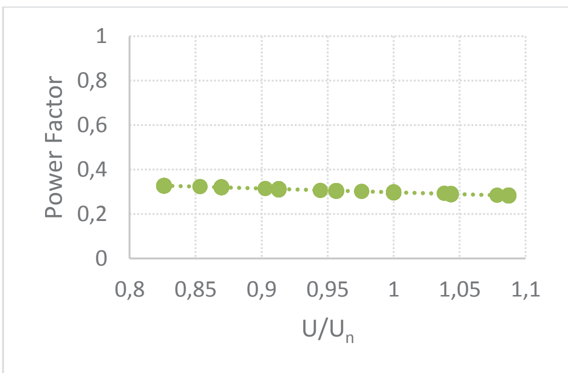

Figure 40. Power factor as a function of voltage for old Fluorescent lamp with one light source

Figure 41. shows the static load behaviour of the new fluorescent lamp with two light sources in the case of active and reactive power. Figure 41a. shows active power behaviour of old fluorescent lamp with two light sources where $K_2^P = 1.,K_1^P = -0.17$ and $K_0^P = 0.17$ and Figure 41b. shows reactive power of old fluorescent lamp with two light sources where $K_2^Q = 2.17, K_1^Q = -1.79$ and $K_0^Q = 0.62$.

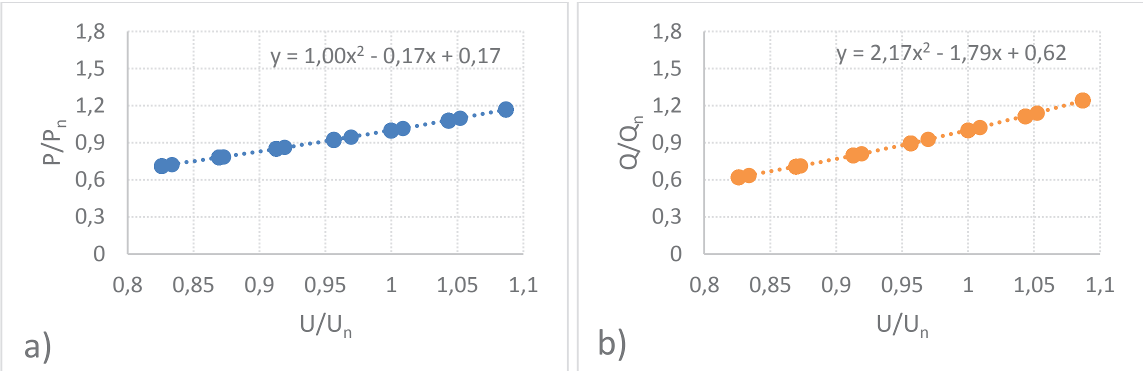

Figure 41. Static load behavior of the old fluorescent lamp with two light sources: source: a) Active power; b) Reactive power

Figure 42. shows the power factor as a function of voltage for old fluorescent lamp with two light sources.

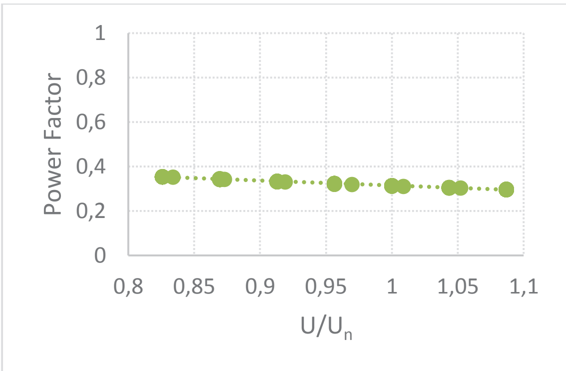

Figure 42. Power factor as a function of voltage for old Fluorescent lamp with two light sources

In compare to the new lamp the impedance coefficient is higher and therefore the old fluorescent with two light sources has impedance load character. The power factor is smaller than new types and causes higher reactive power drop.

Figure 43. shows the light load as a function of voltage for old fluorescent lamp with one light source. Figure 43a. shows the active power as a function of voltage. The derivation of active power is almost 0.4 W/V as same as the new fluorescent lamp. Figure 43b. shows the reactive power as a function of voltage, where $\frac{dQ}{dV}$ is 2.04 vars/V.

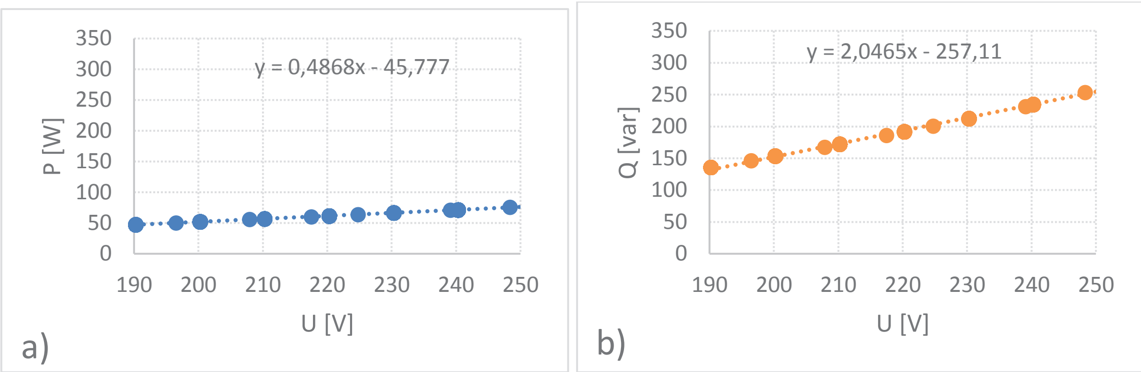

Figure 43. Light load as a function of voltage for old fluorescent lamp with one light source: a) Active power; b) Reactive power

Figure 44. shows the light load as a function of voltage for old fluorescent lamp with one light source. Figure 44a. shows the active power as a function of voltage with 0.67 W/V. Figure 44b. shows the reactive power as a function of voltage with $\frac{dQ}{dV} =$ 2.79 vars/V.

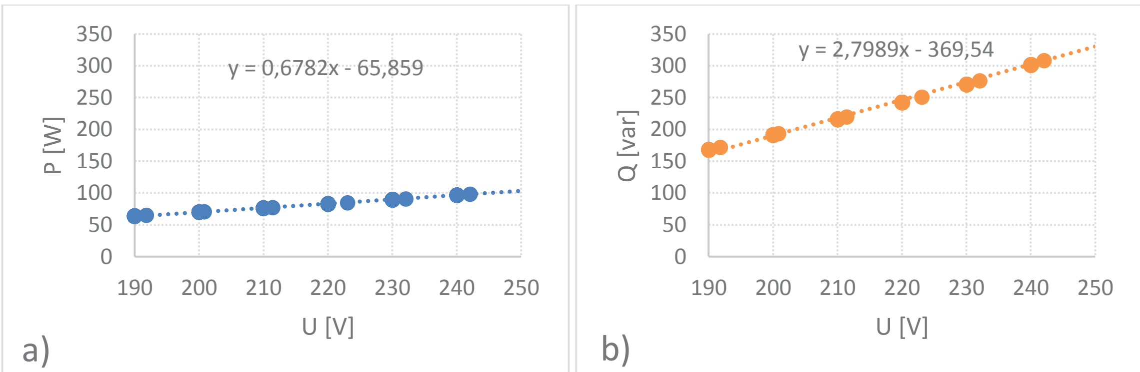

Figure 44. Light load as a function of voltage for old fluorescent lamp with two light sources: a) Active power; b) Reactive power

The impedance coefficient is almost zero and therefore it can be described through the linear model. It can be seen the active power is almost as same as the new types but the reactive power is higher than the new ones because of capacitor loss.

- **High pressure discharge lamp**

Table 3. shows the electrical parameters of high pressure lamp on the nominal voltage.

	new	old
Voltage	229.37 V	229.52 V
Active power	136.67 W	125.59 W
Reactive power	214.75 var	198.75 var
Power factor	0.63	0.53

Table 3. Electrical parameters of high pressure lamp on the nominal voltage

Figure 45. shows the static load behaviour of the new high pressure lamp in the case of active and reactive power. Figure 45a. shows active power behaviour of new high pressure discharge lamp where $K_2^P = -0.18, K_1^P = 2.43$ and $K_0^P = -1.24$ and Figure 45b. shows reactive power behaviour of new high pressure discharge lamp where $K_2^Q = 3{,}53, K_1^Q = -5{,}22$ and $K_0^Q = 2{,}69$. The lamp has mostly constant current load character. The coefficient of current component is higher than other coefficient which leads to proportional voltage dependence.

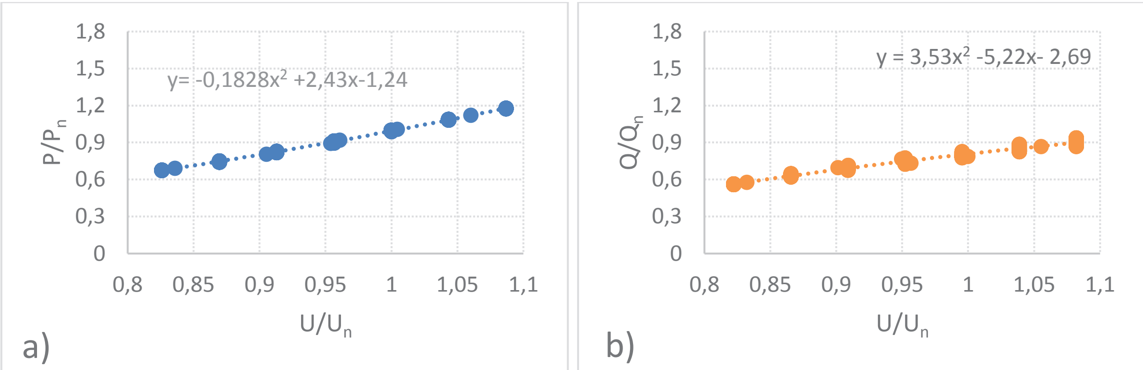

Figure 45. Static load behavior of the new high pressure discharge lamp: a) Active power; b) Reactive power

Figure 46. shows the power factor as a function of voltage for new high pressure discharge lamp. The new type of this lamp in compare to fluorescent lamp has a higher power factor which leads to lower reactive power drop. An increase of voltage leads to an increase of power factor.

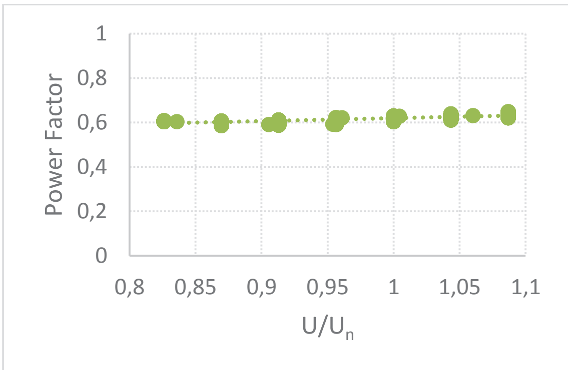

Figure 46. Power factor as a function of voltage for new discharge high pressure lamp

Considering on conventional polynomial equation, high pressure discharge lamp has linear profile. Figure 47. shows light load as a function of voltage for new high pressure lamp. Figure 47a. shows the active power and Figure 47b. shows the reactive power as a function of voltage. The derivation of active power is almost double of derivation of active power in fluorescent lamp but the drop of reactive power is half of the drop in fluorescent lamp:

$$\frac{dP}{dV} = 1.1\, W/V\,, \frac{dQ}{dV} = 1.2\, W/V$$

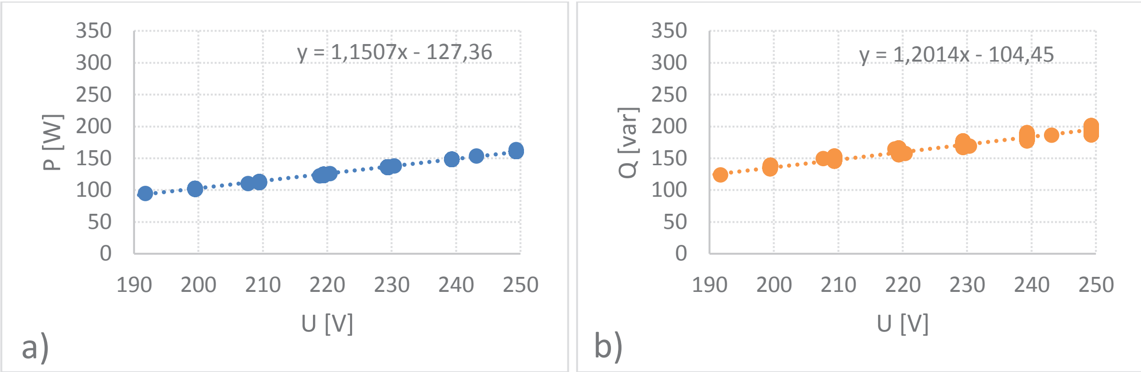

Figure 47. Light load as a function of voltage for new discharge high pressure lamp: a) Active power; b) Reactive power

Figure 48. shows the static load behaviour of the old high pressure lamp in the case of active and reactive power. Figure 48a. shows the active power behavior of old high pressure discharge lamp where $K_2^P = 1.97, K_1^P = -1.85$ and $K_0^P = 0.86$ and Figure 48b. shows the reactive power behavior of the old high pressure discharge lamp where $K_2^P = 0.98, K_1^P = 0.25$and $K_0^P = -0.20$.

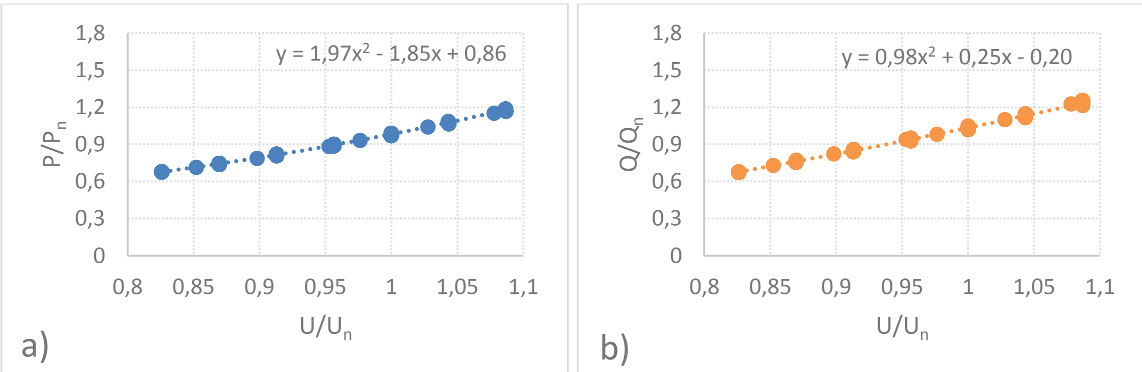

Figure 48. Static load behavior of the old high pressure discharge lamp: a) Active power; b) Reactive power

Figure 49. shows the power factor as a function of voltage for old high pressure discharge lamp. It can be seen that the static load characteristic is almost as same as the new type and it can be described through the impedance load but the power factor is lower than the new types.

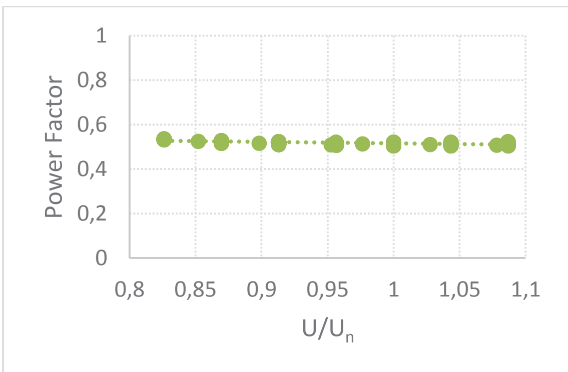

Figure 49. Power factor as a function of voltage for new discharge high pressure lamp

Figure 50. shows the light load as a function of voltage for old discharge high pressure lamp. Figure 50a. shows the active power as a function of voltage, where $\frac{dP}{dV}$ is approximately 1.05 W/V. Figure 50b shows the reactive power as a function of voltage. It can be seen that the reactive power drop $\frac{dQ}{dV}$ is 1.8 vars/V and it is higher than the new one because of capacitors loss.

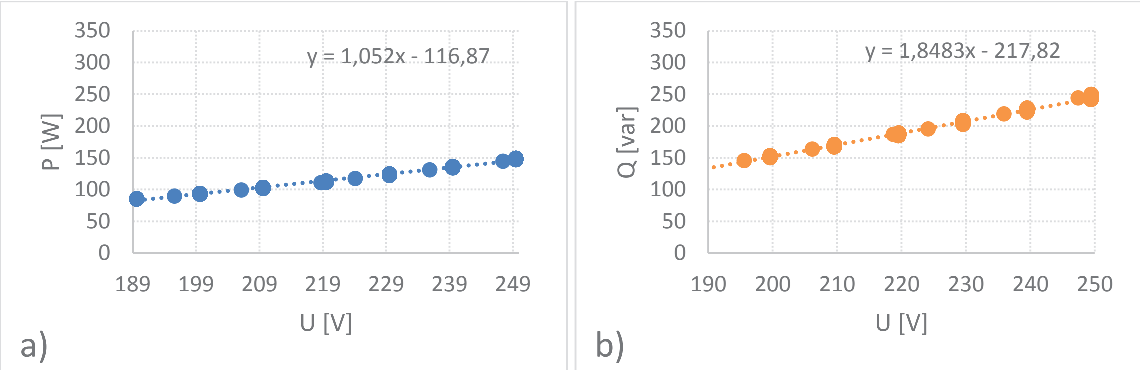

Figure 50. Light load as a function of voltage for old discharge high pressure lamp: a) Active power; b) Reactive power

- **Light emitting diodes**

In compare to the other lighting it can be seen that either the old technology whit not programmable ballast or new technology where the programming and dimming of the lamp is possible, have mostly constant power model. In this kind of lamp voltage variation doesn't impact the load characteristic because static load characteristic has high power coefficient.Table 4 shows an overview of electrical parameters of measured LEDs. It can be seen that the programmable ballast with power electronic provides higher power factor

	100Xlight source	60Xlight source	24Xlight source
Voltage	229.8 V	229.93 V	230.39 V
Active power	102.62 W	84.62 W	15.35 W
Reactive power	146.32 var	148.41	11.09 var
Power factor	0,57	0,49	0,8

Table 4. Electrical parameters of LEDs on the nominal voltage

Figure 51. shows the static load behaviour of LEDWAY in the case of active and reactive power. Figure 51a. shows active power behaviour of LEDWAY whit 100 light sources with $K_2^P = 0.16, K_1^P = 0.36$ and $K_0^P = 0.48$. Figure 51b. shows the reactive power behaviour of LEDWAY with $K_2^Q = 1.43, K_1^Q = 0.01$ and $K_0^Q = -0.01$. LEDWAY is defined as a mostly constant power load because of high K_0^Pcoefficient high coefficient.

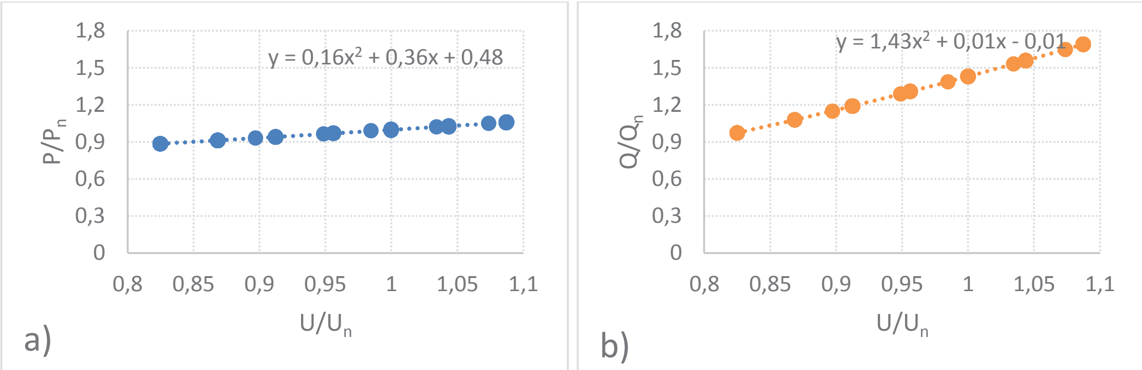

Figure 51. Static load behavior of LEDWAY with 100 light sources: a) Active power; b) Reactive power

Figure 52. shows the power factor as a function of voltage for LEDWAY with 100 light sources. As discussed this ballast doesn´t correct the power factor and the power factor decreases with the voltage decrease.

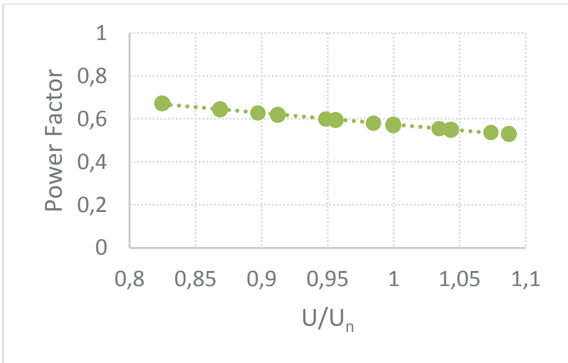

Figure 52. Power factor as a function of voltage for LEDWAY with 100 light sources

Figure 53. shows the static load behaviour of SPL60 in the case of active and reactive power. Figure 53a. shows the behaviour of nominal active power of SPL60 with 60 light sources. The static load coefficient are $K_2^P = 0.31, K_1^P = 0.25$ and $K_0^P = 0.45$. SPL60 static characteristic is as like as LEDWAY and has high mostly constant power component. Figure 53b. shows the behaviour of nominal active power of SPL60 with 60 light sources. The static load coefficients are $K_2^Q = 0.89, K_1^Q = 0.22$ and $K_0^Q = -0.11$.

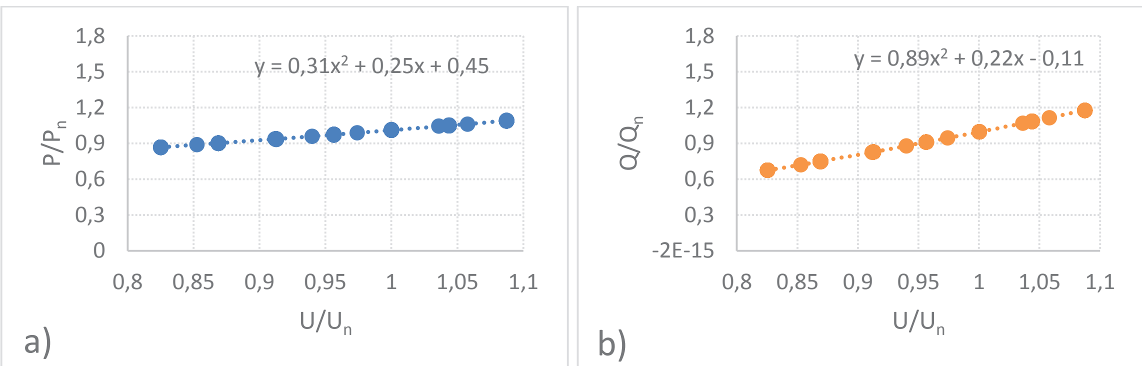

Figure 53. Static load behavior of SPL60 with 60 light sources: a) Active power; b) Reactive power

Figure 54. shows the the power factor as a function of voltage for SPL60 with 60 light sources.

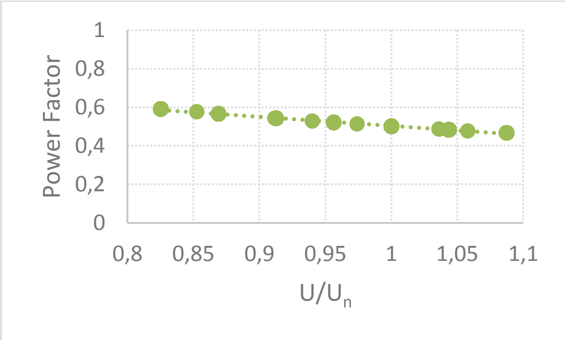

Figure 54. Power factor as a function of voltage for SPL60 with 60 light sources

Figure 55. shows the static load behaviour of BRS419 in the case of active and reactive power. Figure 55a. shows the behaviour of nominal active power of BRS419 with 24 light sources. The static load coefficients are $K_2^P = 0.53, K_1^P = -0.33$ and $K_0^P = 0.79$. SPL60 static characteristic is as like as LEDWAY and SPL60 and has high mostly constant power component. Figure 55b. shows the behaviour of nominal active power of SPL60 with 60 light sources. The static load coefficients are $K_2^Q = 0.55, K_1^Q = 1.03$ and $K_0^Q = -0.58$.

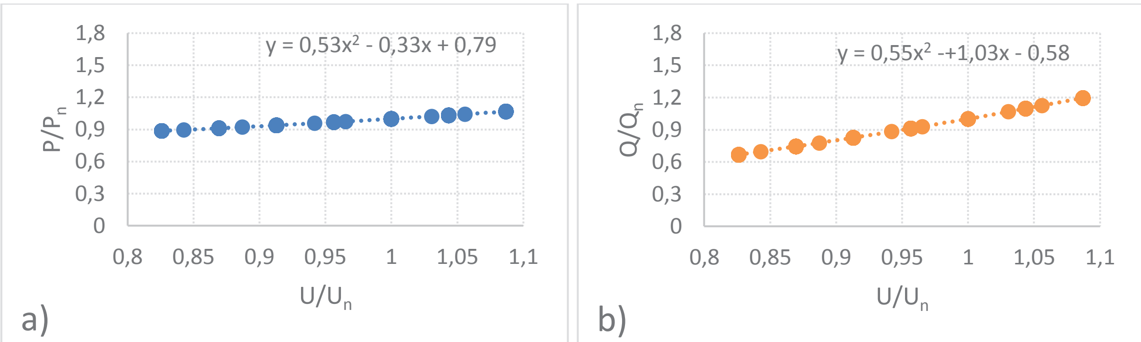

Figure 55. Static load behavior of BRS419 with 24 light sources: a) Active power; b) Reactive power

Figure 56. shows the power factor as a function of voltage for BRS419 with 24 light sources. The power factor of this type of LED is higher than the power factor of LEDWAY and SPL60.

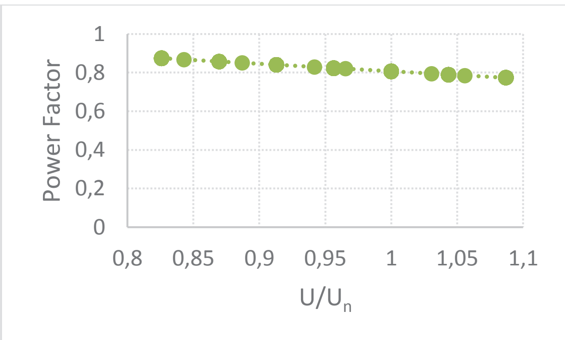

Figure 56. Power factor as a function of voltage for BRS419 with 24 light sources

Figure 57. shows the light model as a function of voltage for LEDWAY. Figure 57a. shows the active power as a function of voltage and Figure 57b. shows the reactive power as a function of voltage, where $\frac{\mathrm{dP}}{\mathrm{dV}}$ is 0.2 W/V and reactive power drop $\frac{\mathrm{dQ}}{\mathrm{dV}}$ is approximately 1.2 vars/V.

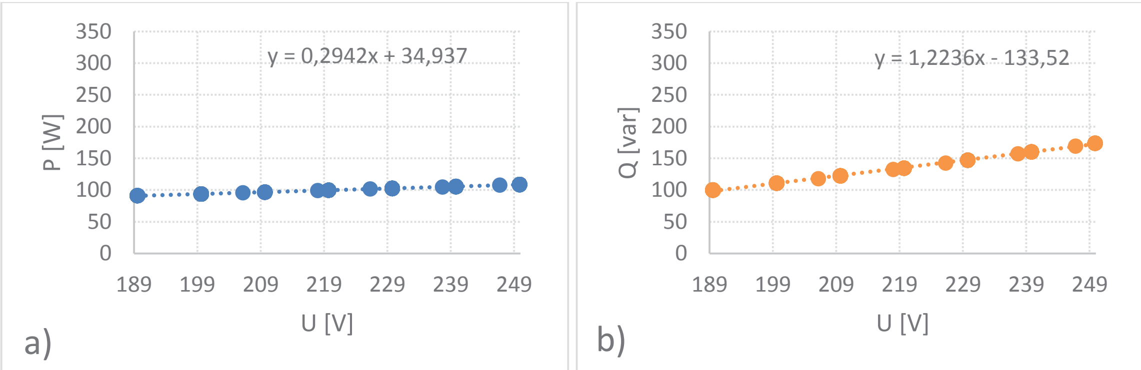

Figure 57. Light load as a function of voltage for LEDWAY with 100 light sources: a) Active power; b) Reactive power

Figure 58. shows the light load as a function of voltage for SPL60. Figure 58a. shows the active power as a function of voltage, where $\frac{\mathrm{dP}}{\mathrm{dV}} = 0.2\ \mathrm{W/V}$. Figure 58b. the reactive power as a function of voltage with $\frac{\mathrm{dQ}}{\mathrm{dV}} = 1.2\ \mathrm{var/V}$. The drop is as same as the reactive power drop of LEDWAY.

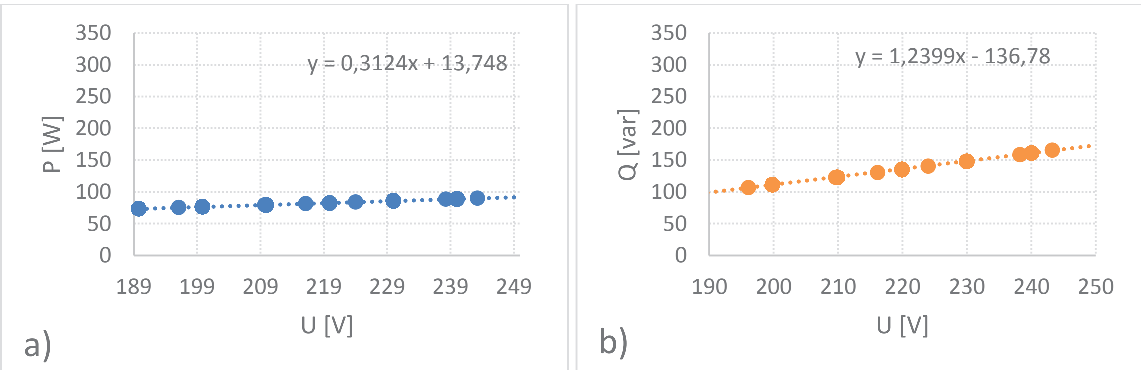

Figure 58 Light load as a function of voltage for LED with 60 light sources: a) Active power; b) Reactive power

Figure 59. shows the light model as a function of voltage for BRS419. Figure 59a. shows the active power as a function of voltage and Figure 59b. shows the reactive power as a function of voltage, where $\frac{\mathrm{dP}}{\mathrm{dV}}$ is 0.04 W/V and reactive power drop $\frac{\mathrm{dQ}}{\mathrm{dV}}$ is almost 0.09 vars/V. The derivations of active and reactive power are lower in compare to the LEDs without programmable ballast.

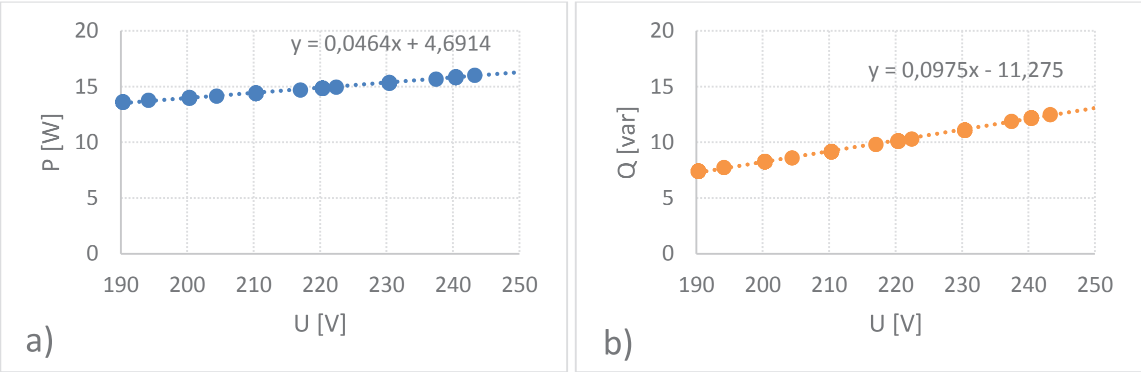

Figure 59. Light load as a function of voltage for LED with 24 light sources: a) Active power; b) Reactive power

Considering on conventional model can be seen that the impedance coefficient is almost zero and the lighting can be described thought the linear model. The derivations of active and reactive are very low. The new technology provides opportunity to replace high pressure discharge lamp in future.

The impedance, current a power component percentage of static load model based on nominal values are depicted in Table 5.

Table 5. The impedance, current and power component percentage of static load model based on nominal values

Lamp type	Light source	Status	V_n [V]	P_n [W]	Q_n [var]	$\cos\rho$	K_2^P	K_1^P	K_0^P	K_2^Q	K_1^Q	K_0^Q
Fluorescent	1X	new	230.2	64	162.49	0.35	-0,12	1,95	-0,82	1,29	0,25	-0,04
		old	230.1	65.97	212	0.29	0.45	0.83	-0.28	1,53	-0.72	0.19
Fluorescent	2X	new	230	83.48	172.04	0.43	-0.04	1,75	0.71	1,45	-0.38	-0.08
		old	230.06	89.56	270.43	0.31	1	-0.17	0.17	2,17	-1.79	0.62
HPL	1X	new	229.37	136.7	214.75	0.63	-0,18	2,43	-1,24	3,53	-5,22	2,69
		old	229.52	125.6	198.75	0.53	1,97	-1.85	0.86	0,98	0.25	-0.20
LED	100X	new	229.8	102.6	146.32	0.57	0.16	0.36	0.48	1,43	0.01	-0.01
	60X	old	229.93	84.62	148.41	0.49	0.31	0.25	0.45	0,89	0.22	-0.11
	24X	new	230.39	15.35	11,09	0.8	0,53	-0,33	0,79	0,55	1,03	-0,58

Table 6. shows the percentage of current and power component based on original values.

Lamp type	Light source	Status	$\cos(\rho)$	H_1^P	H_0^P	H_1^Q	H_0^Q
Fluorescent	1X	new	0.35	0.47	-45.83	1.56	-197.12
		old	0.29	0,48	-45.77	2.04	-257.11
Fluorescent	2X	new	0.43	0,6	-56,38	1,8	-242,27
		old	0.31	0,67	-65,85	2,79	-369,54
HPL	1X	new	0.63	1,15	-127,36	1,2	-104,45
		old	0.53	1,05	-116,87	1,84	-217,82
LED	100X	new	0.57	0,29	34,93	1,22	-133,52
	60X	old	0.49	0,31	13,74	1,23	-136,78
	24X	new	0.8	0,04	4,69	0,09	-11,27

Table 6. Percentage of current and power component based on original values

3.4. Harmonic analysis

Figure 60. shows the relationship between TDH and the voltage according to the IEEE 1035 for fluorescent lamp with one light source and two light sources. It can be seen either the new types or the old types of lamps have lowest TDH on 220 volts. The highest TDH of old lamps occurs on 250 volts. The maximum value is 3.19 % by lamp with one source and is 5.08 % by two sources. The highest value of TDH of new lamps occurs on 190 volts. The TDH of new lamps is 3% by one source and is 5.2 by two sources.

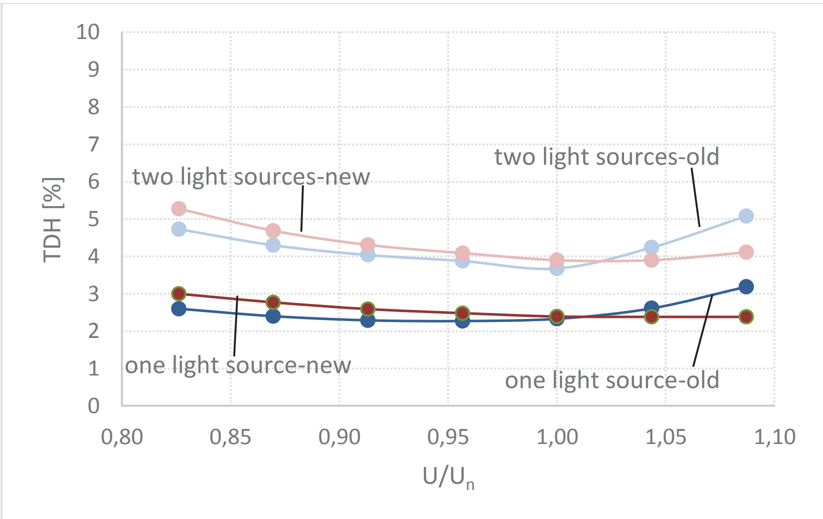

Figure 60. The relationship between TDH and the voltage according to the IEEE 1035 for fluorescent lamps

Figure 61. shows an overview of Fluorescent lamp absolute current harmonic with one light source on nominal voltage. It can be seen the 3d current harmonic has the highest value with 23.42 mA for old types and 17.86 for new types. The 3d, 5th and

7th current harmonics have exponential rising behavior and increase with the voltage increase. The 9th current harmonic decreases with an increase of voltage.

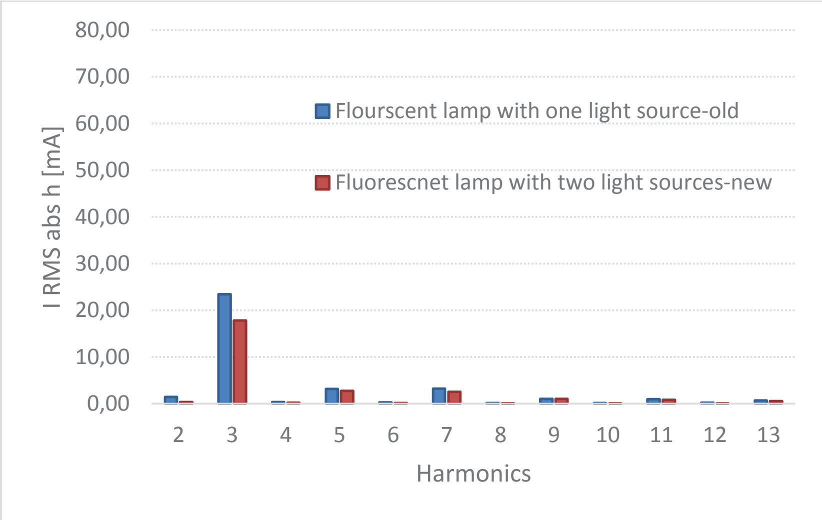

Figure 61. Overview of Fluorescent lamp absolute current harmonics with one light source on nominal voltage

Figure 62. shows an overview of fluorescent lamp absolute current harmonics for two light sources on nominal voltage. The 3d current harmonic has the highest value. The 5th current harmonic is higher than the 7th harmonic current. The deviation of 3d, 5th, 7th and 9th current harmonic over the voltage is as same as fluorescent lamps with one light source.

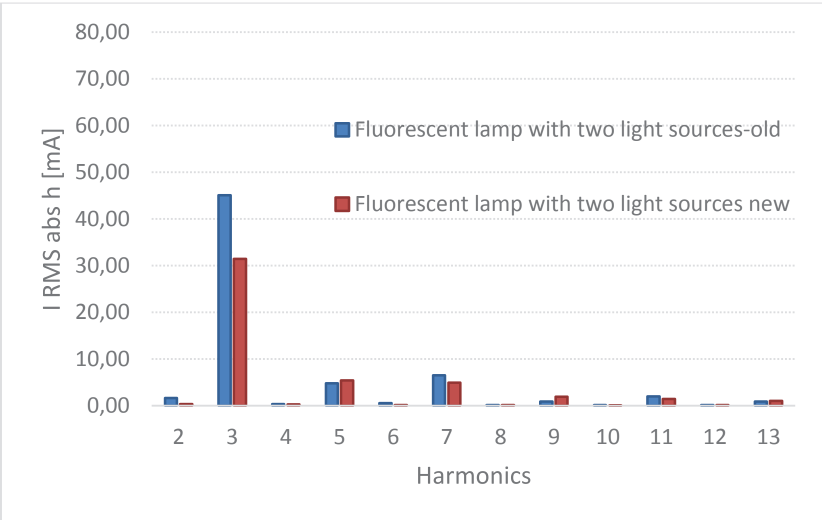

Figure 62. Overview of Fluorescent lamp absolute current harmonics with two light sources on nominal voltage

Figure 63. shows the relationship between the TDH in percent and the voltage according to the IEEE 1035 for NARVA high pressure lamps. It can be seen that the value of TDH of high pressure lamp is higher in compare to the fluorescent lamps. The minimum value occurs on 190 volts where by old type is 5.3% and by new type

is 7.8%. The maximum value of TDH is on 250 volts. The TDH of old type is 7.61% and the TDH of new type is 9.4%.

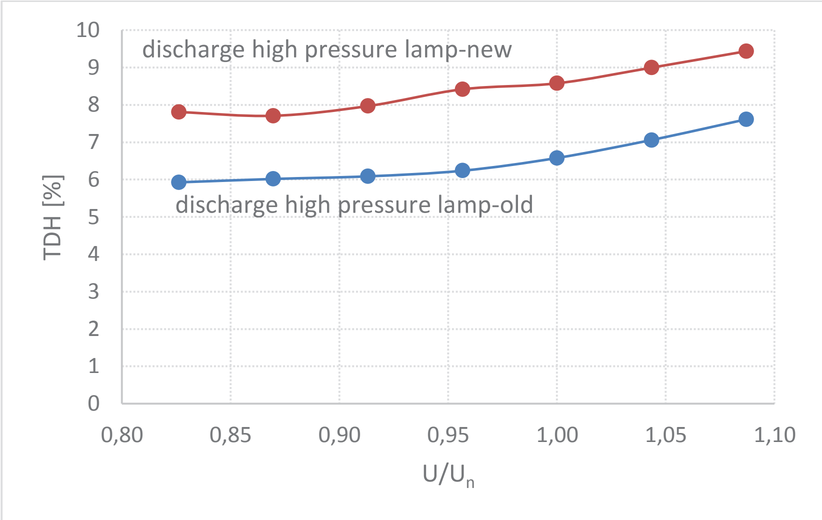

Figure 63. The relationship between the TDH in percent and the voltage according to the IEEE 1035 for high pressure sodium lamps

Figure 64. shows an overview of NARVA high pressure lamps absolute current harmonics on nominal voltage. The 3d current harmonic has highest value with 75.44 mA for new types and 64.90 for the old types. 3d current harmonic increases with an increase of voltage. The 5^{th} and 9^{th} current harmonics have exponential behavior but the 7^{th} current harmonic increases marginally with the voltage increase.

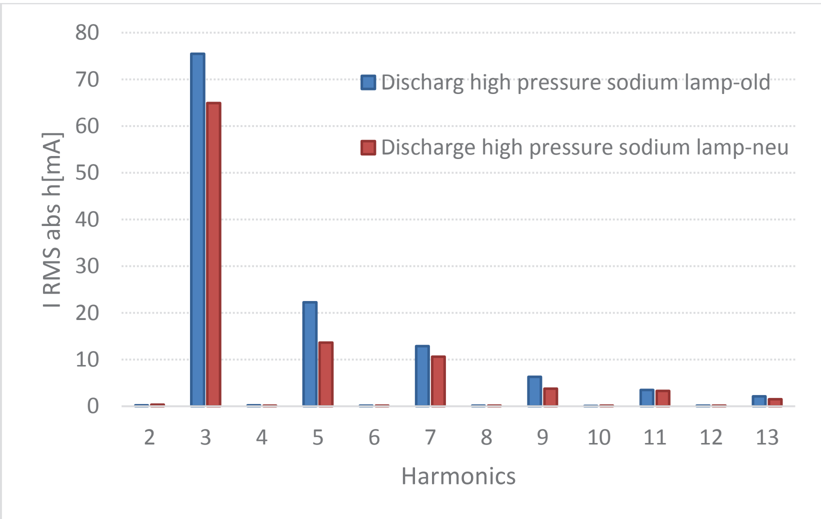

Figure 64. Overview of NARVA high pressure lamps absolute current harmonics on nominal voltage

Figure 65. shows an overview of POWEBALL high pressure lamp absolute current harmonics on nominal voltage. The behavior of POWERBALL is as same as NARVA. As depicted the value of 3d current harmonic for new type is 61.82 mA and thus lowers than NARVA.

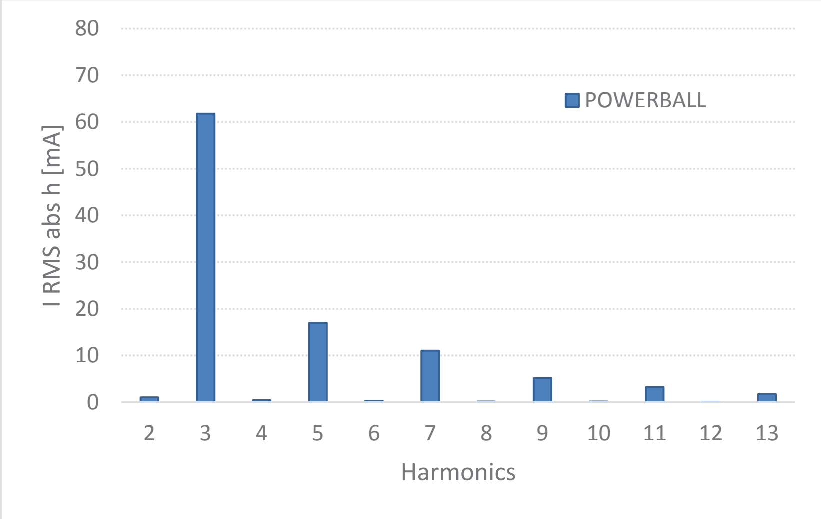

Figure 65. Overview of POWEBALL high pressure lamp absolute current harmonics on nominal voltage

Figure 66. shows the relationship between the TDH in percent and the voltage according to the IEEE 1035 for BRS419 LEDWAY and SPL60. By LEDWAY and SPL60 can be seen that the TDH decreases with the voltage decrease. The maximum TDH value of SPL60 is 3.2% on 190 volt and the maximum value of LEDWAY is 6.09%. The minimum TDH is 2.38 by SPL60 and 4.11% by LEDWAY. The TDH of BRS419 is between 9.9% to10.0%.

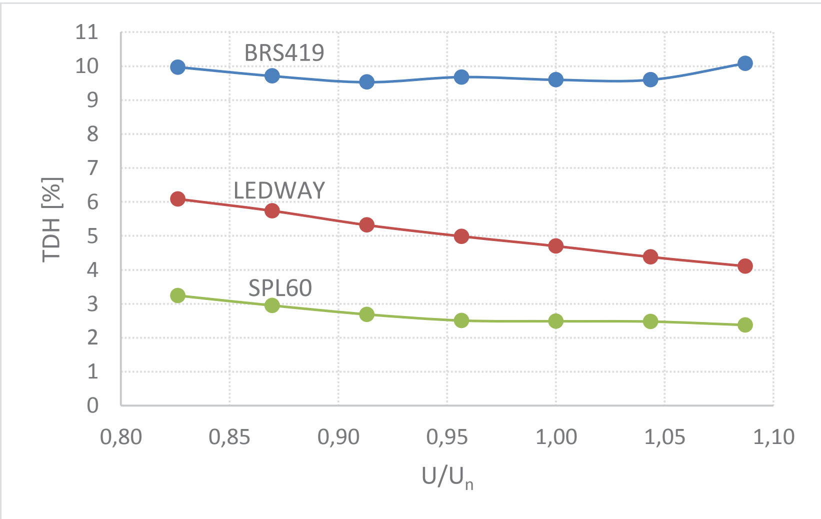

Figure 66. The relationship between the TDH in percent and the voltage according to the IEEE 1035 for LEDs

Figure 67. shows an overview of BRS419 absolute current harmonics on nominal voltage. As depicted the 3d current harmonic has the highest value with 6.9 mA but in compare to discharge lamps the 5^{th} and 7^{th} harmonics are almost half of the 3d current harmonic.

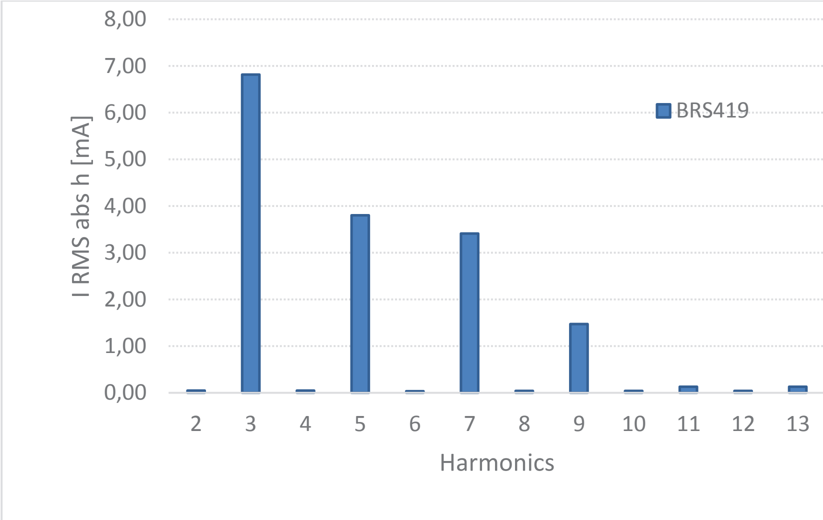

Figure 67. Overview of BRS419 absolute current harmonics on nominal voltage

Figure 68. shows an overview of LEDWAY and SPL60 absolute current harmonics on nominal voltage. By the LEDWAY The 9th harmonic is higher than 5th and 7th. The 3d harmonic is almost 32.0 mA and by SPL60 is almost 15.0 mA.

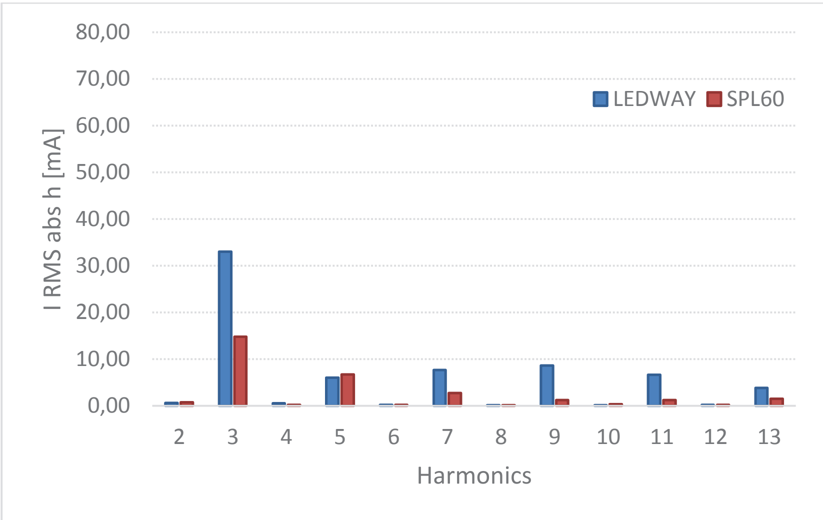

Figure 68. Overview of LEDWAY and SPL60 absolute current harmonics on nominal voltage

Table 7. shows the THD in percent at 230 volts for the measured lamps. THD of fluorescent is at lowest with one light source. It can be seen that old one which is not connected to capacitor has lower TDH and power factor. TDH is higher in a winter day as summer day. The ballast and ignition circuit in high pressure sodium lamps cause high value of TDH. BRS419 causes high value of TDH in compare to the other lamps.

Lamp type	Status	Temperature[^{0}C]	$\cos\varphi$ (230 V)	THD[%] (230 V)
Fluorescent lamp 1Xlight source NARVA	old	20.9	0.29	2.33
	new	21.9	0.35	2.39
	old	**0.3**	0.31	2.52
Fluorescent lamp 2Xlight source NARVA	old	21.4	0.31	3.68
	new	21.9	0.43	3.90
	old	**0.1**	0.33	3.9
High pressure Sodium lamp NARVA	old	21.4	0.53	6.58
	new	22.4	0.63	8.58
High pressure Sodium lamp OSRAM	new	21.5	0.56	6.52
SPL-60 2XModul 50Xlight source	old	23.1	0.49	2.49
LEDWAY 5X20 LED light source	new	23.1	0.57	4.7
LED BRS419 1Xmodule 24Xlight source	new	23.0	0.8	9.6

Table 7. The THD in percent at 220 volt

4. Electrical behaviour of light feeders

Street lightning is supplied with three phases. Street lightings are connected alternated to different phases to guarantee a balanced load. Therefore, there are performed one phase power flow calculation. Simulations are performed by using SINAUT Spectrum from Fa. Siemens, where it is possible to use the ZIP load model. Figure 69. shows an overview of the street lightning connection on the three phase power grid. The geographical distance between two poles is about 50m [28].

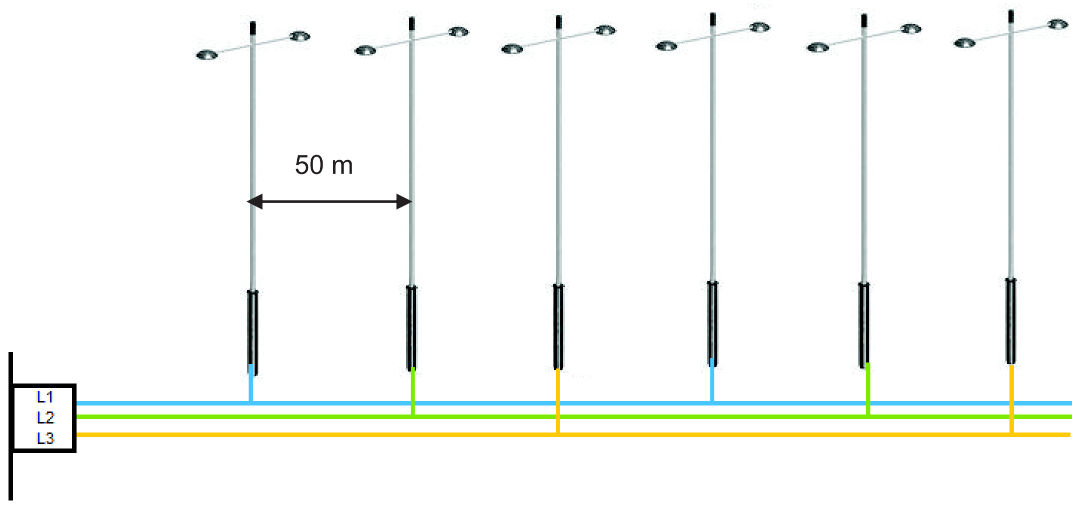

Figure 69. Overview of the street lightning connection on the three phase power grid

But the distance between two poles connected at the same phase is 150m. Within this study is considered on only phase simulation where the distance between two lamps results 150 meter. Figure 70. Shows an overview of the street lighting connection on the one phase power grid.

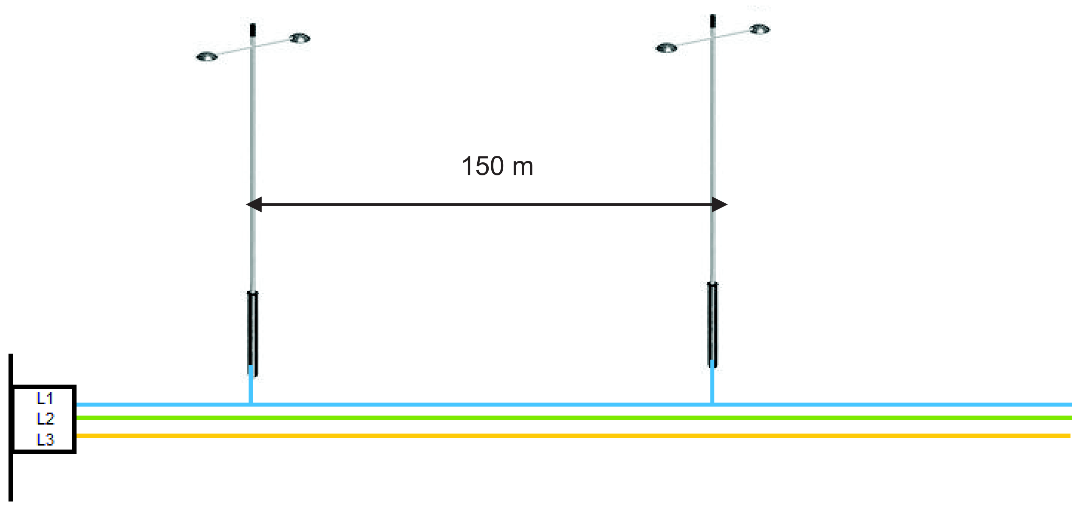

Figure 70. Overview of the street lightning connection on the one phase power grid

According to the guideline DIN VDE 0271, ICE 502 regarding to technical description run PVC insulating 0.6/1 KV energy cables. NAYY-O 4X50 mm^2 as supply cable and NYY-O 4X10 mm^2 as outgoing cable will be used. The wire of outgoing circuit runs as following: Beginning with brown wire then black wire at the second then the gray wire and at the end is the blue wire. The same scheme is applied for final fuse box. The lighting is connected as following [29]:

- Brown cable is for special installation
- Black wire for regulation
- Gray wire for lighting supply

The technical data of cable are given in Table 8:

article discretion	R_i $[\Omega/km]$	I_K $[kA]$	X_b $[\Omega/km]$	D_A $[mm]$	G $[kg/km]$
NAYY-O 4X50	0.641	3.8	84.82	30	1151
NYY-O 4X10	1.83	1.15	94.56	18.3	720

Table 8. Technical data of cable [30]

4.1. Simulation results of fluorescent lamps connected in a Feeder

In this chapter the calculation results of a feeder are shown which contains five new fluorescent lamps with one light source. Figure 71. shows an overview of the calculated feeder contains fluorescent lamps with one light source.

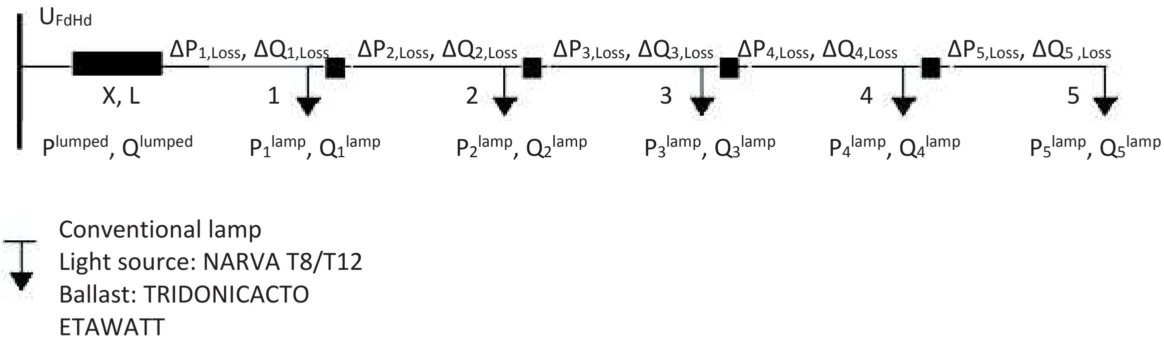

Figure 71. Overview of the calculated feeder contains fluorescent lamps with one light source

U_{FdHd} is the voltage at the feeder head and lumped Powers are defined as following:

$$P^{lumped} = \sum_{i=1}^{5} P_i^{lamp} + \Delta P_i \quad (4.1)$$

$$Q^{lumped} = \sum_{i=1}^{5} Q_i^{lamp} + \Delta Q_i \quad (4.2)$$

ΔP_i and ΔQ_i: power demand of cable,

P_i^{lamp} and Q_i^{lamp}: power demand of a lamp

Figure 72. shows the active power, reactive power and voltage as a function of feeder length for the different feeder head voltages. Figure 72a. shows the power for voltage at feeder head 207 V. From the graph can be seen that the voltage decreases along the feeder by 0.25 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=53.91 W and Q(1)=132 var, while lamp 5 consumes P(5)= 53,63 W and Q(5) =131.1 var.

Figure 72b. shows the power for voltage at feeder head 230 V. From the graph can be seen that the voltage decreases along the feeder by 0.26 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=63.83 W and Q(1)=165.3 var, while lamp 5 consumes P(5)=63.58 W and Q(5)=164.4 var.

Figure 72c. shows the power for voltage at feeder head 250 V. From the graph can be seen that the voltage decreases along the feeder by 0.26 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=73.2 W and Q(1)=200.5 var, while lamp 5 consumes P(5)=72.9W and Q(5) =199.4 var.

As conclusion with the increasing of the voltage on the beginning of the feeder the active power consummation of lamps increases by about 35.8 % while reactive power consummation increases by about 51.9 %.

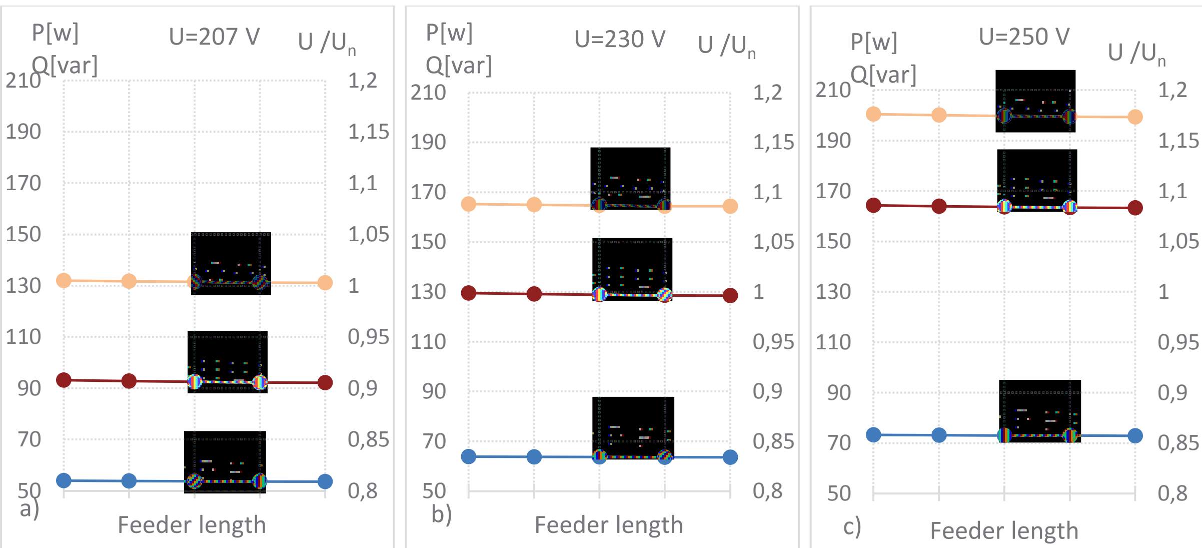

Figure 72. Active power, reactive power and voltage as a function of feeder length for fluorescent lamp for different feeder head voltages: a) 20 7V; b) 230 V; c)250 V

Figure 73. shows the voltage profil for different voltage values on feeder head. Results show that with the increasing of the voltage on feeder head, voltage drop in feeder increases.

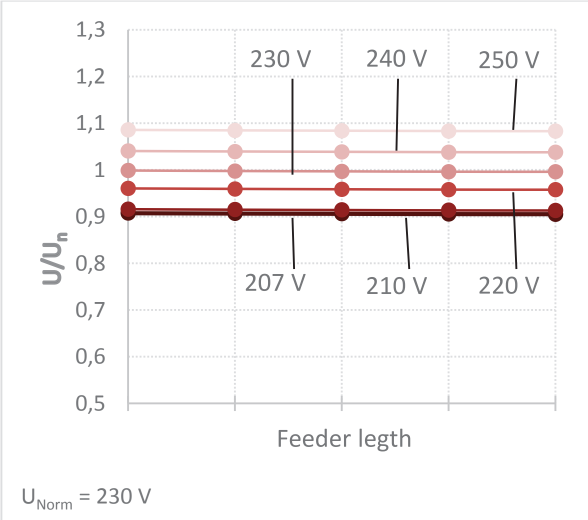

Figure 73. Voltage profiles for different voltage values on feeder head

Figure 74. shows the relationship between power demand and feeder length for 207V to 250V. Figure 74a. shows the active power as a function of feeder length. Figure 74b. shows the reactive power as a function of feeder length. Change in voltage impacts the reactive power more than active power. As conclusion the following results can be seen:

$$\Delta P^{250\,V} = P_1^{250\,V} - P_5^{250\,V} = 0.3\;W \qquad \Delta Q^{250\,V} = Q_1^{250\,V} - Q_5^{250\,V} = 1.1\;var$$

$$\Delta P^{207\,V} = P_1^{207\,V} - P_5^{207\,V} = 0.28\;W \qquad \Delta Q^{207\,V} = Q_1^{207\,V} - Q_5^{207\,V} = 0.9\;var$$

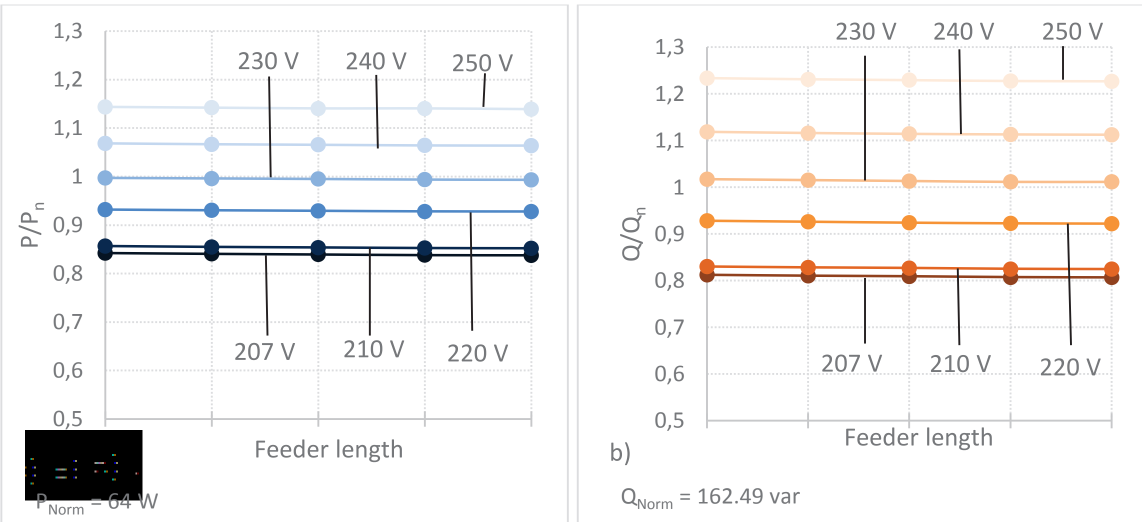

Figure 74. The relationship between power demand and feeder length for different voltage values on feeder head: a) Active power; b) Reactive power

Figure 75. shows the comparison between the static load behavior of the fluorescent lamp and the lumped load at feeder begin. Figure 75a. shows the static load characteristic for active power. The coefficients of ZIP model for active power are as following:

For one lamp: $K_2^P = -0.12\,;\; K_1^P = 1.95\,;\; K_0^P = -0.82$

For the lumped load: $K_2^P = 0.65\ ;\ K_1^P = -0.33\ ;\ K_0^P = 0.67$

Figure 75b. shows the static load characteristic for reactive power. The coefficients of ZIP model for reactive power are as following:

For one lamp: $K_2^Q = 1.29\ ;\ K_1^Q = 0.25\ ;\ K_0^Q = -0.04$

For the lumped load: $K_2^Q = 0.48\ ;\ K_1^Q = -0.0038\ ;\ K_0^Q = 0.51$

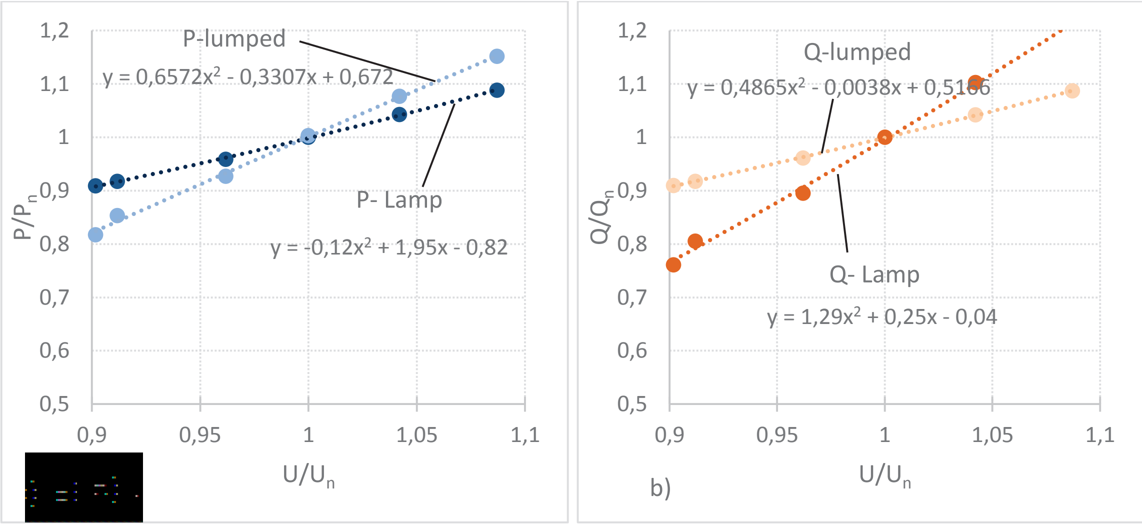

Figure 75. Static load behavior of the fluorescent lamp and the lumped load at feeder begin: a) Active power; b) Reactive power

Based on criteria as defined on 2.2.1 the fluorescent lamps have a mostly constant current load behavior but the lumped load behaves more as a mostly constant power load.

4.2. Simulation results of discharge high pressure lamps connected in a feeder

Figure 76. shows an overview of the feeder, which contains five new discharge high pressure lamps.

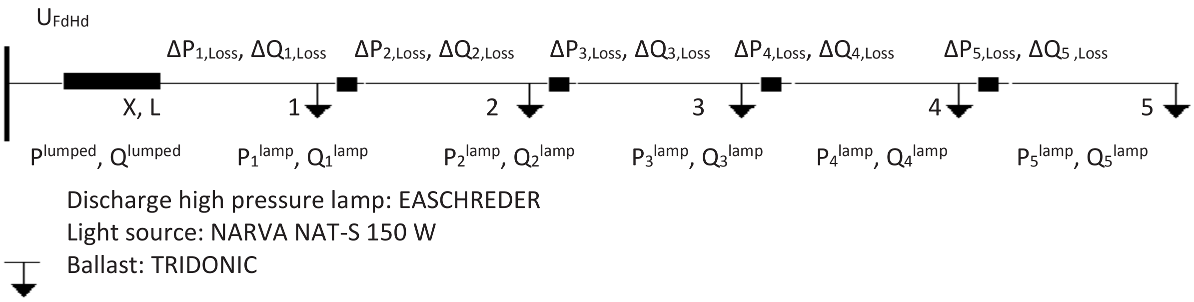

Figure 76. Overview of the feeder contains five new discharge high pressure lamps

Figure 77. shows the active power, reactive power and voltage as a function of feeder length for different feeder head voltages. Figure 77a. shows the power for voltage at feeder head 207 V. From the graph can be seen that the voltage

decreases along the feeder by 0.53%. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=111.4 W and Q(1)=144.5 var, while lamp 5 consumes P(5)=110.1 W and Q(5)=143.1 var.

Figure 77b. shows the power for voltage at feeder head 230 V. From the graph can be seen that the voltage decreases along the feeder by 0.54 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=135.3 W and Q(1)=167 var, while lamp 5 consumes P(5)=133.8 W and Q(5)=165.8 var.

Figure 77c. shows the power for voltage at feeder head 250 V. From the graph can be seen that the voltage decreases along the feeder by 0.54 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=160.4 W and Q(1)=185.9 var, while lamp 5 consumes P(5)=158.8W and Q(5) =184.8 var

As conclusion with the increasing of the voltage on the beginning of the feeder the active power consummation of lamps increases by about 44 % while reactive power consummation increases by about 28.6 %.

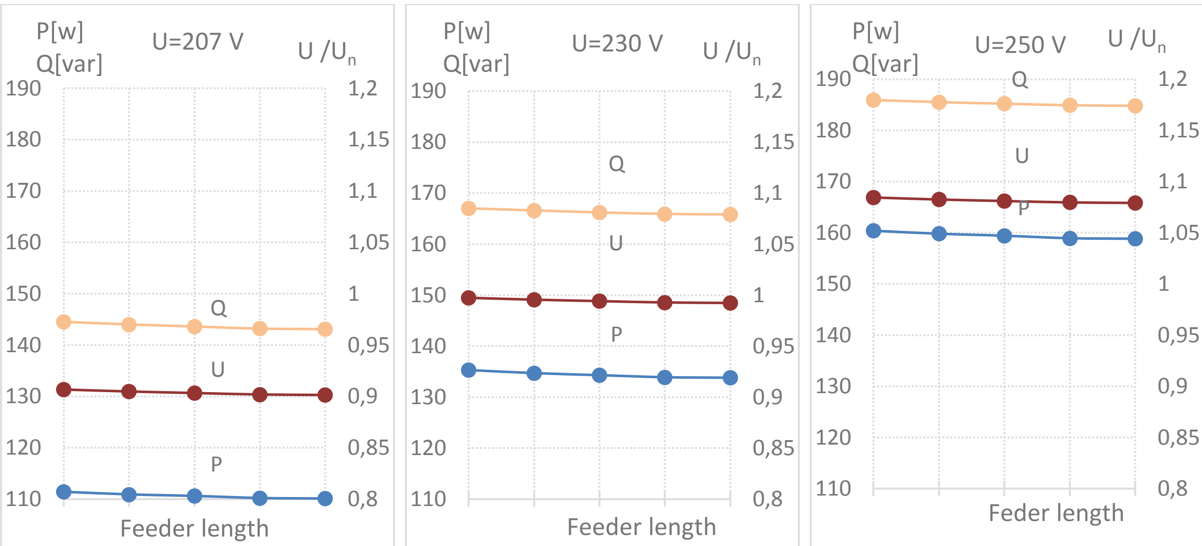

Figure 77. Active power, reactive power and voltage as a function of feeder length for discharge high pressure sodium lamp for different feeder head voltages: a) 20 7V; b) 230 V; c)250 V

Figure 78. shows the voltage profil for voltage values on feeder head. Results show that with the increasing of the voltage on feeder head, voltage drop in feeder increases.

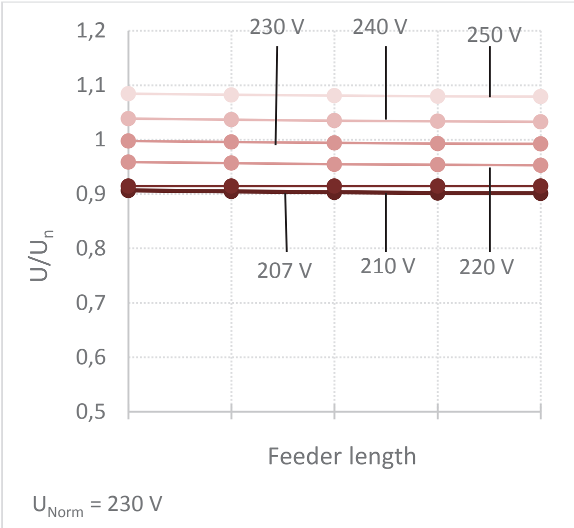

Figure 78. Voltage profiles for different voltage values on feeder head

Figure 79. shows the relationship between power demand and feeder length for different voltage values on feeder head. Figure 79a. shows the active power as a function of feeder length. Figure 79b. shows the reactive power as a function of feeder length. Change in voltage impacts the active power more than reactive power As conclusion following results can be seen:

$$\Delta P^{250\,V} = P_1^{250\,V} - P_5^{250\,V} = 1.6\ W \qquad \Delta Q^{250\,V} = Q_1^{250\,V} - Q_5^{250\,V} = 1.1\ \ var$$

$$\Delta P^{207\,V} = P_1^{207\,V} - P_5^{207\,V} = 1.3\ W \qquad \Delta Q^{207\,V} = Q_1^{207\,V} - Q_5^{207\,V} = 1.4\ var$$

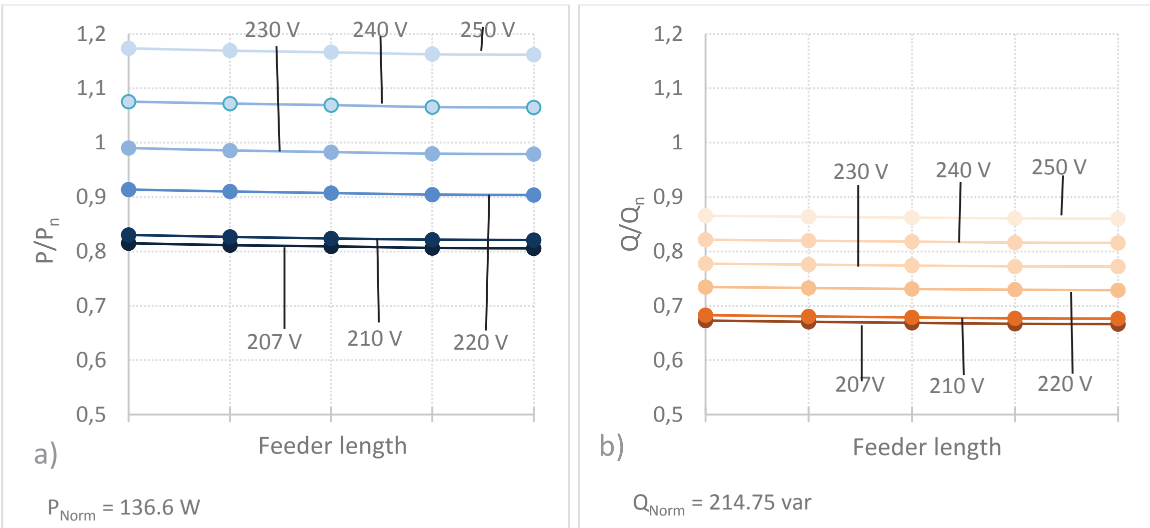

Figure 79. The relationship between power demand and feeder length for different voltage values on feeder head: a) Active power; b) Reactive power

Figure 80. shows the comparison between the static load behavior of the discharge high pressure lamp and the lumped load at feeder begin. Figure 80a. shows the static load characteristic for active power. The coefficients of ZIP model for active power are as following:

For one lamp: $K_2^P = -0.182\,;\; K_1^P = 2.43\,;\; K_0^P = -1.24$

For the lumped load: $K_2^P = 0.1\,;\; K_1^P = 0.79\,;\; K_0^P = 0.1$

Figure 80b. shows the static load characteristic for reactive power. The coefficients of ZIP model for reactive power are as following:

For one lamp: $K_2^Q = 3.53\,;\; K_1^Q = -5.22\,;\; K_0^Q = 2.69$

For the lumped load: $K_2^Q = 0.2\,;\; K_1^Q = 0.57\,;\; K_0^Q = 0.22$

As it is depicted, the lamp and the feeder have a mostly constant current characteristic.

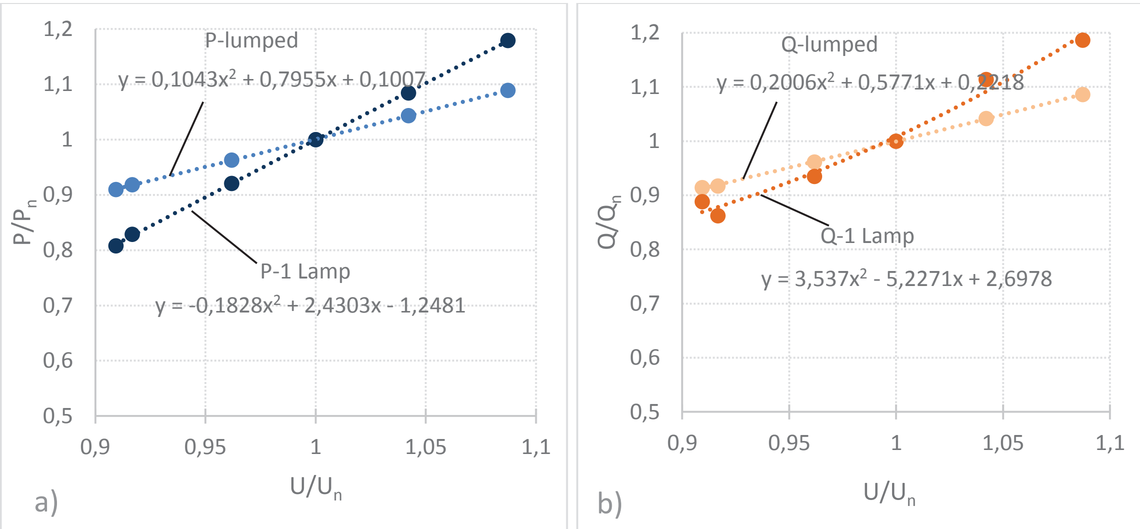

Figure 80. Static load behavior of the discharge high pressure lamp and the lumped load at feeder begin: a) Active power; b) Reactive power

Based on criteria defined on 2.2.1 either the lamps or the limped load behave as a mostly constant current load, where the mostly constant current coefficient of the lamps are higher than this coefficient of lumped load.

4.3. Simulation results of LED- BRS419

Figure 81. shows an overview of the calculated feeder, which contains five new BRS419.

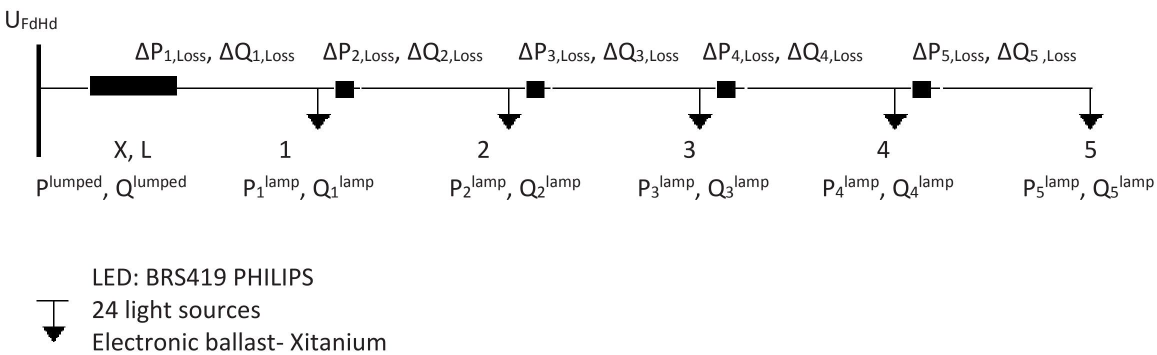

Figure 81. Overview of the calculated feeder contains five new BRS419

Figure 82. shows the active power, reactive power and voltage as a function of feeder length for BRS419 for different feeder head voltages. Figure 82a. shows the power for voltage at feeder head 217 V. From the graph can be seen that the voltage decreases along the feeder by 0.06%. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=14.72 W and Q(1)=10.16 var, while lamp 5 consumes P(5)=14.71 W and Q(5)=10.15 var.

Figure 82b. shows the power for voltage at feeder head 230 V. From the graph can be seen that the voltage decreases along the feeder by 0.06 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=15.34 W and Q(1)=11.5 var, while lamp 5 consumes P(5)=15.33 W and Q(5)=11.49 var.

Figure 82c. . shows the power for voltage at feeder head 250 V. From the graph can be seen that the voltage decreases along the feeder by 0.06 %. Therefore, because of the static load characteristic, lamps consummation on the feeder are slightly different. Lamp 1 consumes P(1)=16.4 W and Q(1)=13.72 var, while lamp 5 consumes P(5)=16.4W and Q(5) =13.71 var

As conclusion with the increasing of the voltage on the beginning of the feeder the active power consummation increases by about 11.4 % while reactive power consummation increases by about 35 %.

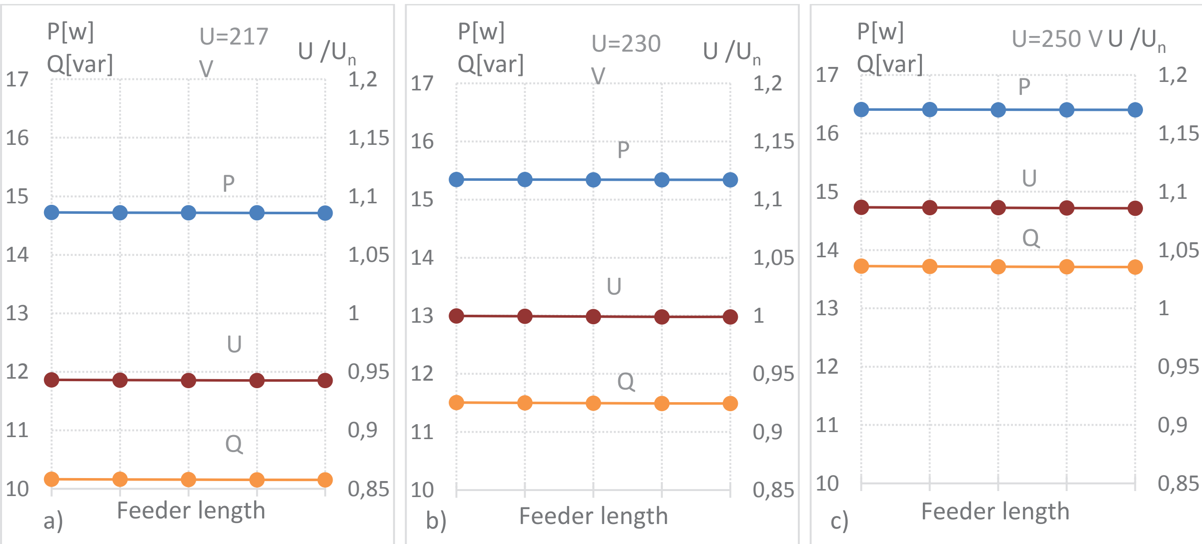

Figure 82. Active power, reactive power and voltage as a function of feeder length for BRS419 for different feeder head voltages: a) 20 7V; b) 230 V; c)250 V

Figure 83. shows voltage profil for different voltage values on feeder head. Results show that with the increasing of the voltage on feeder head, voltage drop in feeder increases.

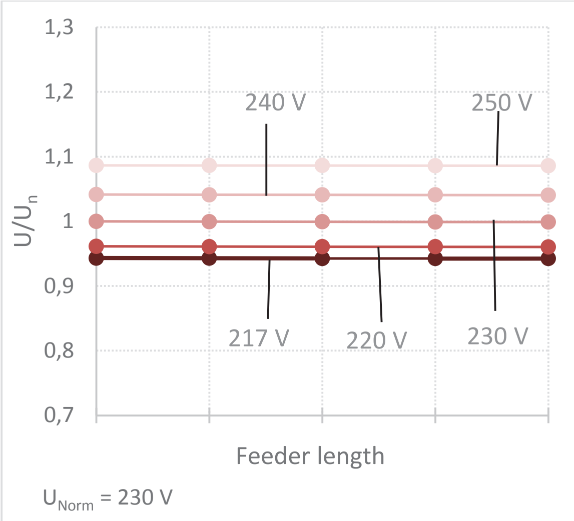

Figure 83. Voltage profiles for different voltage values on feeder head

Figure 84. shows the relationship between power demand and feeder length for different voltage values on feeder head. Figure 84a. shows the active power as a function of feeder length. Figure 84b. shows the reactive power as a function of feeder length. Change in voltage impacts the reactive power more than active power. As conclusion the following results can be seen:

$$\Delta P^{250\,V} = P_1^{250\,V} - P_5^{250\,V} = 0.006\ W \qquad \Delta Q^{250\,V} = Q_1^{250\,V} - Q_5^{250\,V} = 0.016\ var$$

$$\Delta P^{207\,V} = P_1^{207\,V} - P_5^{207\,V} = 0.007\ W \qquad \Delta Q^{207\,V} = Q_1^{207\,V} - Q_5^{207\,V} = 0.014\ var$$

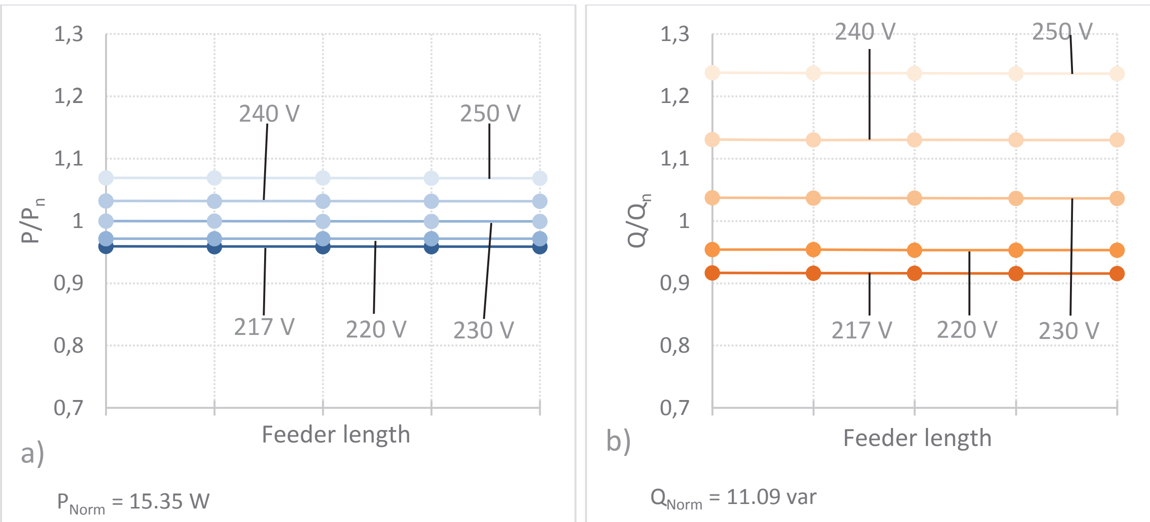

Figure 84. The relationship between power demand and feeder length for 217V to 250V: a) Active power; b) Reactive power

Figure 85. shows the comparison between the static load behavior of BRS419 lamp and the lumped load at feeder begin. Figure 85a. shows the static load characteristic for active power. The coefficients of ZIP model for active power are as following:

For one lamp: $K_2^P = 0.53;\ K_1^P = -0.33\ ;\ K_0^P = 0.79$

For the lumped load: $K_2^P = 0.14\,;\ K_1^P = 0.7\,;\ K_0^P = 0.15$

Figure 85b. shows the static load characteristic for reactive power.The coefficients of ZIP model for reactive power are as following:

For one lamp: $K_2^Q = 0.55\,;\ K_1^Q = 1.03\,;\ K_0^Q = -0.53$

For the lumped load: $K_2^Q = -0.21\,;\ K_1^Q = 1{,}42\,;\ K_0^Q = -0.21$

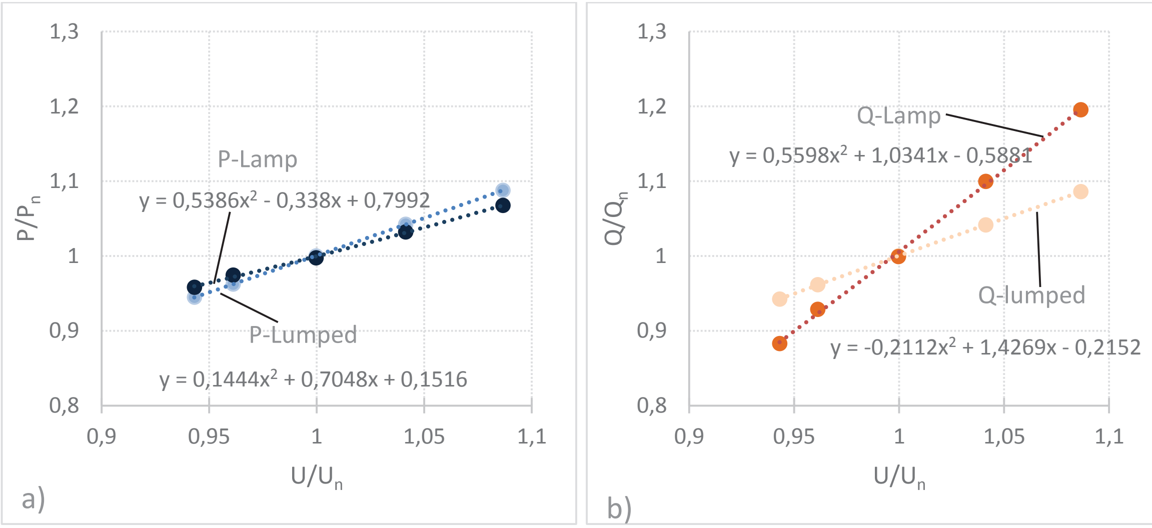

Figure 85. The comparison between the static load behavior of BRS419 and the lumped load at the feeder begin; a) Active power; b) Reactive power

Based on criteria as defined on the lamps have a mostly constant power the lamps but the lumped load behaves more as a constant current load.

5. Conclusion

Despite the capacitive ballast for almost all lamps (excluding LED BRS419 1Xmodule 24Xlight source) is measured a small *cosρ*.

Old fluorescent and high pressure sodium lamps show a smaller THD and *cosρ* than the new ones on nominal value.

LED lamps show a higher *cosρ* than fluorescent and high pressure sodium lamps.

Two sample measurements in almost 0 ° C have shown that both TDH and *cosρ* increases slightly at lower temperatures.

Fluorescent lamps have almost a mostly constant current behavior.

Discharge lamps have almost a mostly constant current behavior.

LED lamps have almost a mostly constant power behavior.

Active power consumption of LED lamps is less sensitive on voltage change than fluorescent and discharge lamps. While the reactive power consumption for discharge lamps is less on voltage change than fluorescent and LED.

Energy consumption of lightning feeders increases with the increasing of supplying voltage at the beginning of the feeder independent from the lamp type.

For lightning feeders with fluorescent and LED lamps, the *cosρ* of lumped load will decrease with the increasing of the supplied voltage (at feeder begin). While for the discharge ones the *cosρ* will increase.

6. References

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7. Appendix

This chapter contains detailed measurement results for all types and is in a separate document

8. List of figures

9. List of tables

TECHNISCHE UNIVERSITÄT WIEN

ESEA Institut für Energiesysteme und Elektrische Antriebe

Investigation of street lighting feeders

Appendix

Elmira Torabi Makhsos, BSc

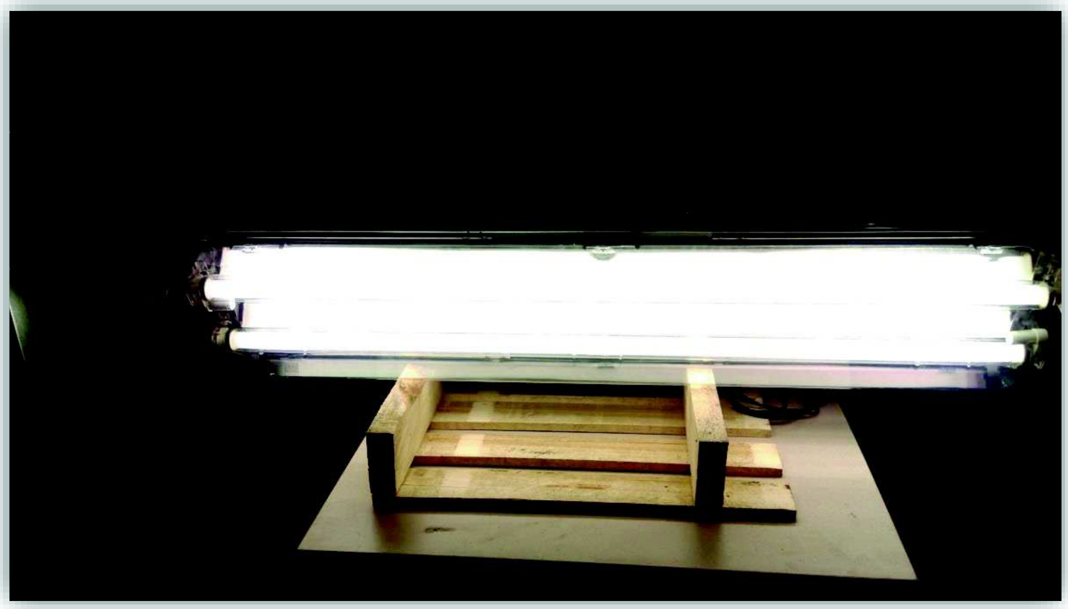
30.05.2016, Vienna

Content

Technische Universität Wien
Institut für Energiesysteme und Elektrische Antriebe
Gußhausstraße 25/370-1
A - 1040 Wien

MEASUREMENT PROTOCOL 1

Conventional lamps
2XLight source: NARVA
Ballast: AUSTRIA EMAIL



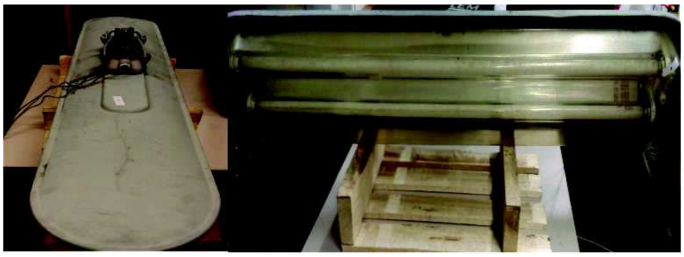
Vienna 12.January 2016

1. Content

2. List of figures

3. Light type

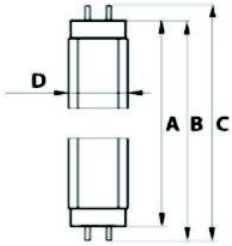
Conventional lamps
2 X NARVA fluorescent lamp
NARVA starter: BSt65
Status: old



4. Technical data

NARVA Fluorescent Lamp: LT - T8/T12 36 W COLOURLUX plus ET.XL
Voltage: 220-240 V
Real power : 36

Size A (max., mm)	1.199,4
Size B (min., mm)	1.204,1
Size B (max., mm)	1.206,5
Size C (max., mm)	1.213,6
Size D (max., mm)	38,0



NARVA starter: BSt65
Voltage: 220 V – 240 V
Power: 4 W – 65.80 W

AUSTRIA EMAIL ballast
Voltage: 220 V
Frequency: 50 Hz
current: 0.43 A
Cos ρ: 0.5

5. Measurement

5.1. Schema

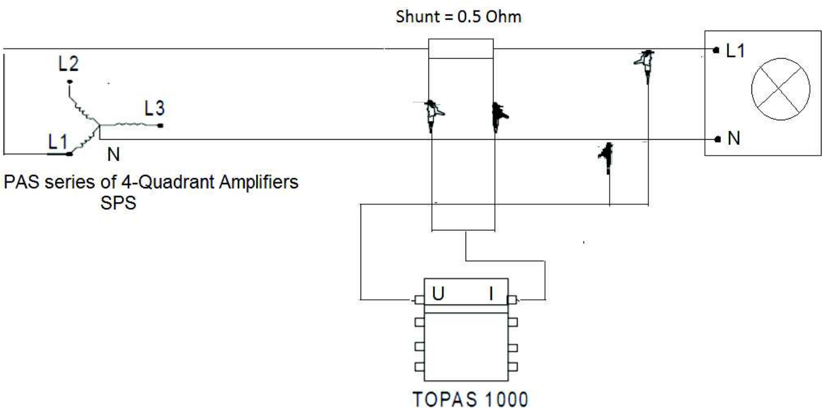


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside **Temperature**: 21.4^{0}C
Voltage range: 190-250 V **Shunt:** 0.5 Ω
Measurement interval: 15 min

The Lamp is pended horizontal in the measurement place. The High of crane is 150 cm. The Lamp is meusured after 15 minutes stability.

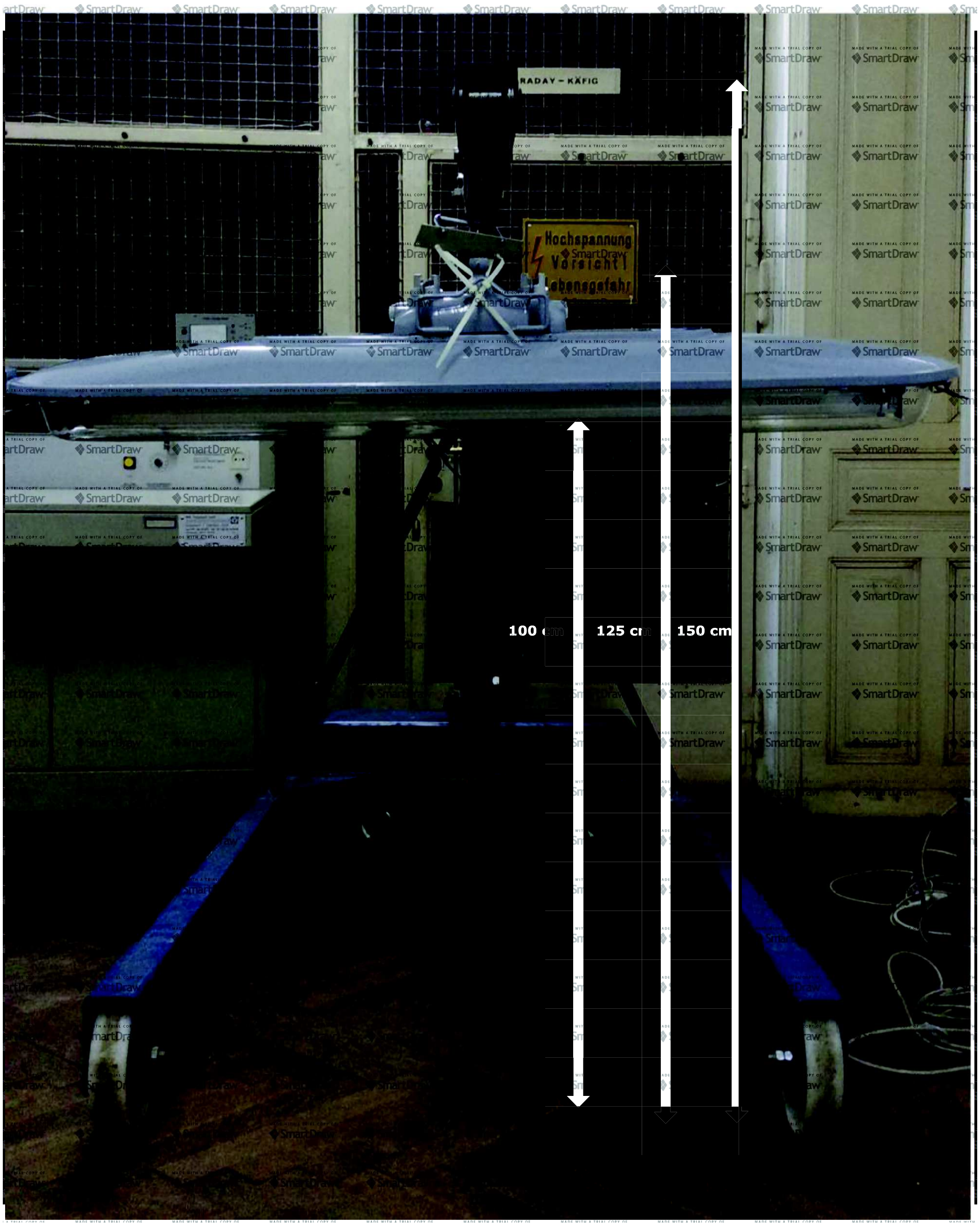


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 230.12 V
Current: I = 1.24 A
Active Power = 89.56 W
Reactive Power = 272.79 var
Apparent Power = 287.32 VA
Power Factor = 0.31

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

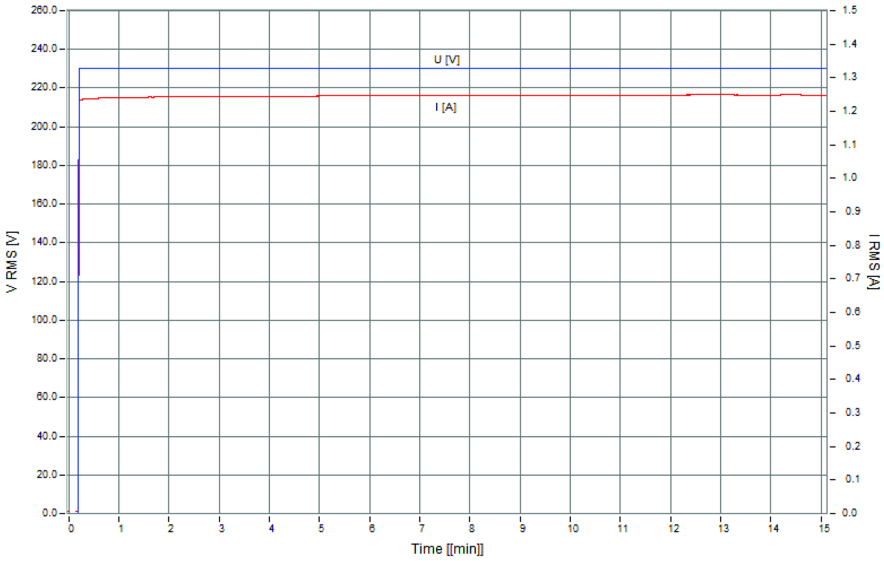


Figure 3. Root Mean Square of voltage and current - 230 V

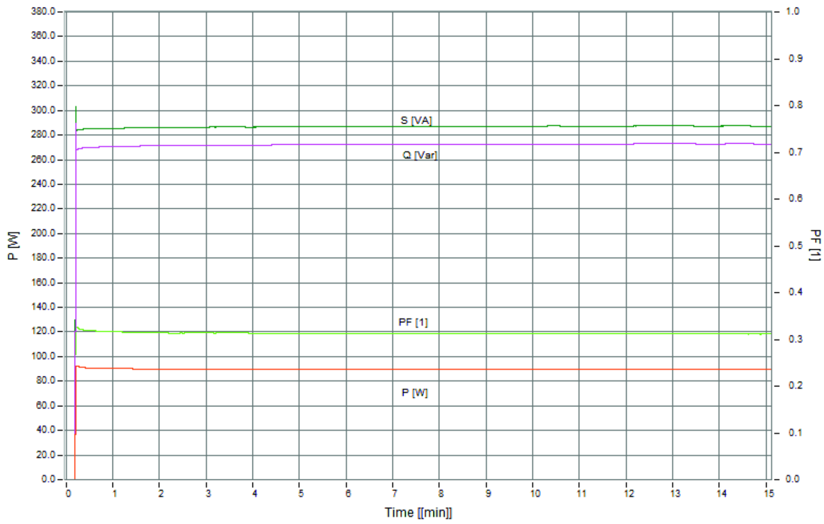


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 230.15	[V]	*****	0.00^0
I L1 = 1.24	[A]	*****	71.70

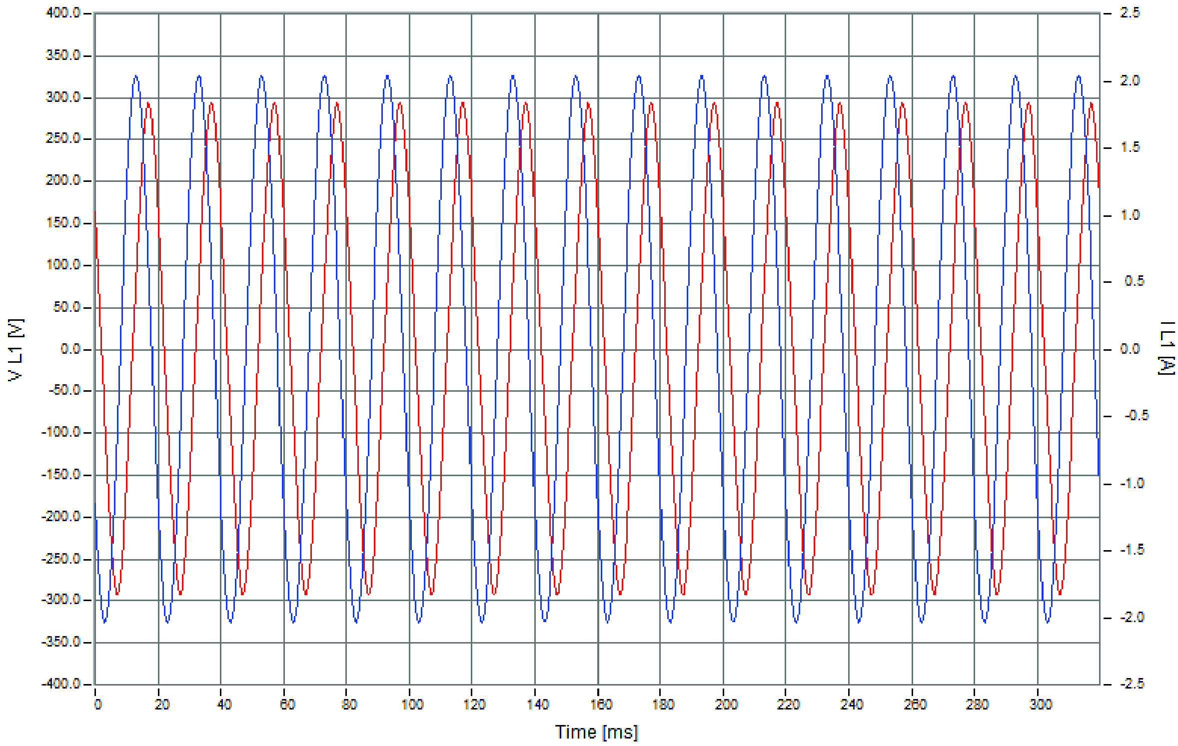


Figure 5. Current and voltage signal curve - 230 V

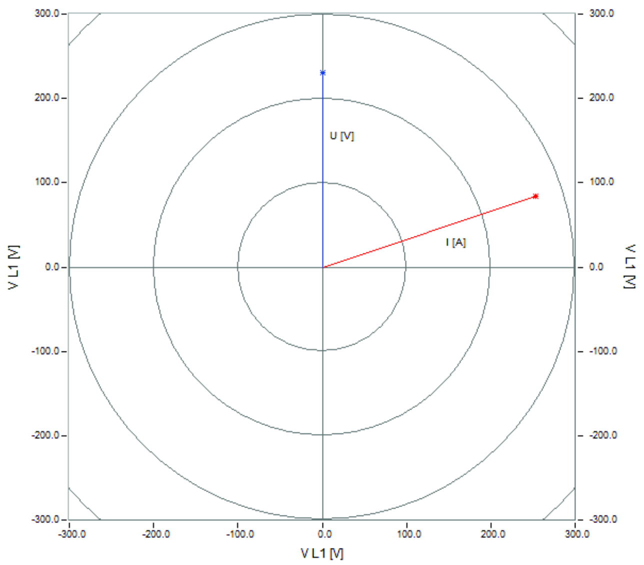


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

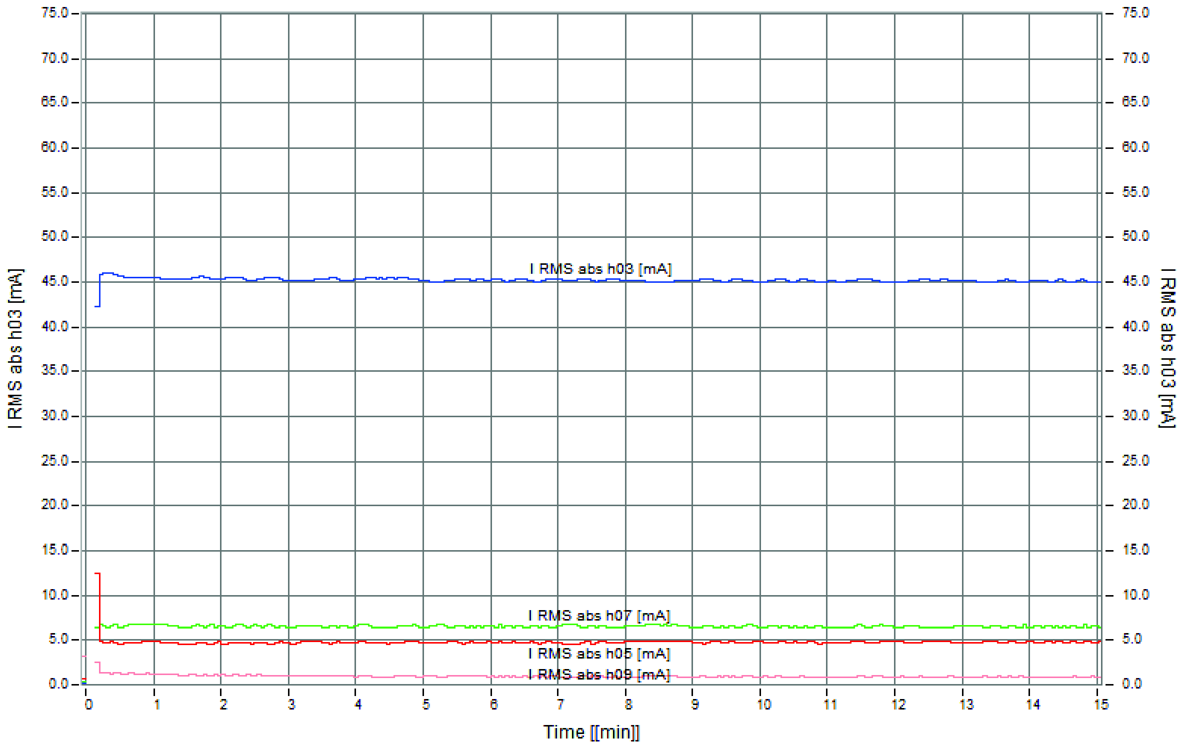


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

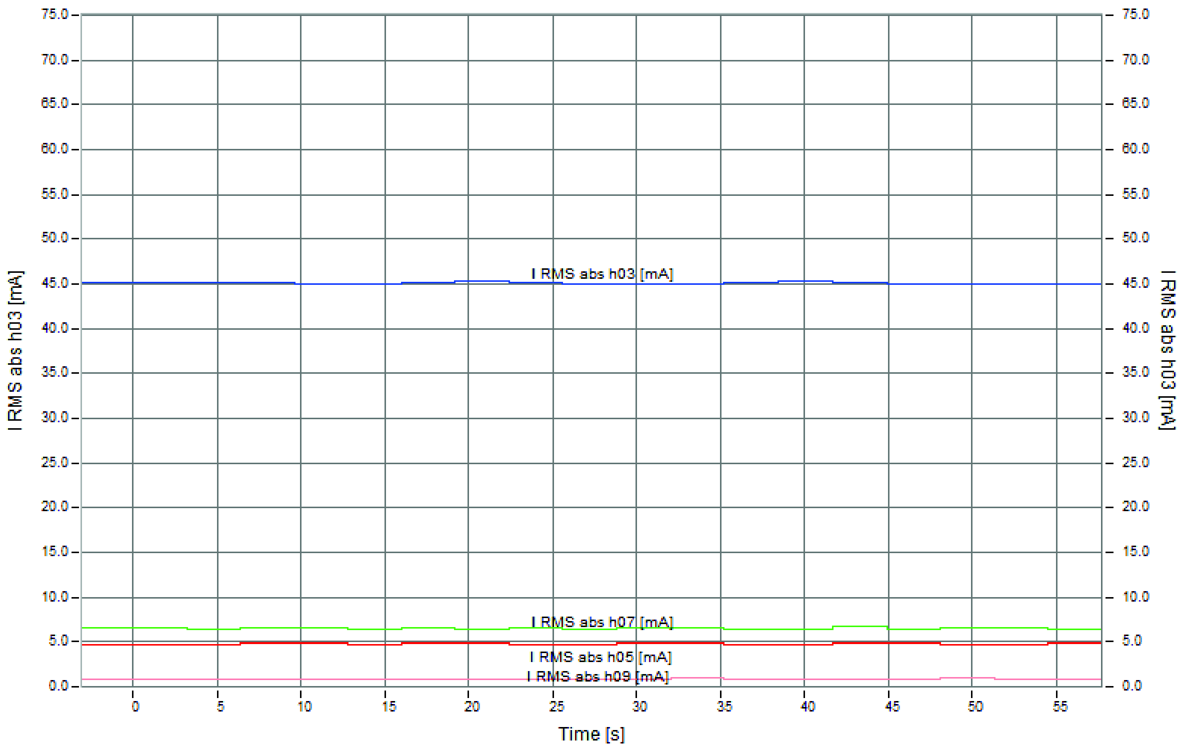


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

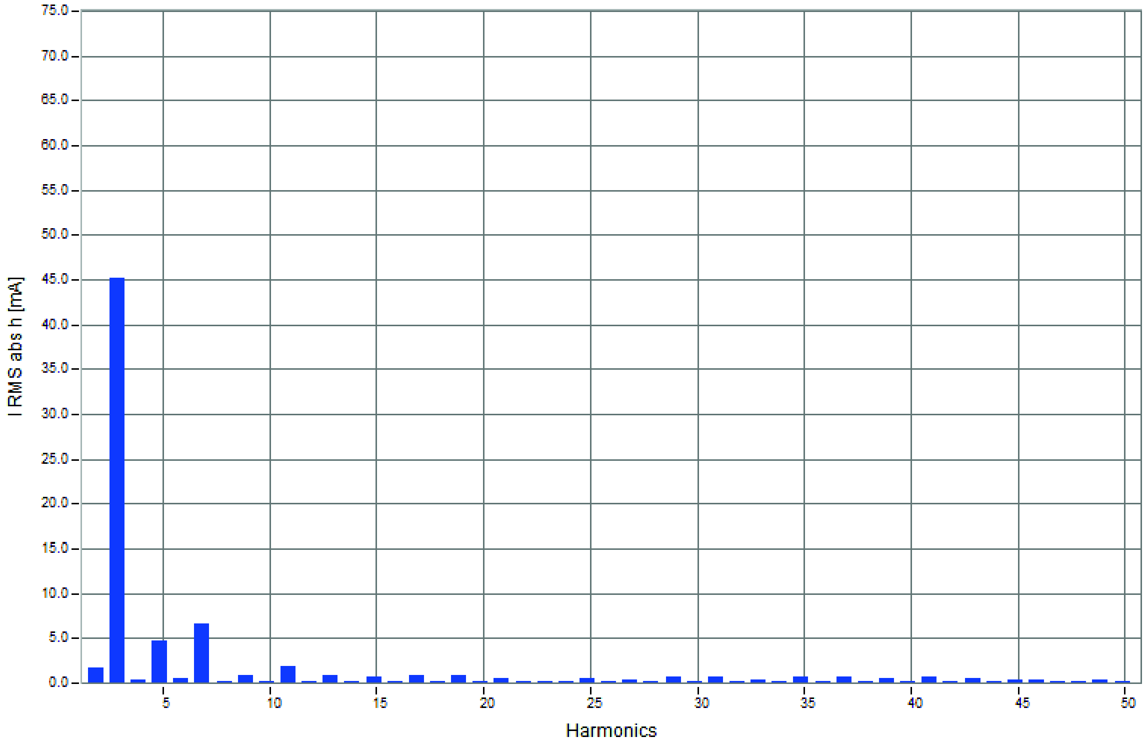


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.68\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.68\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 190.02 V
Current: I = 0.95 A
Active Power = 63.75 W
Reactive Power = 169.46 var
Apparent Power = 181.19 VA
Power Factor = 0.35

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

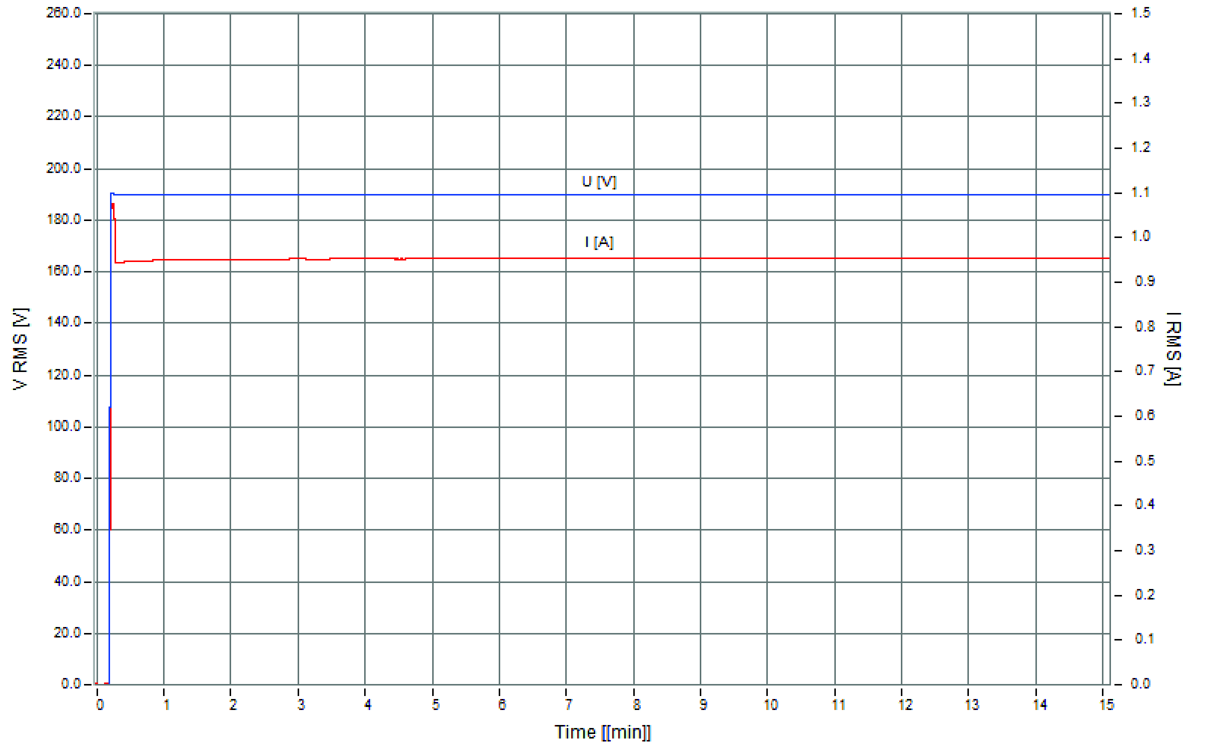


Figure 10. Root Mean Square of voltage and current - 190 V

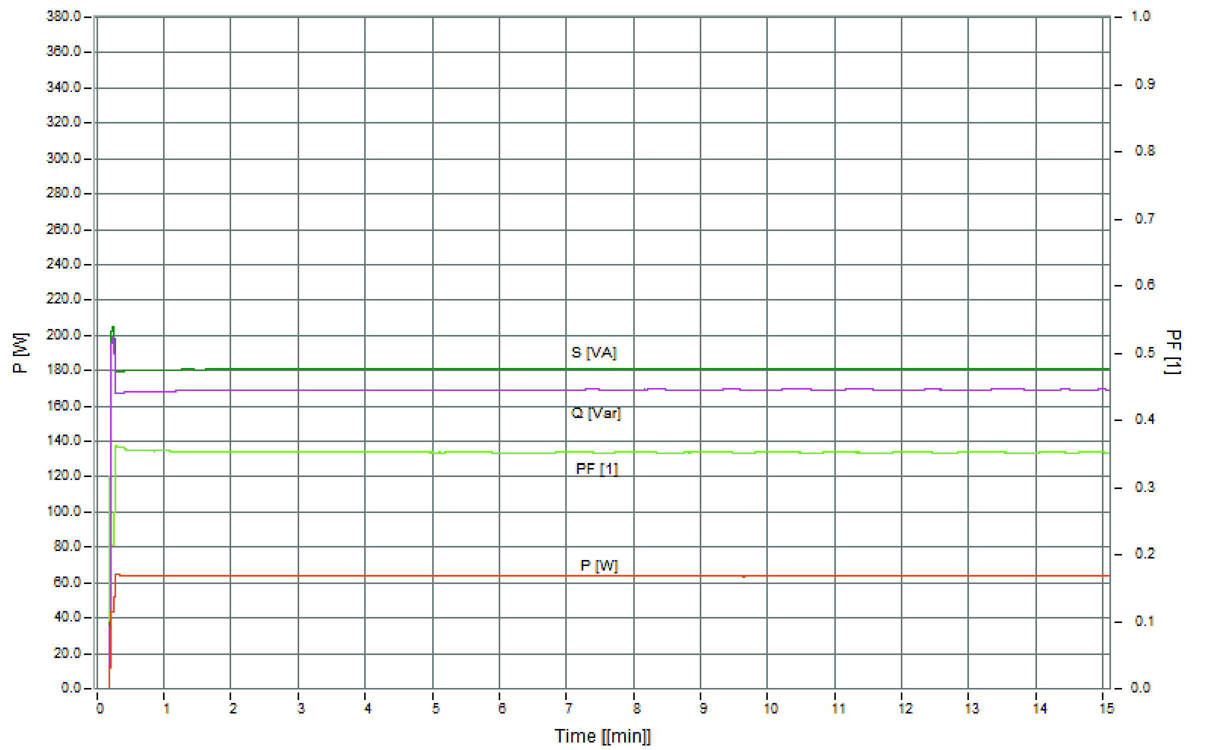


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 190.03	[V]	*****	0.00^0
I L1 = 0.95	[A]	*****	69.40^0

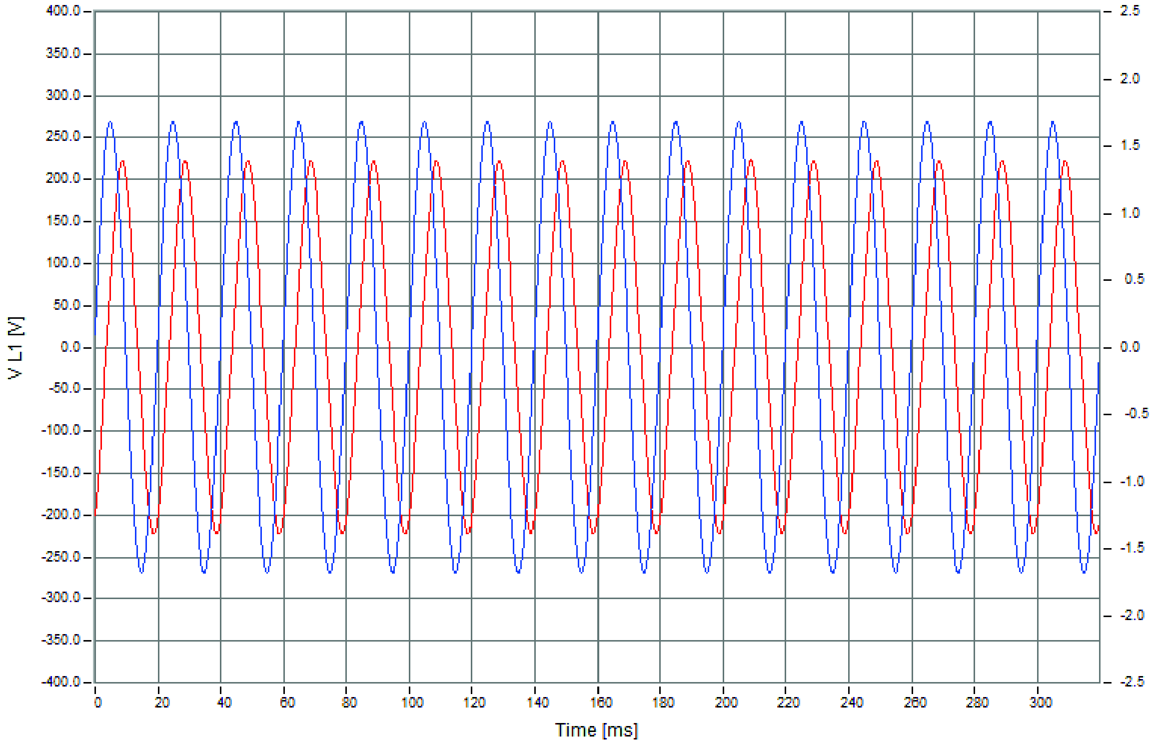


Figure 12. Current and voltage signal curve - 190 V

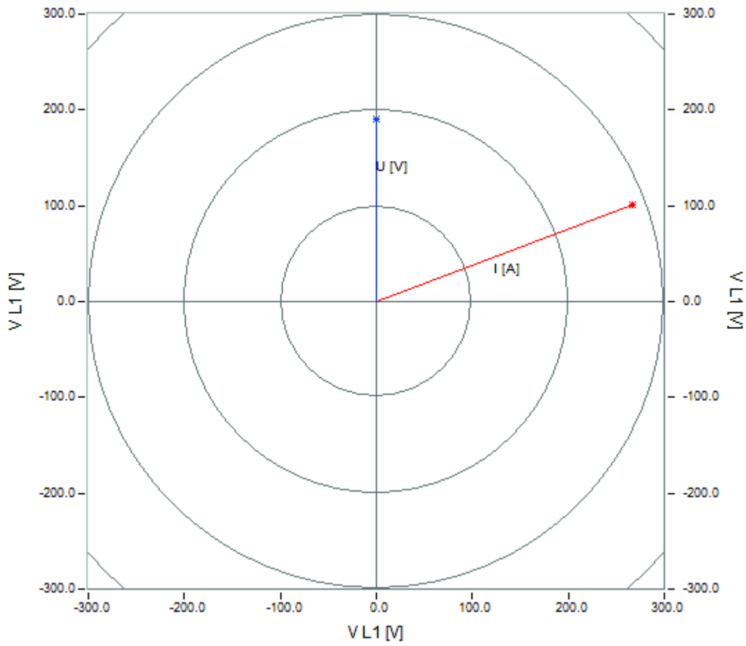


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

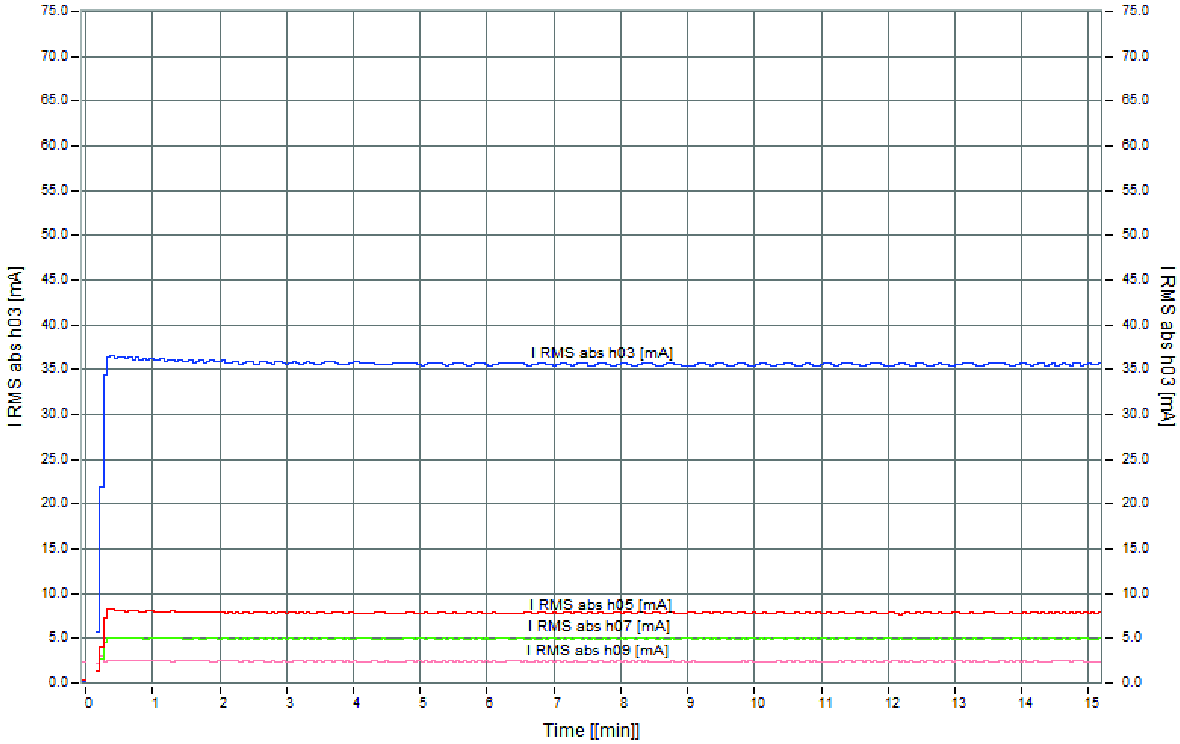


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

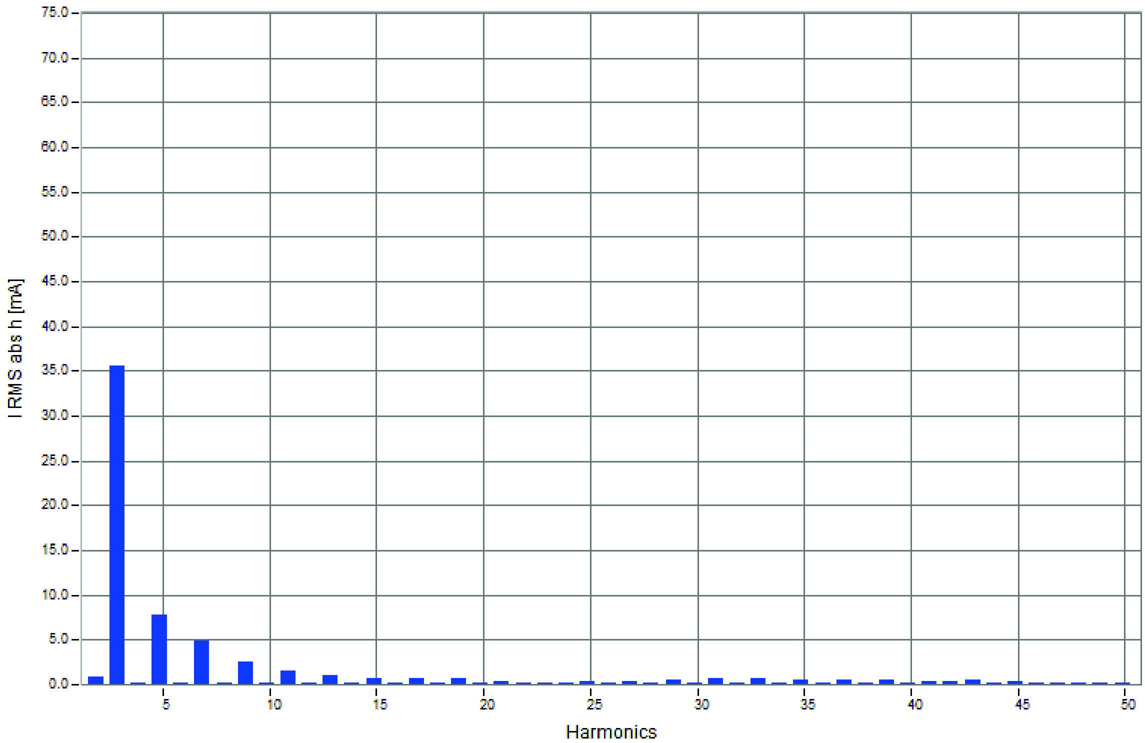


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.88\,\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.87\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 200.03 V
Current: I = 1.02 A
Active Power = 69.96 W
Reactive Power = 193.27 var
Apparent Power = 205.69 VA
Power Factor = 0.34

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

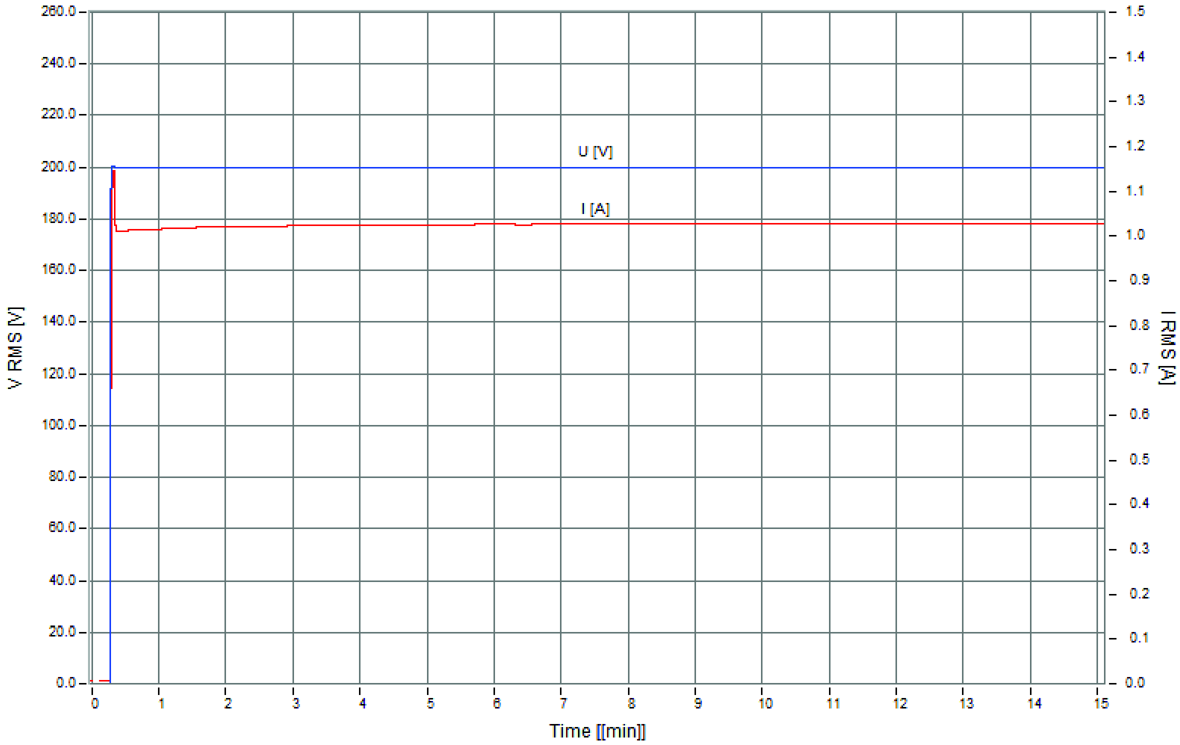


Figure 16. Root Mean Square of voltage and current - 200 V

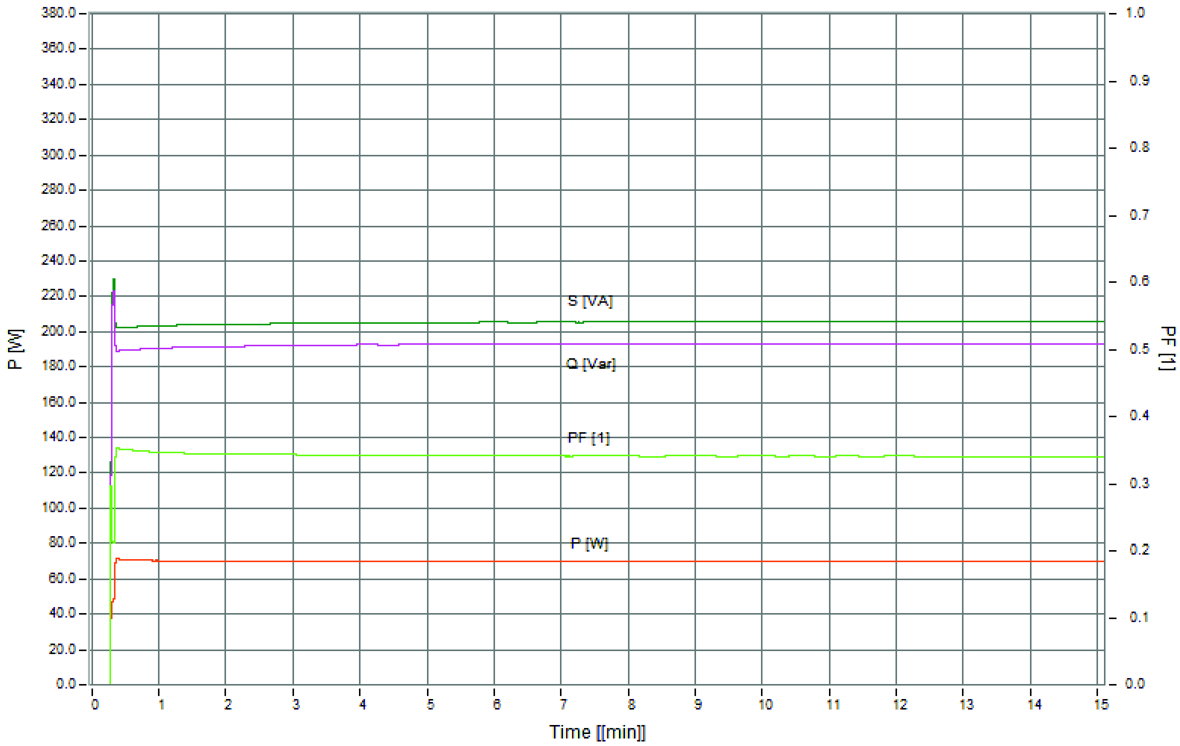


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 200.04 V	[V]	*****	0.00⁰
I L1 = 1.02 A	[A]	*****	69.92⁰

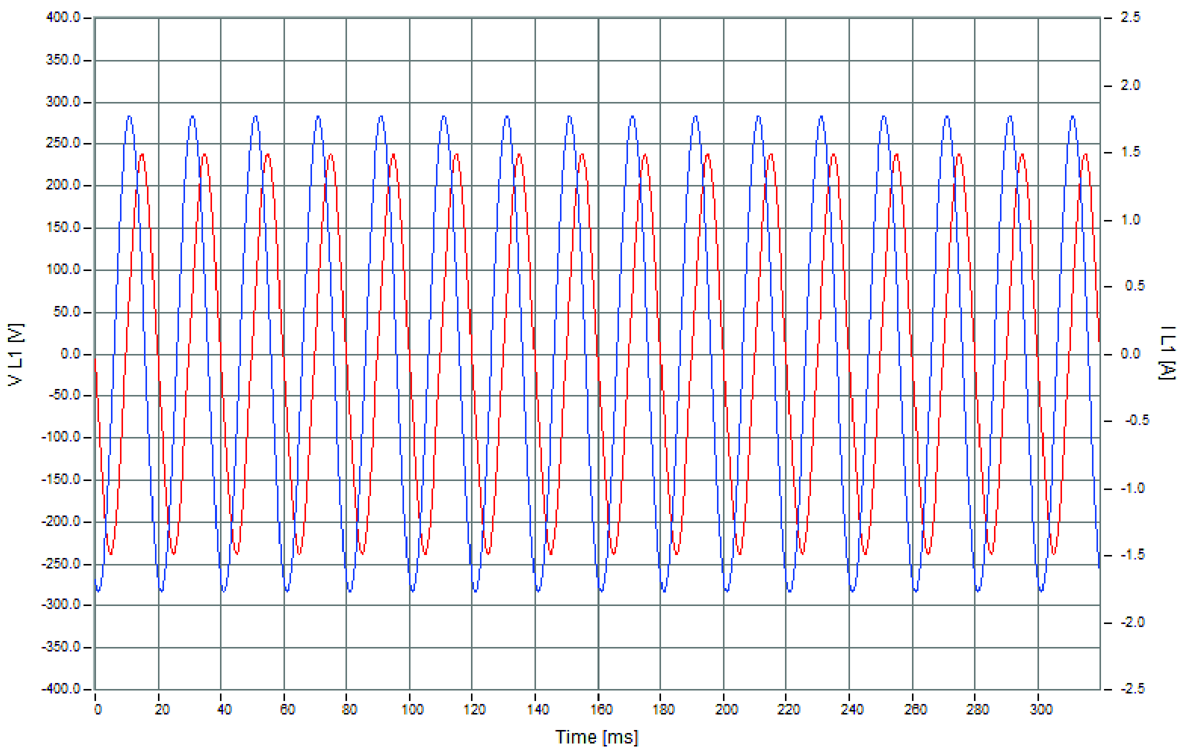


Figure 18. Current and voltage signal curve - 200 V

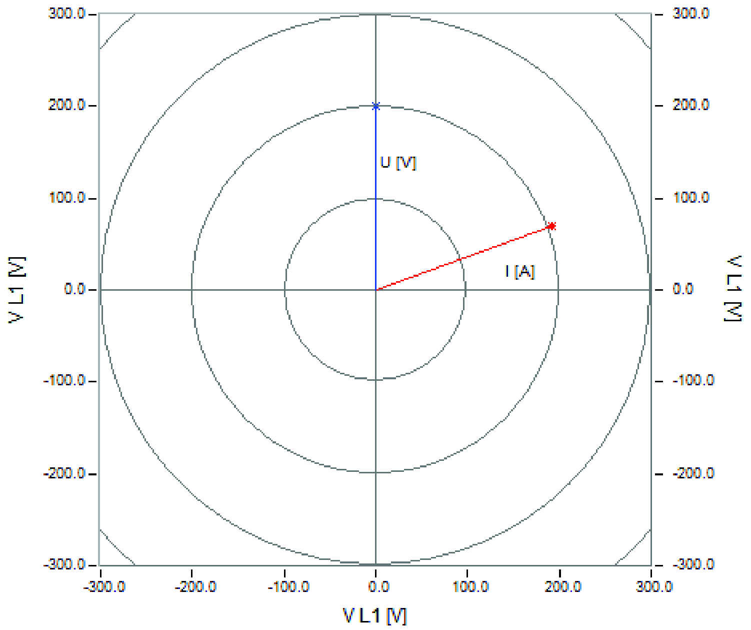


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

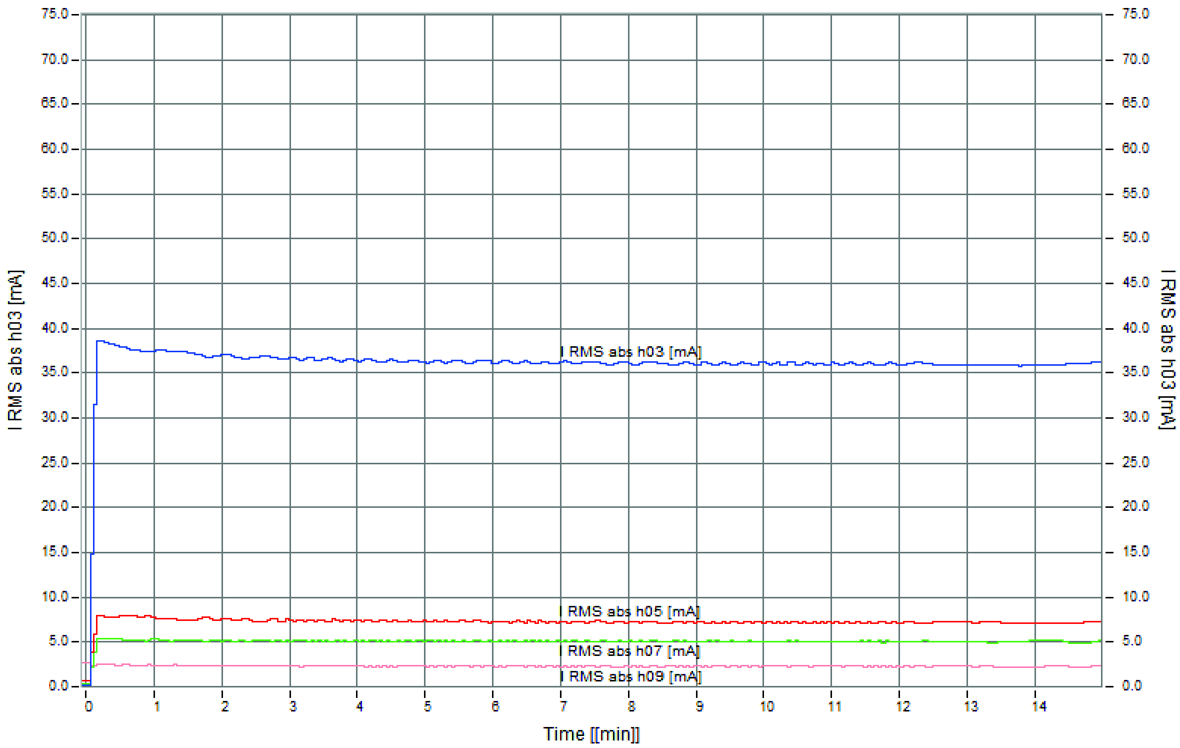


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

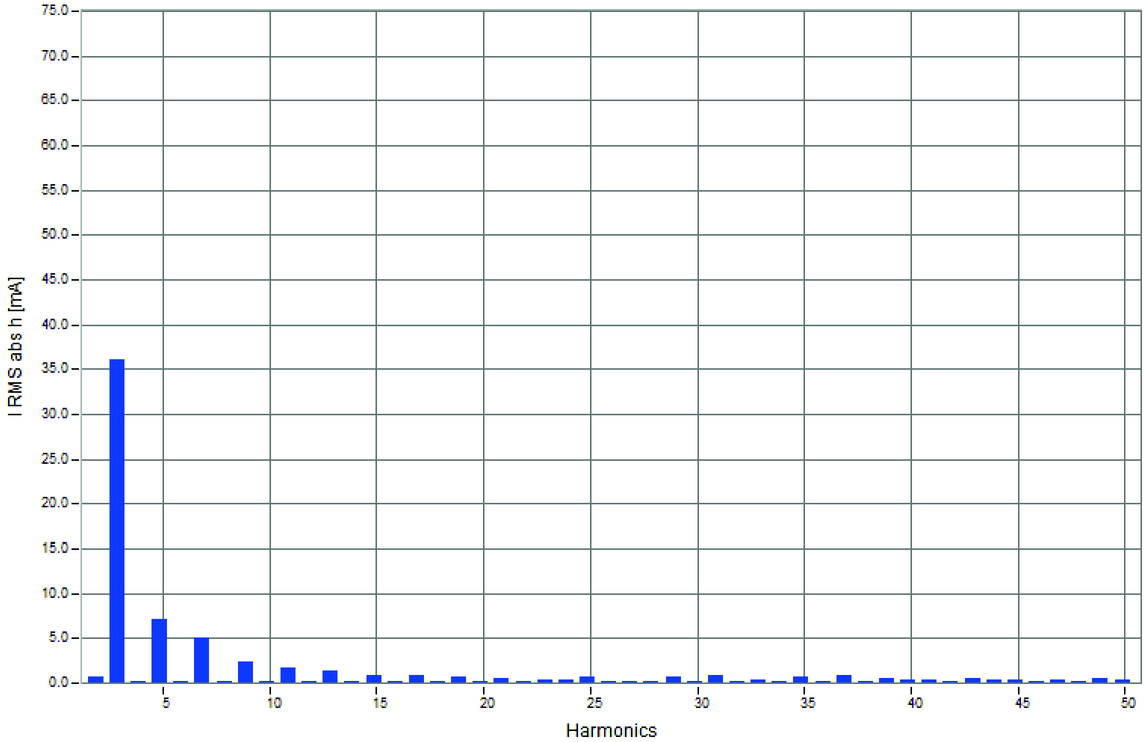


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.62\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.62\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:
Voltage: U = 210.05 V
Current: I = 1.1 A
Active Power = 76.21 W
Reactive Power = 218.35 var
Apparent Power = 231.41 VA
Power Factor = 0.32

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

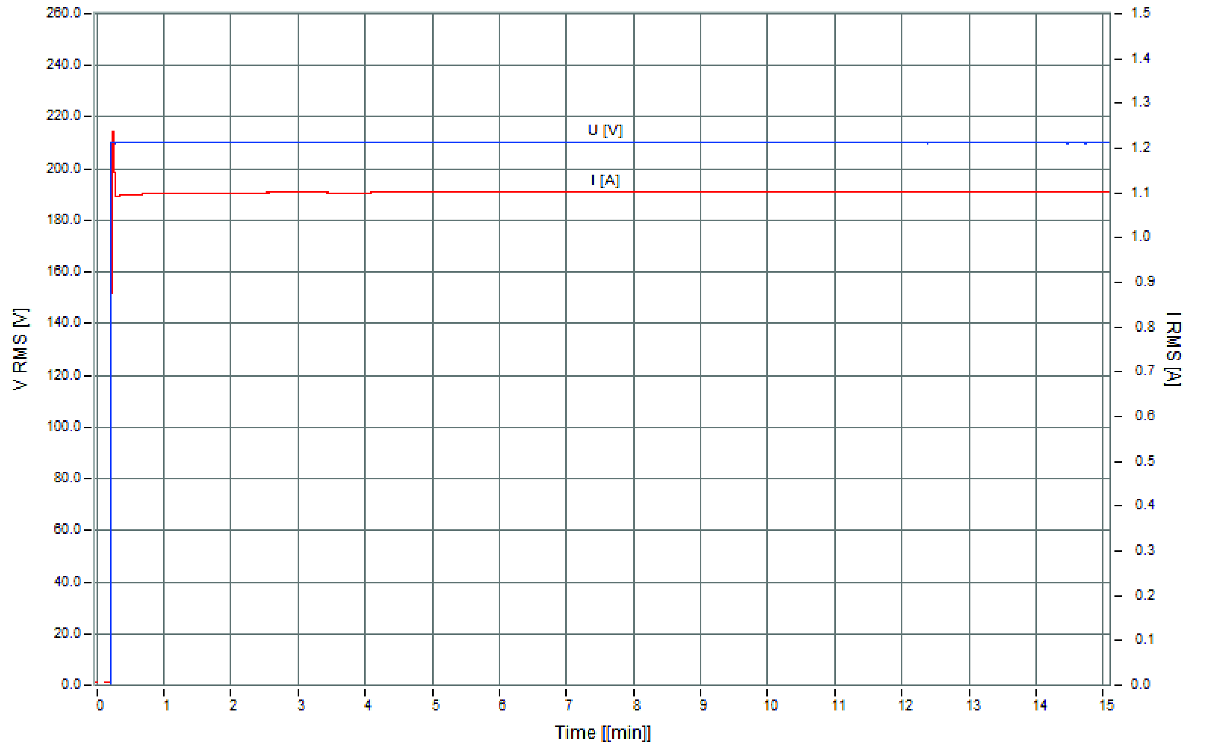


Figure 22. Root Mean Square of voltage and current - 210 V

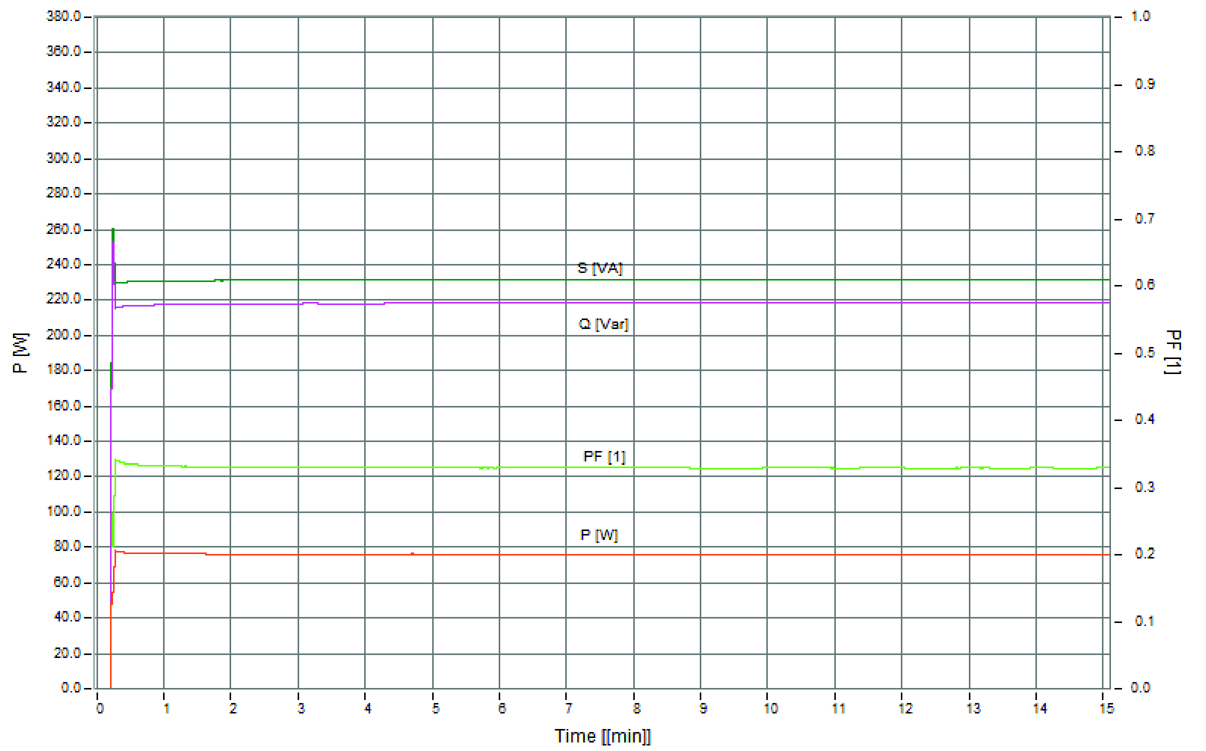


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 210.06 V	[V]	*****	0.00^0
I L1 = 1.1 A	[A]	*****	$70{,}79^0$

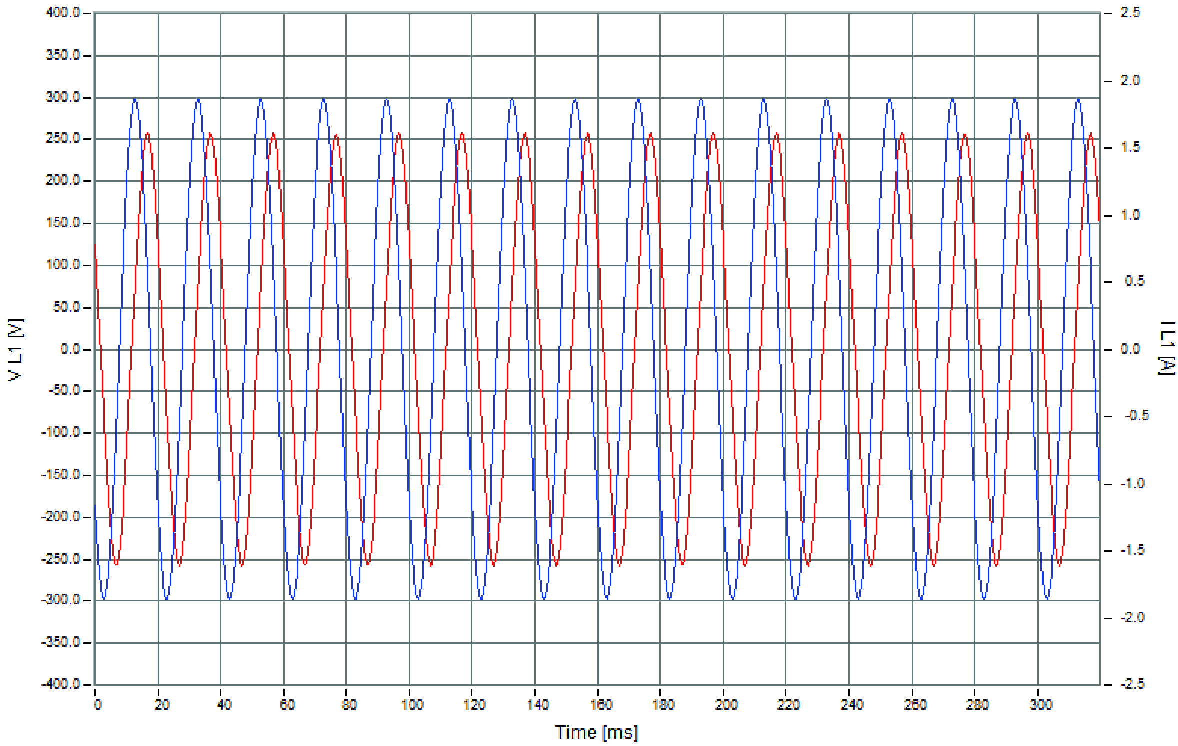


Figure 24. Current and voltage signal curve - 210 V

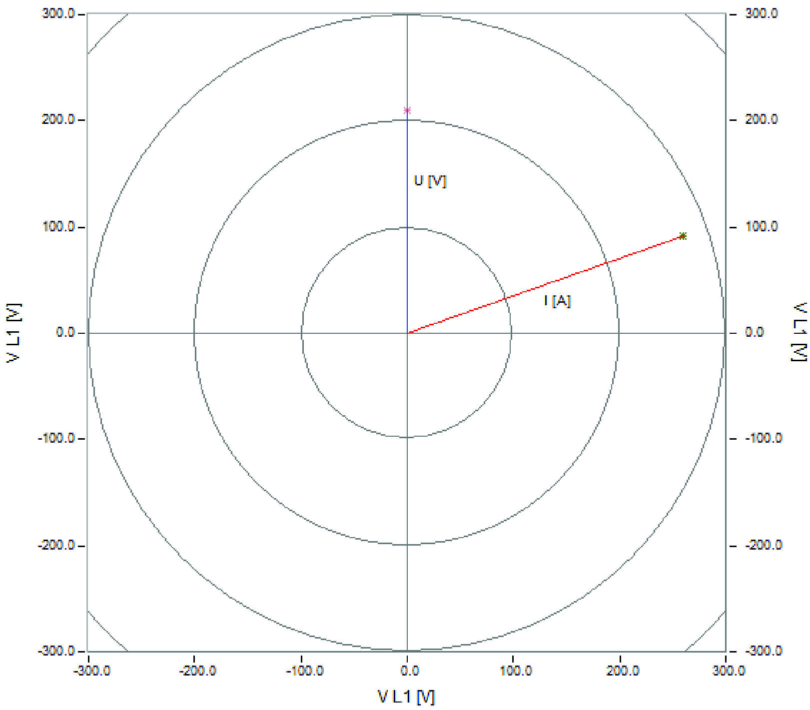


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

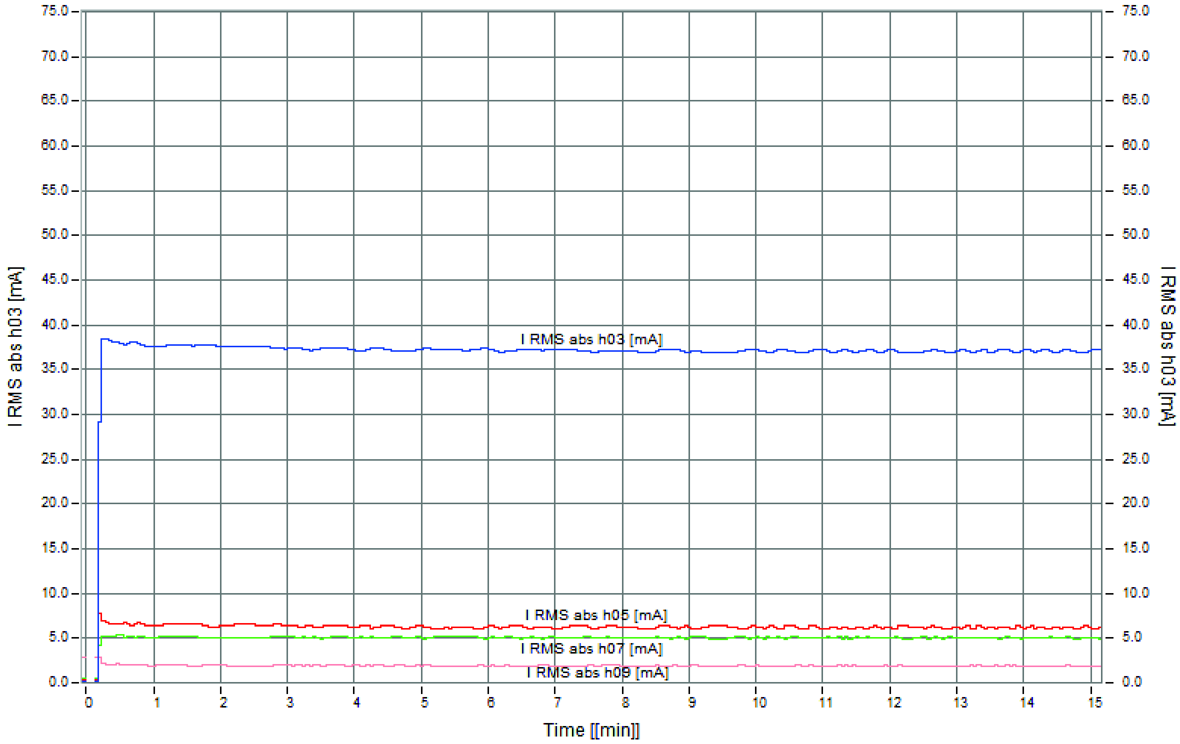


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

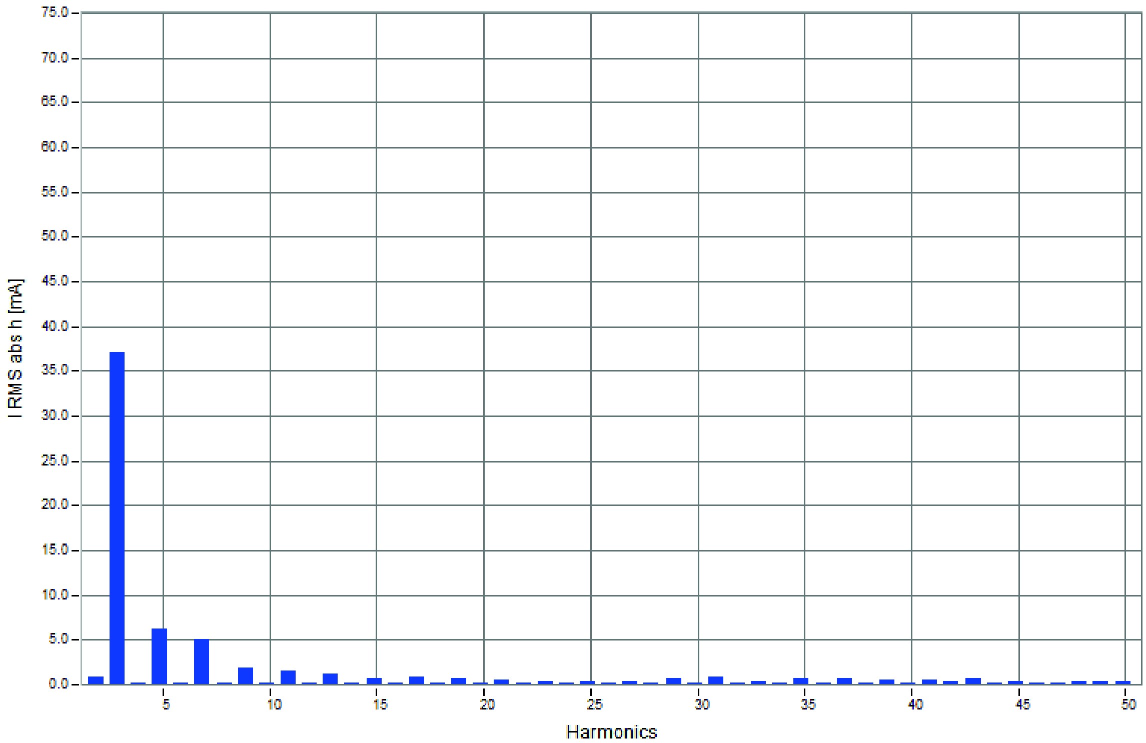


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.46\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.45\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 220.09 V

Current: I = 1.17A

Active Power = 82.73 W

Reactive Power = 244.76 var

Apparent Power = 258.52 VA

Power Factor = 0.32

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

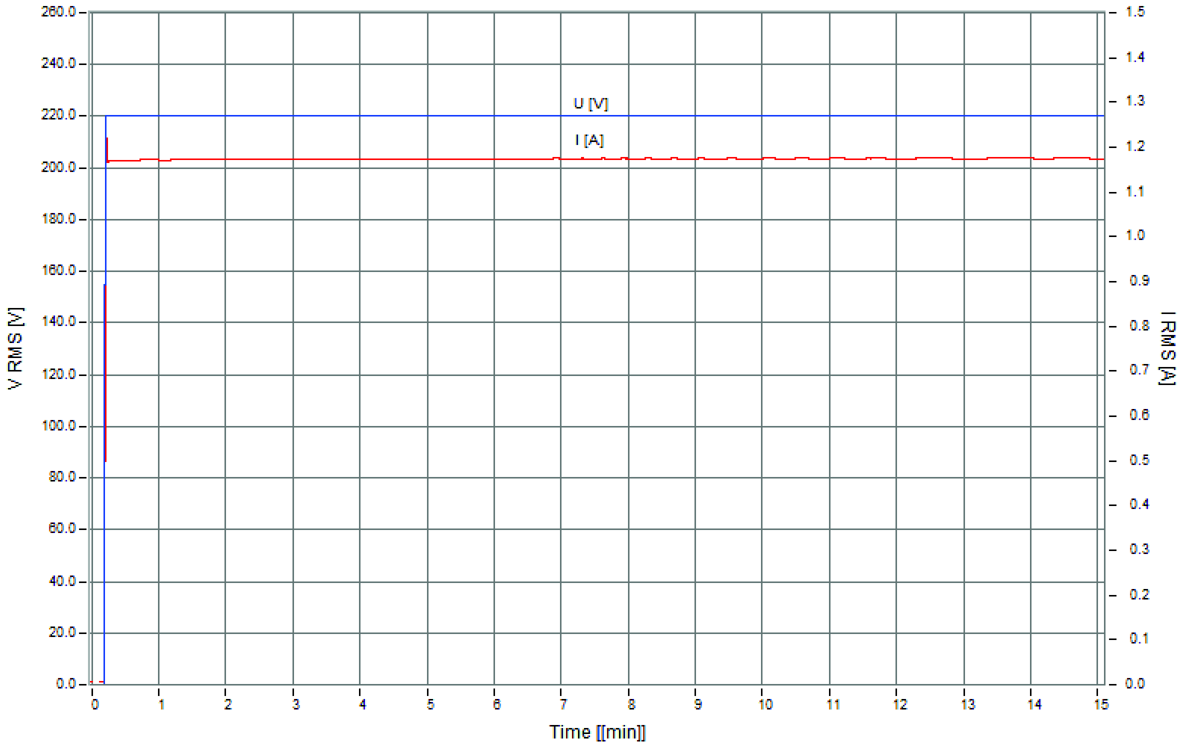


Figure 28. Root Mean Square of voltage and current - 220 V

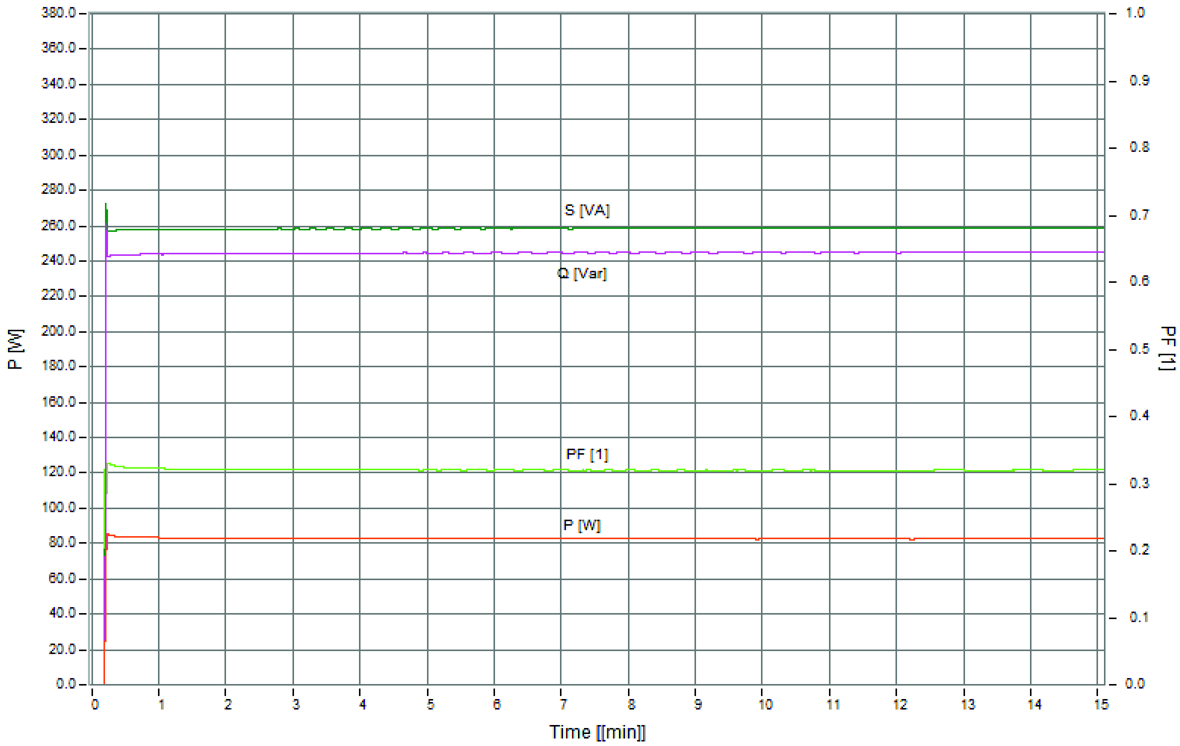


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 220.10 V	[V]	*****	0.00⁰
I L1 = 1.17 A	[A]	*****	71.25⁰

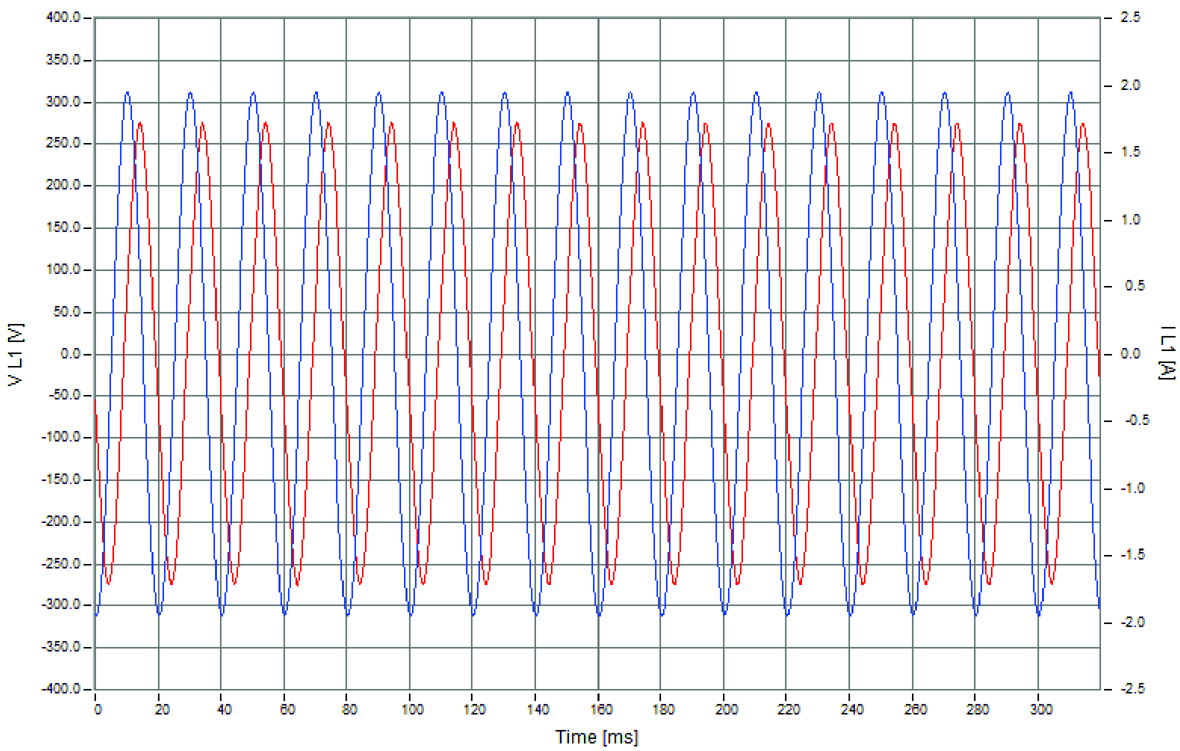


Figure 30. Current and voltage signal curve - 220 V

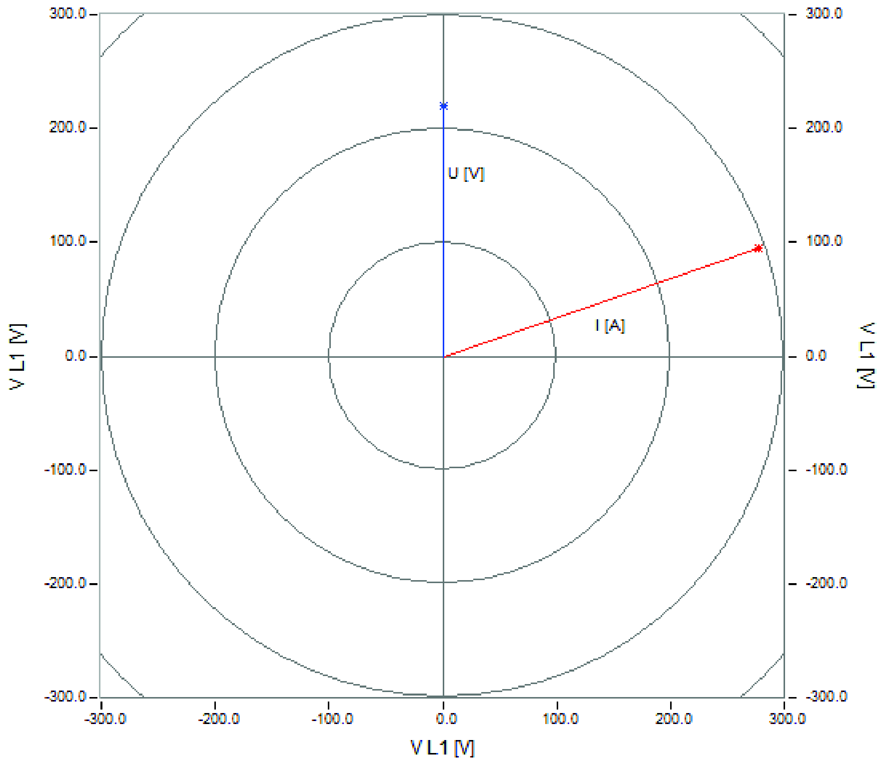


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

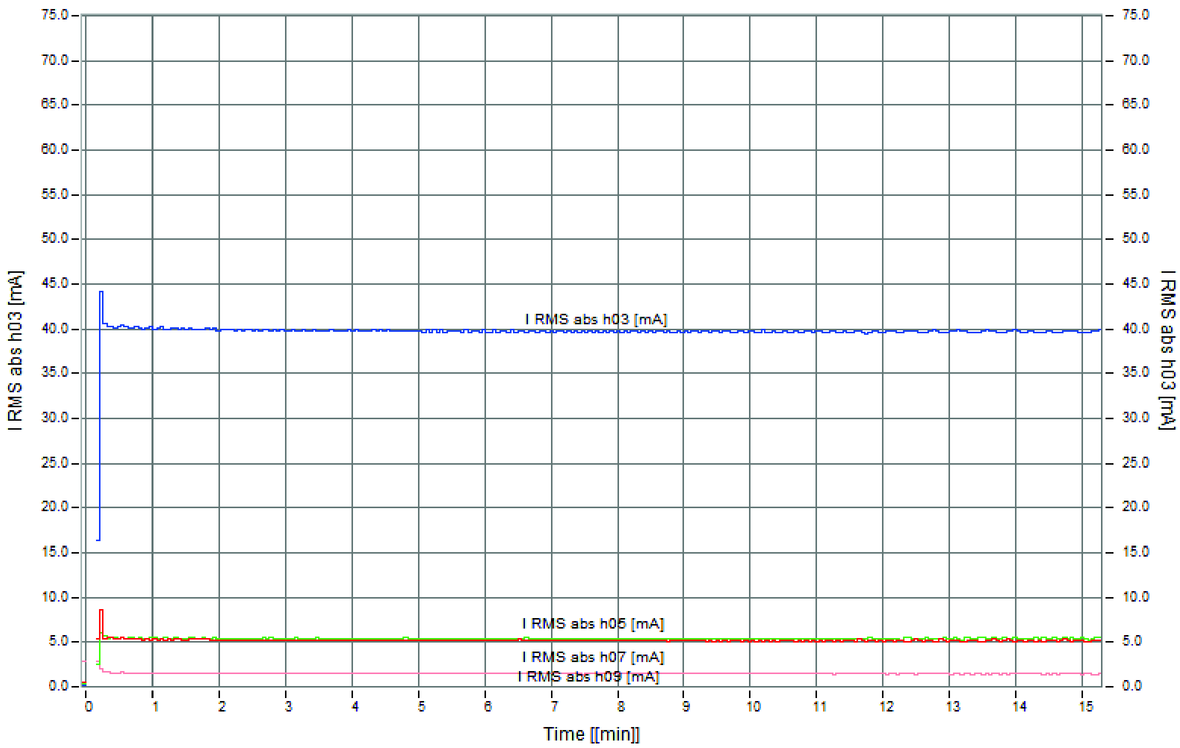


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

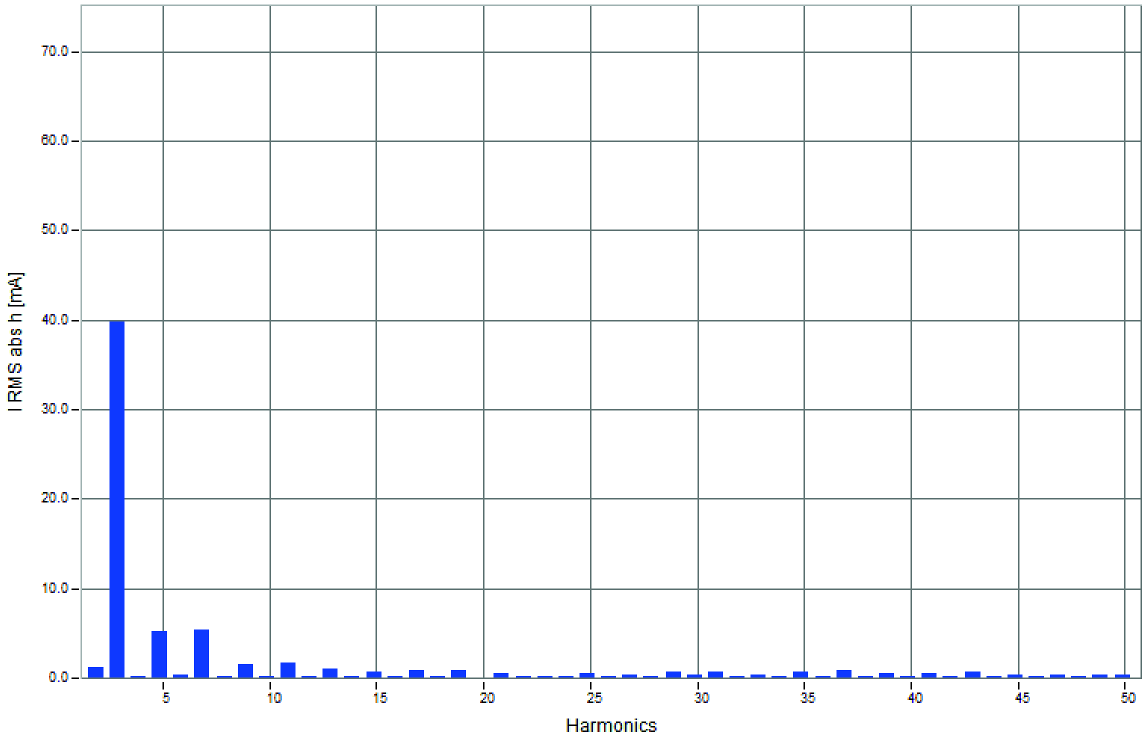


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.45\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.45\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 240.15 V
Current: I = 1.32 A
Active Power = 96.79 W
Reactive Power = 303.22 var
Apparent Power = 318.59 VA
Power Factor = 0.3

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

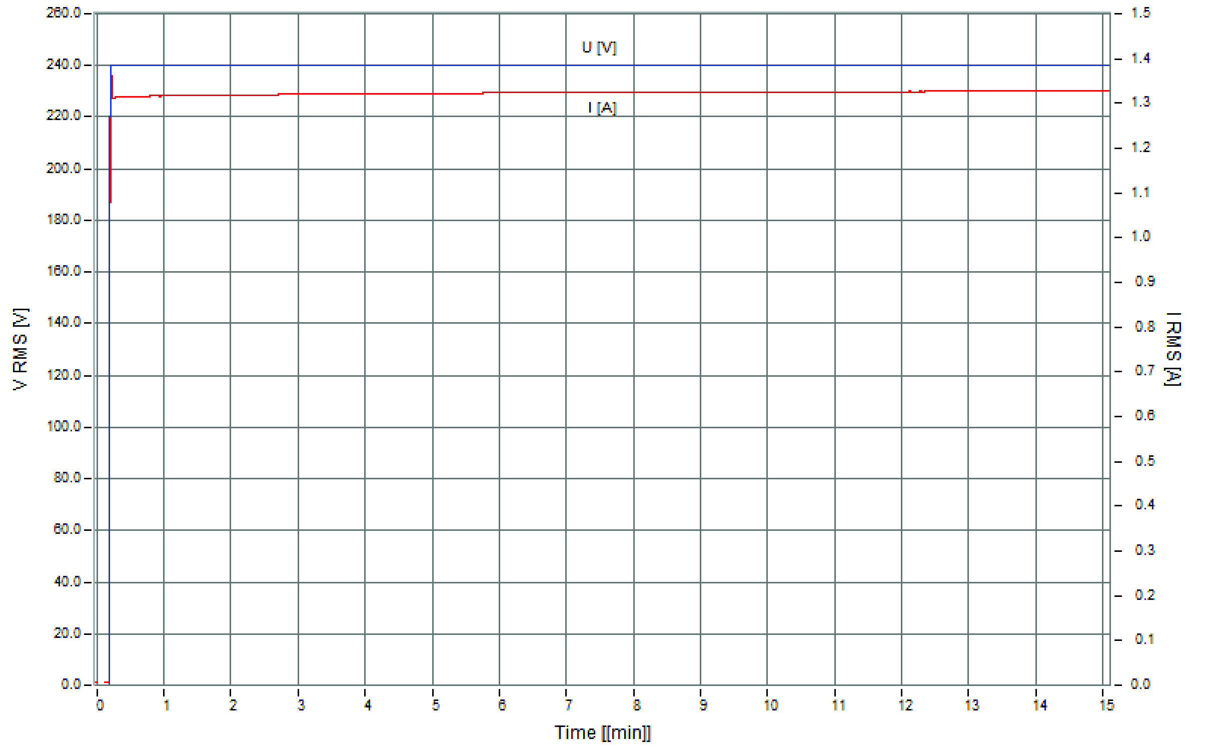


Figure 34. Root Mean Square of voltage and current - 240 V

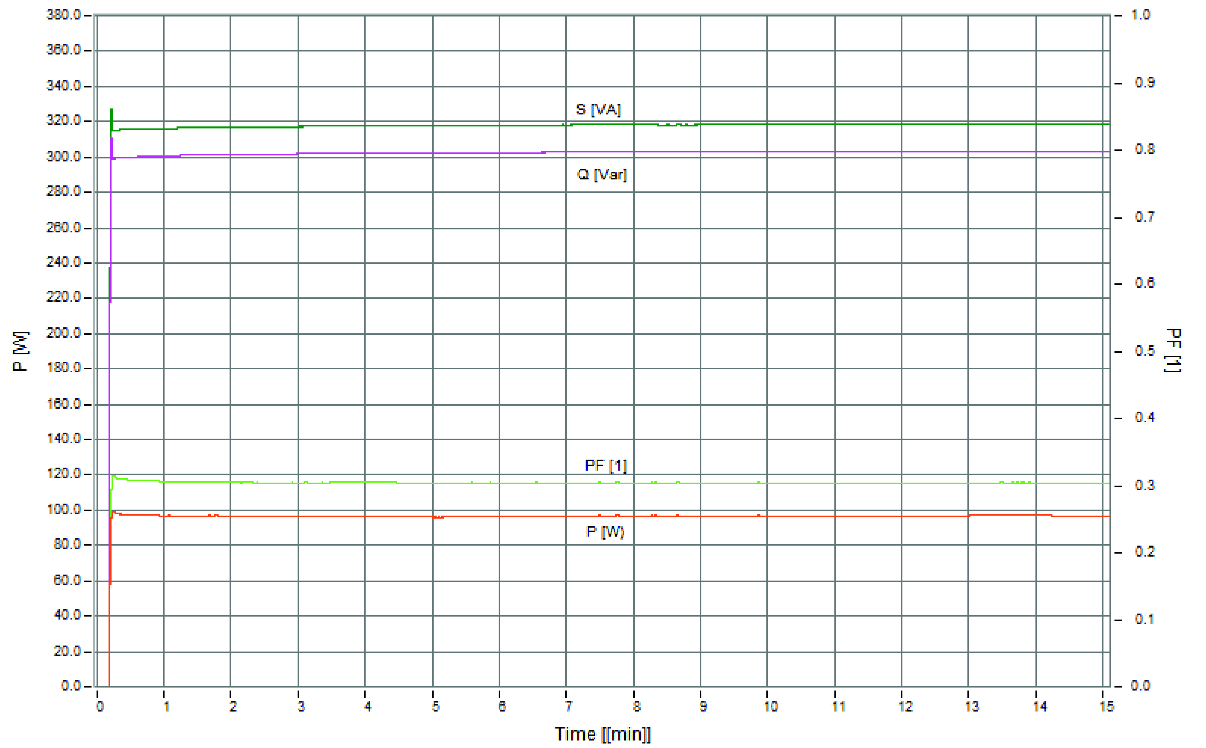


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 240.17	[V]	*****	0.00⁰
I L1 = 1.32	[A]	*****	72.32⁰

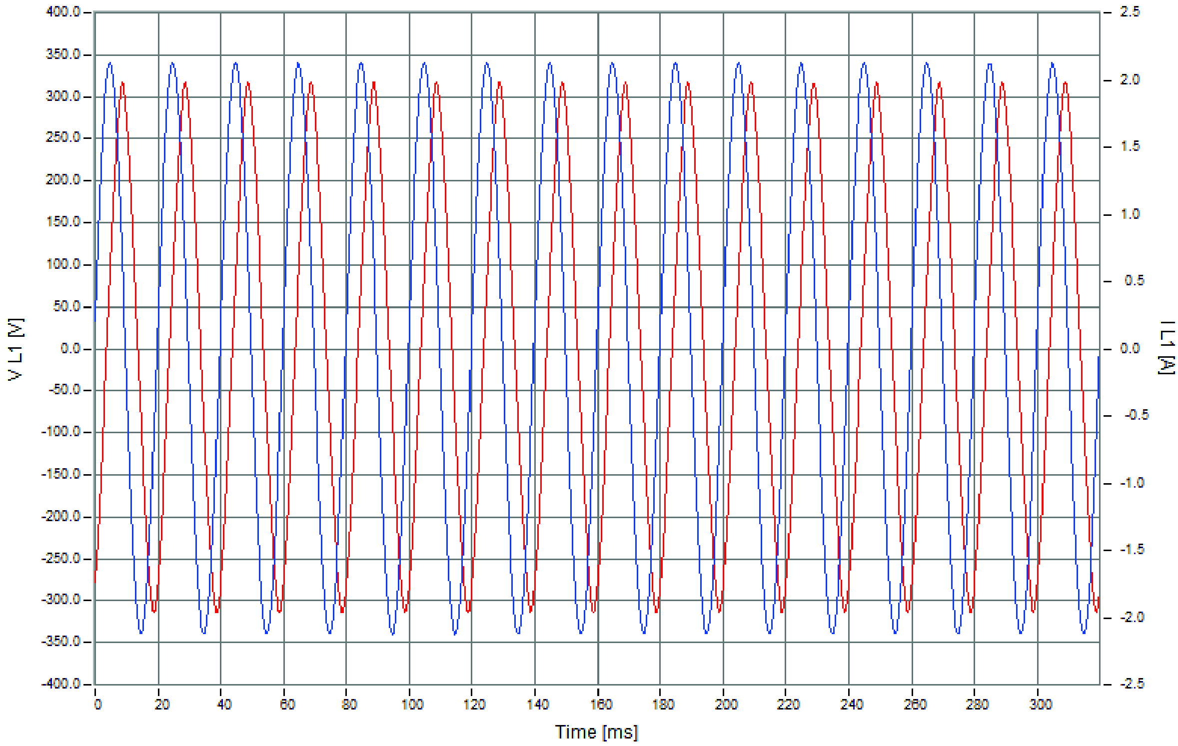


Figure 36. Current and voltage signal curve - 240 V

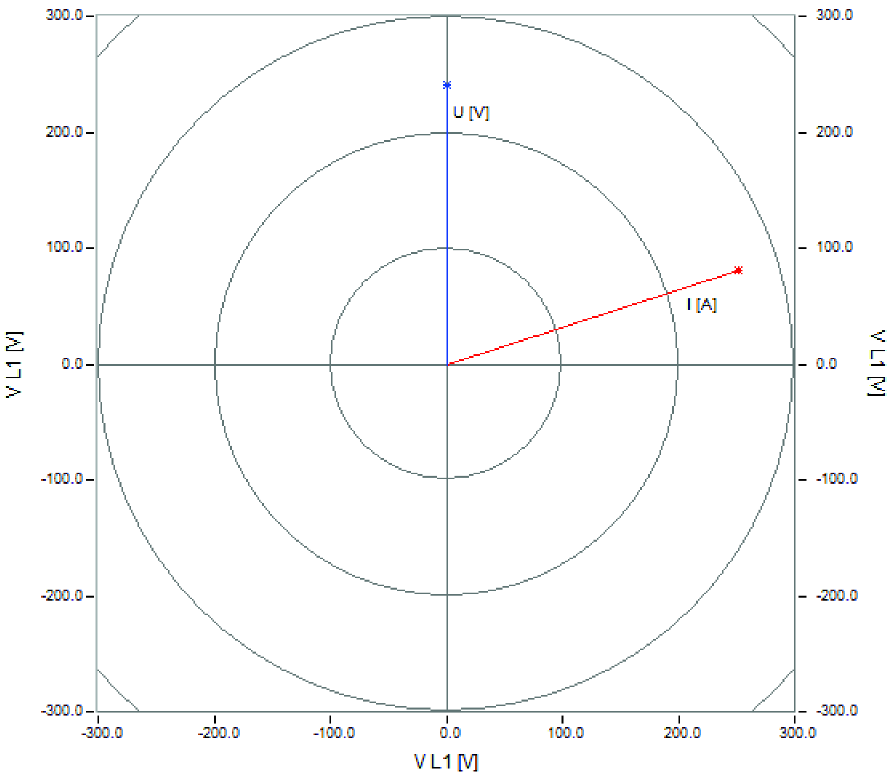


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

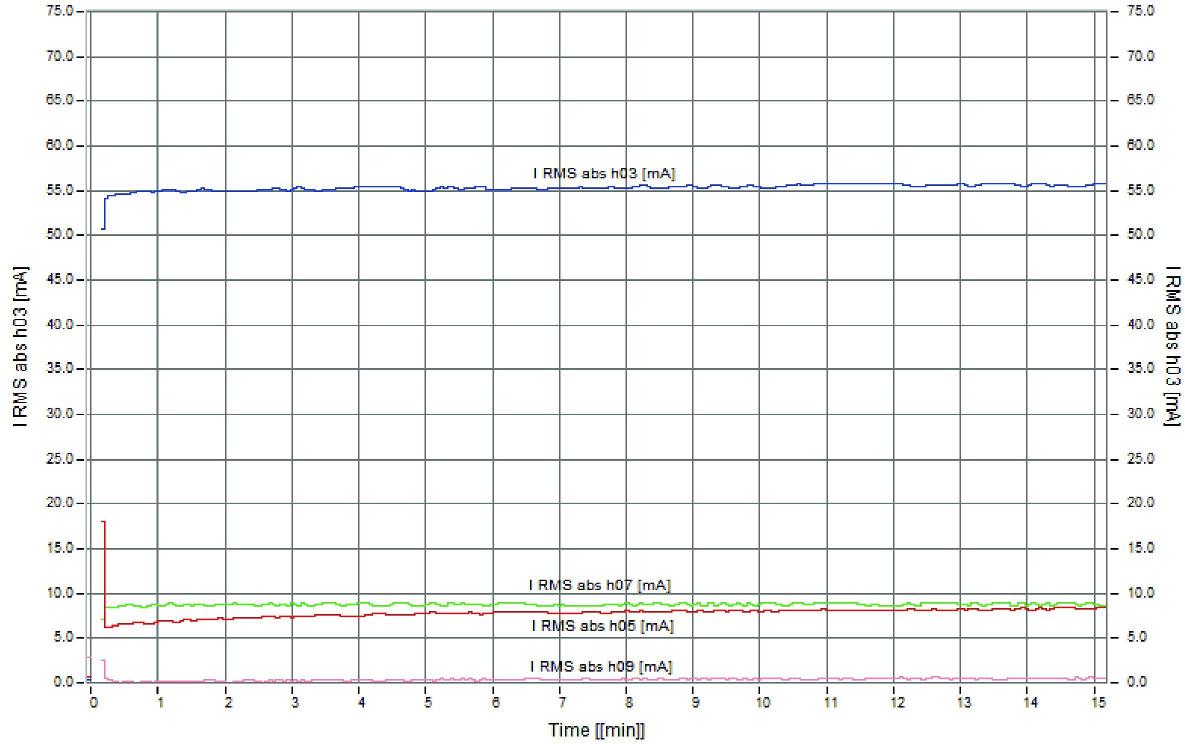


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

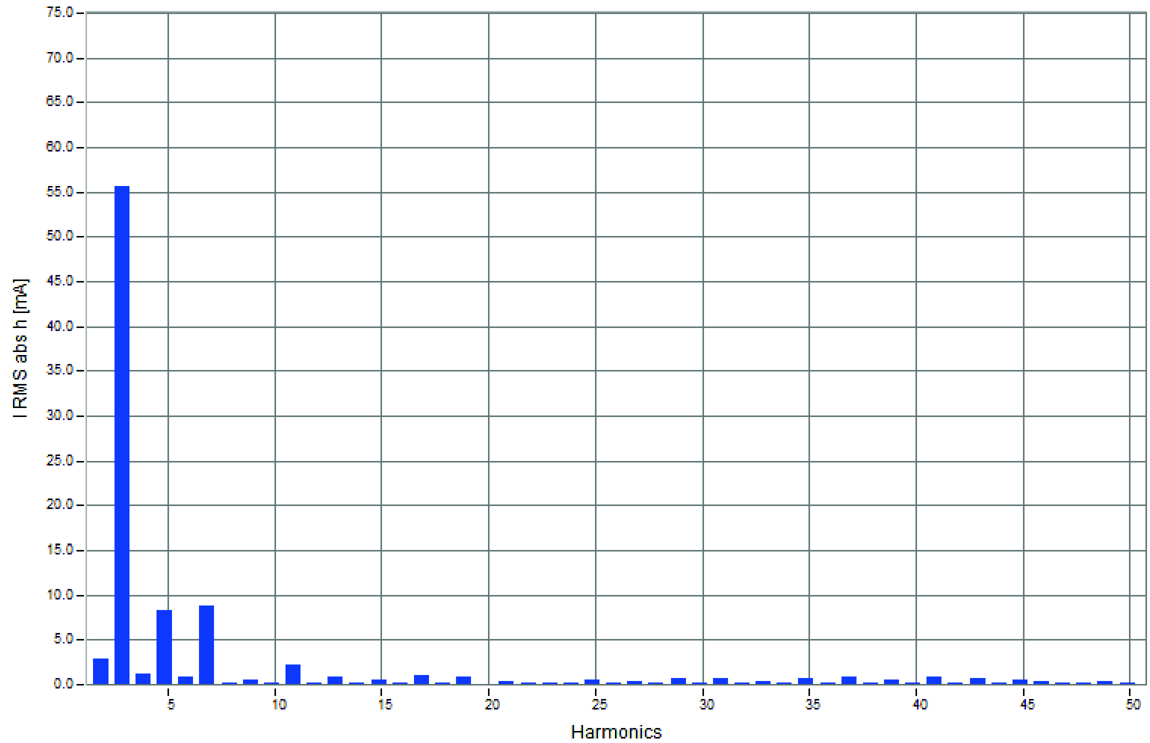


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.3\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.3\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 250.18 V
Current: I = 1.40 A
Active Power = 103.07 W
Reactive Power = 335.73 var
Apparent Power = 352.71 VA
Power Factor = 0.29

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

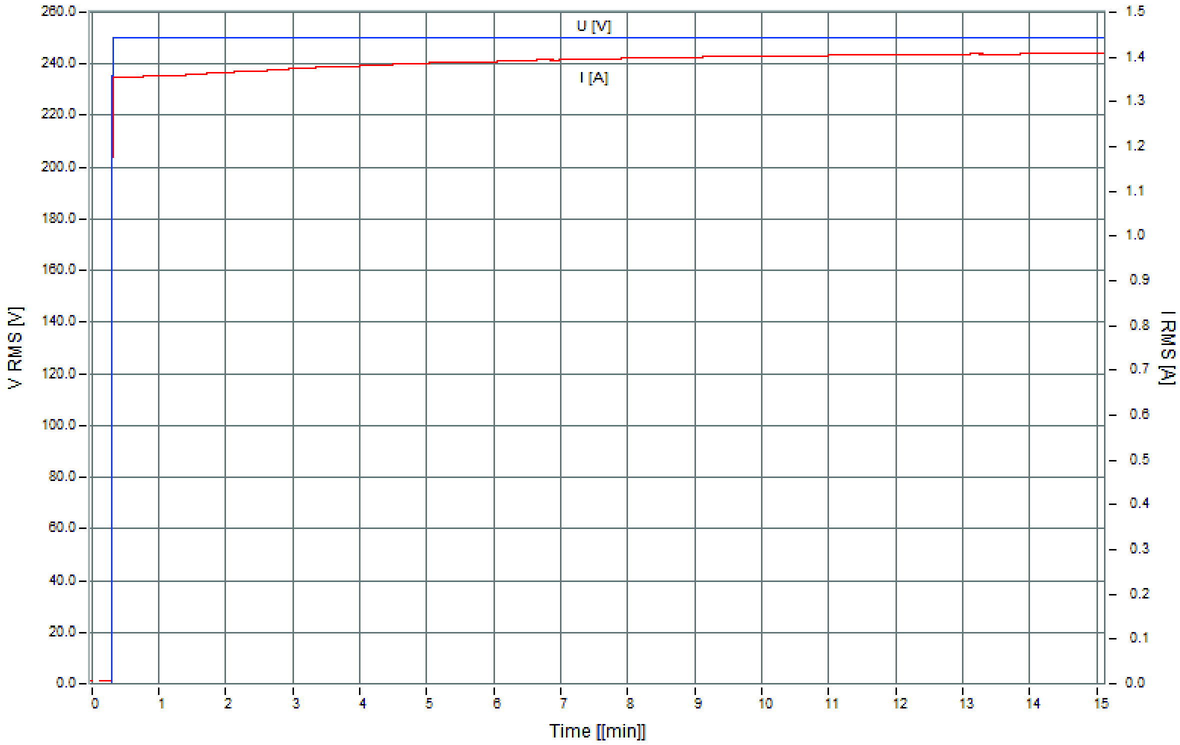


Figure 40. Root Mean Square of voltage and current - 250 V

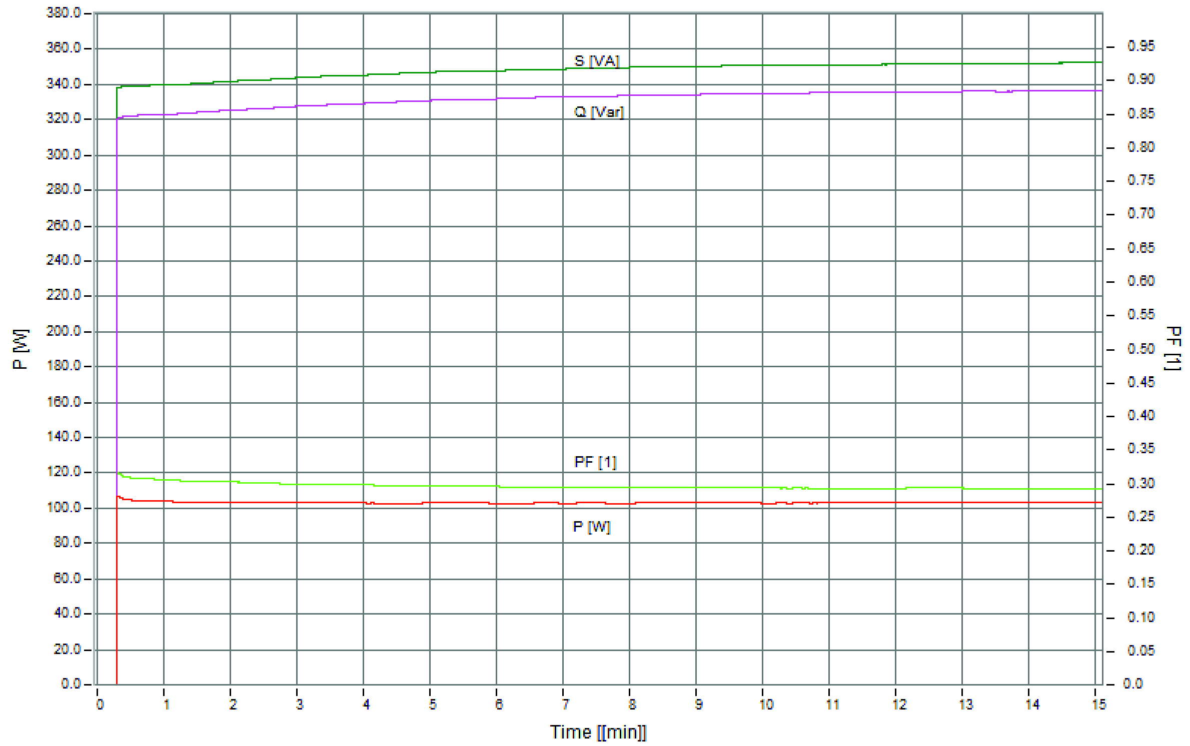


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 250.18	[V]	*****	$0{,}00^0$
I L1 = 1.39 A	[A]	*****	72.83^0

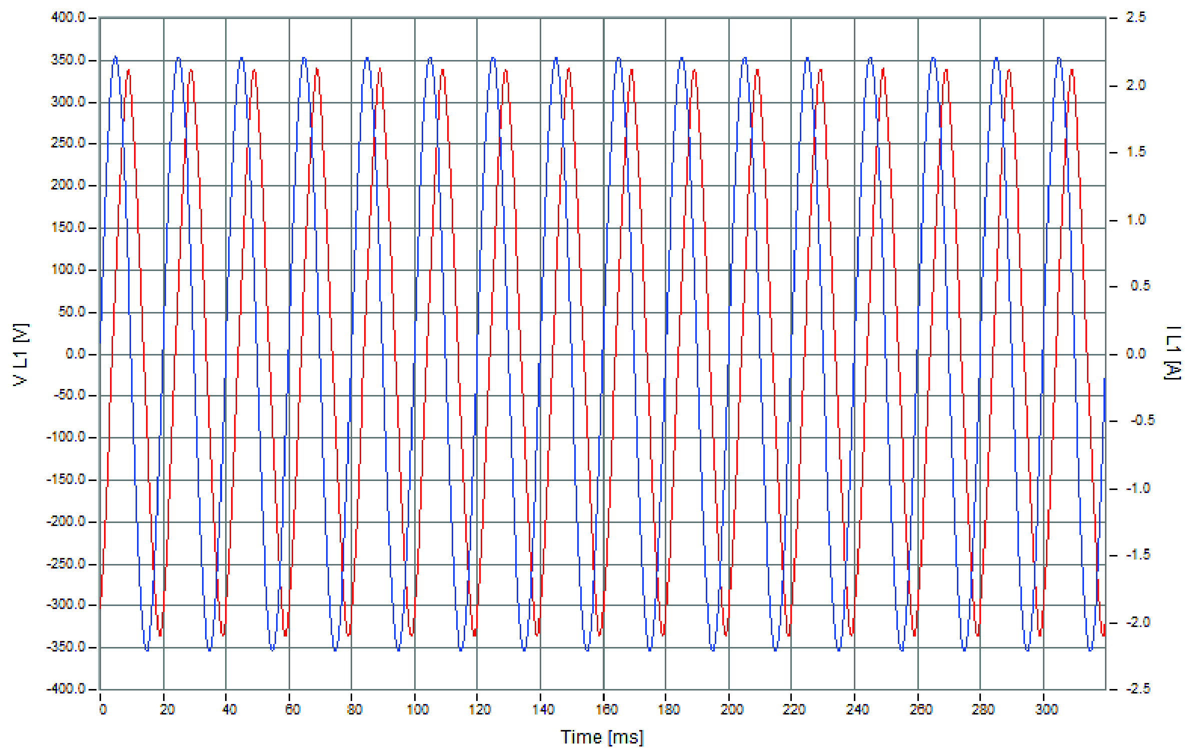


Figure 42. Current and voltage signal curve - 250 V

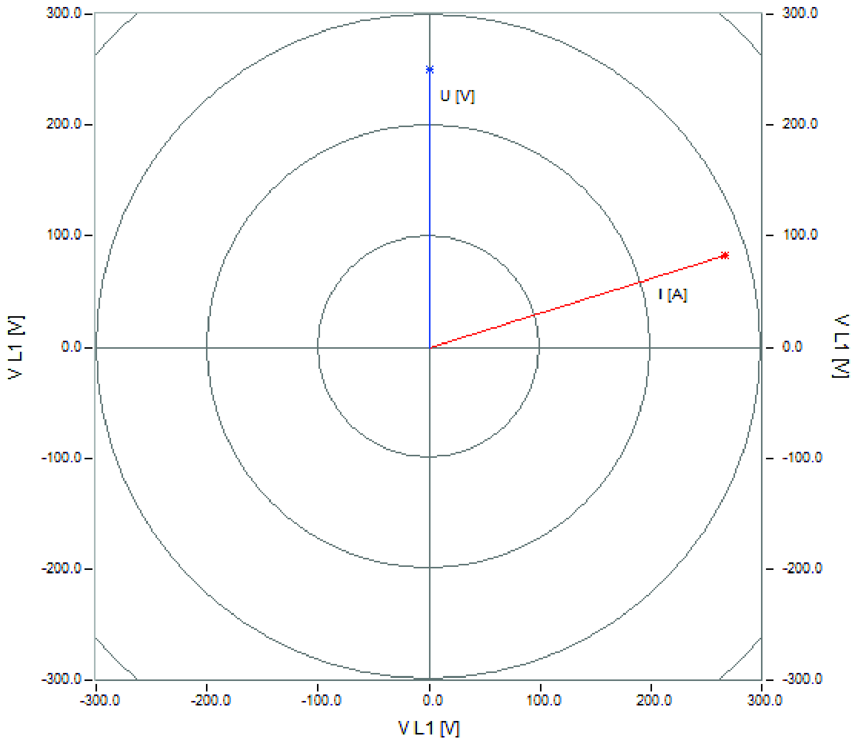


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

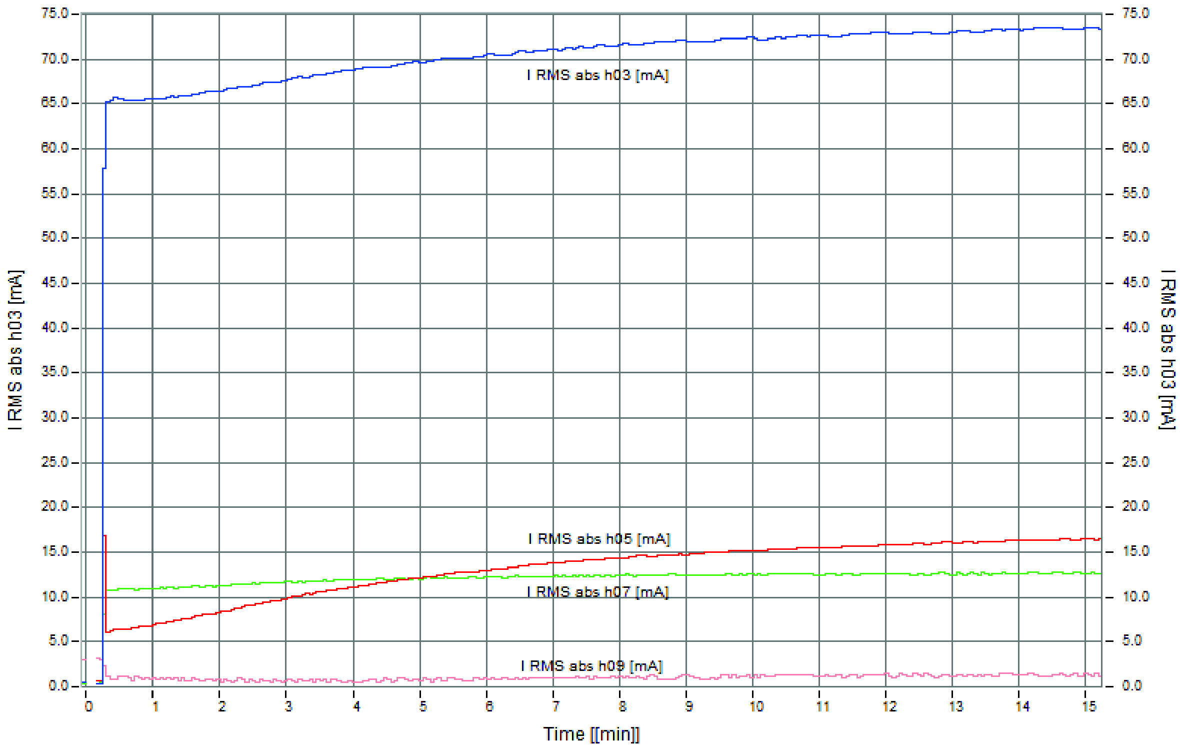


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

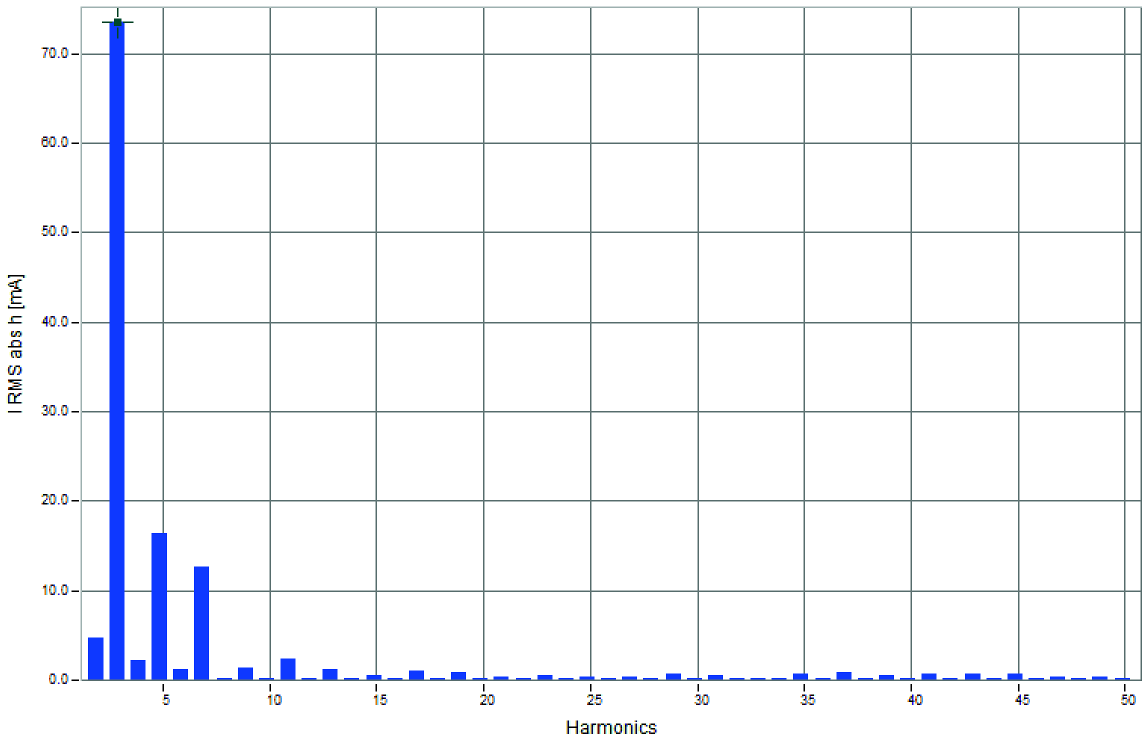


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 5.44\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 5.43\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results concerning the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 5.44%, for the maximum voltage, 1.09 p.u.. The minimum THD, 3.45%, is measured for the voltage 0.96 p.u.

In **Outside at 1^{0}C**, THD reached the maximum value, 5.08%, for the maximum voltage, 1.09 p.u.. The minimum THD, 3.88%, is measured for the voltage 0.96 p.u. The Results indicate the harmonic effect increase with a temperature decrease.

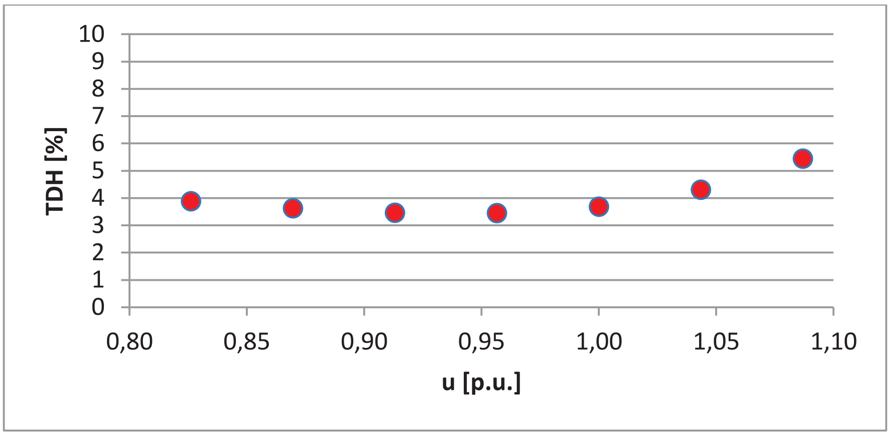
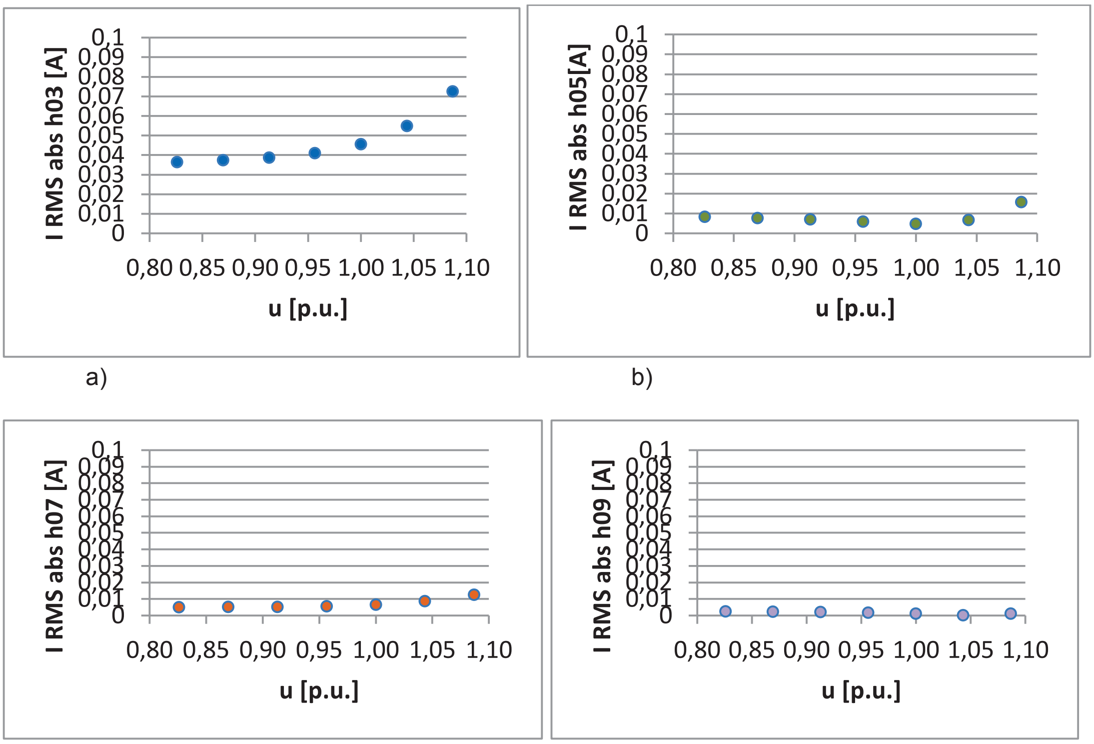


Figure 46. Relationship of THD (according to IEEE) to the voltage in room temperature



c) d)

Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9thharmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 51 a) shows the 3d harmonic, which have a exponential behaviour with minimum of 0.03mA by voltage 0.83 p.u.. Figures 47. b) and c) shows the 5th and the 7th harmonic respectively. In both cases the harmonic values are increasing with the voltage increase. Figure 47. d) shows 9th harmonic which decreases marginally with the voltage increase.

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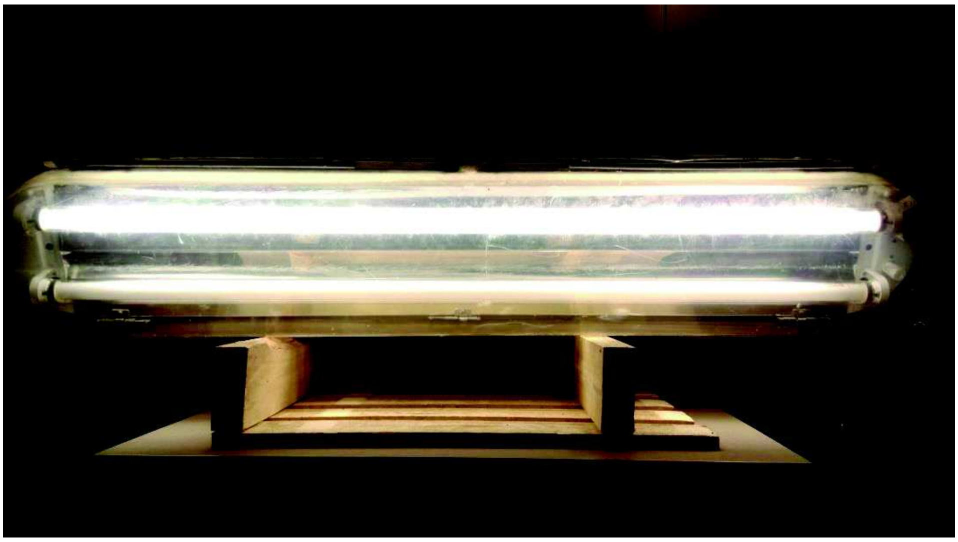
MEASUREMENT PROTOCOL 2

Conventional lamps-old
1XLight source: NARVA
Ballast: AUSTRIA EMAIL



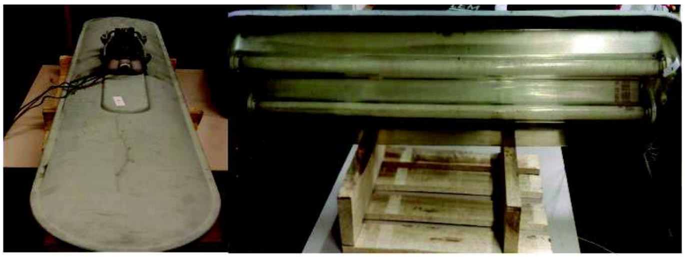
Vienna,20. January 2016

1. Content

2. List of figures

3. Light type

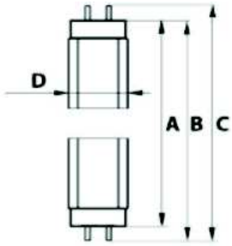
Conventional lamps
1 X NARVA fluorescent lamp
NARVA starter: BSt65
Status: old



4. Technical data

NARVA Fluorescent Lamp: LT - T8/T12 36 W COLOURLUX plus ET.XL
Voltage: 220-240 V
Real power : 36 W

Size A (max., mm)	1.199,4
Size B (min., mm)	1.204,1
Size B (max., mm)	1.206,5
Size C (max., mm)	1.213,6
Size D (max., mm)	38,0



NARVA starter: BSt65
Voltage: 220 V – 240 V
Power: 4 W – 65.80 W

AUSTRIA EMAIL ballast
Voltage: 220 V
Frequency: 50 Hz
current: 0.43 A
Cos ρ: 0.5

5. Measurement

5.1. Schema

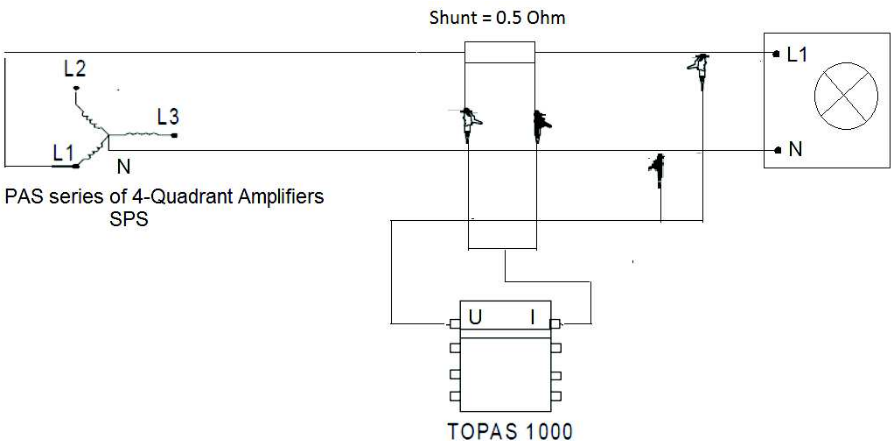


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside **Temperature**: 20.9^{0}C
Voltage range: 190-250 V **Shunt:** 0.5 Ω
Measurement interval: 15 min

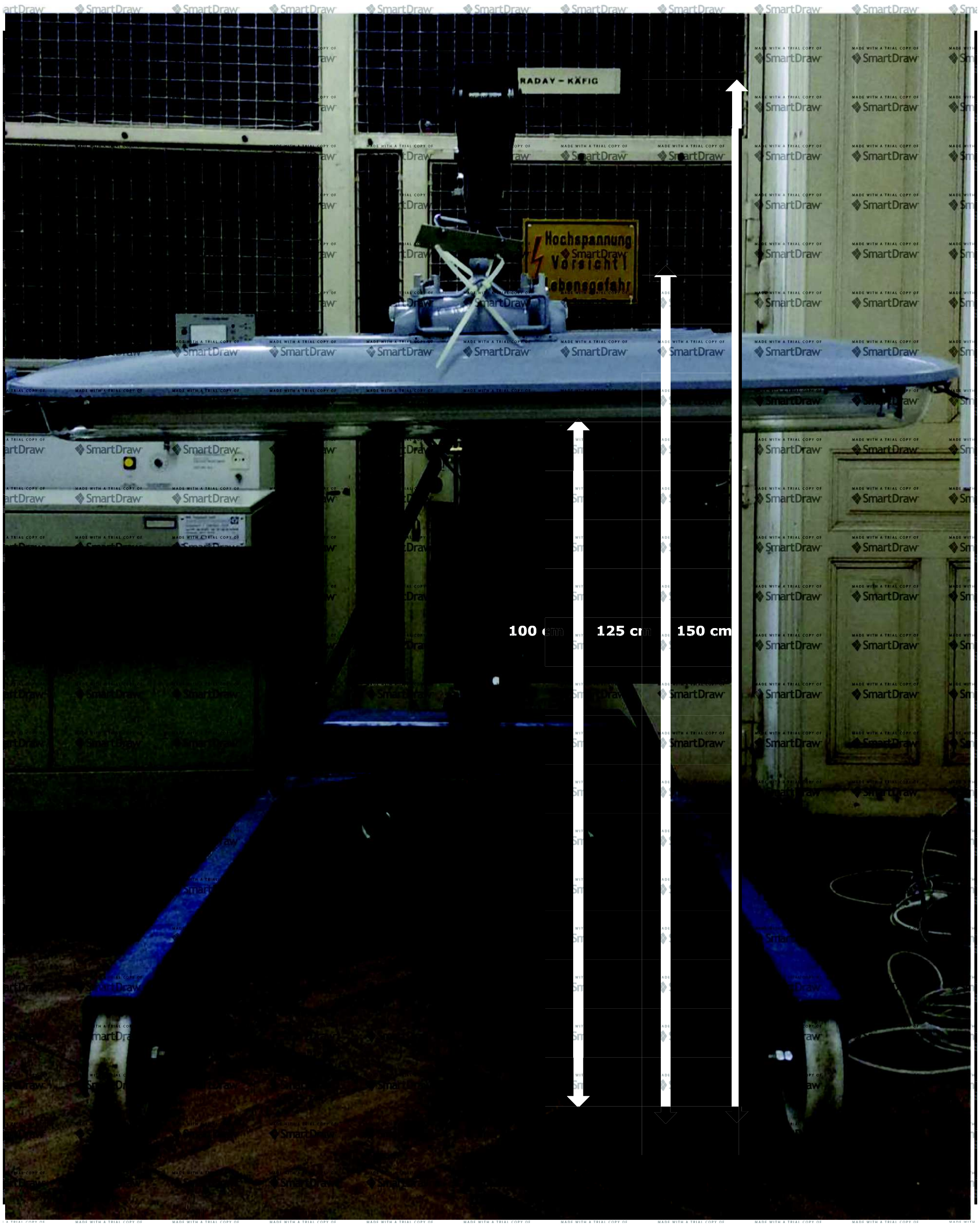


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 230.35 V
Current: I = 0.96 A
Active Power = 65.96 W
Reactive Power = 213.12 var
Apparent Power = 223.23 VA
Power Factor = 0.29

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

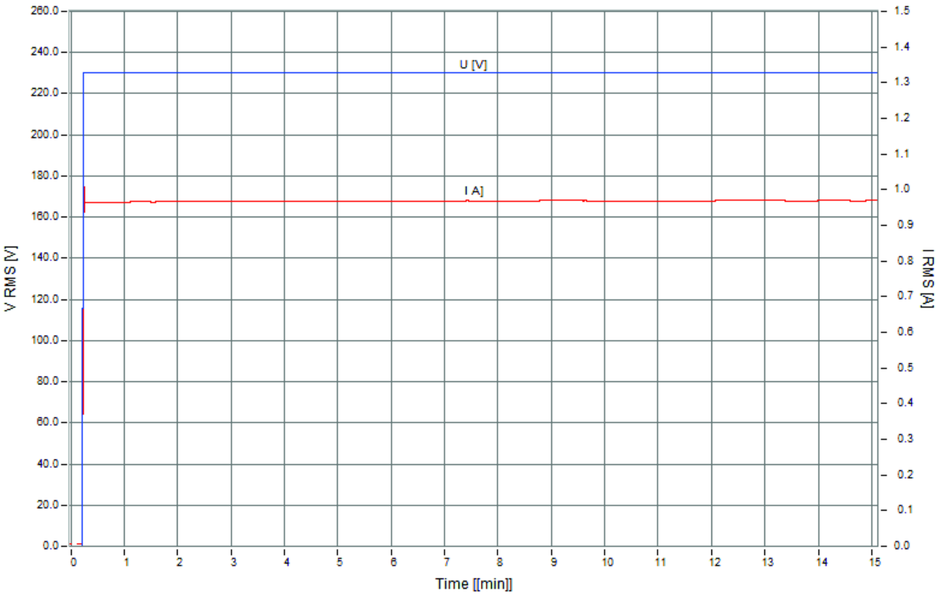


Figure 3. Root Mean Square of voltage and current - 230 V

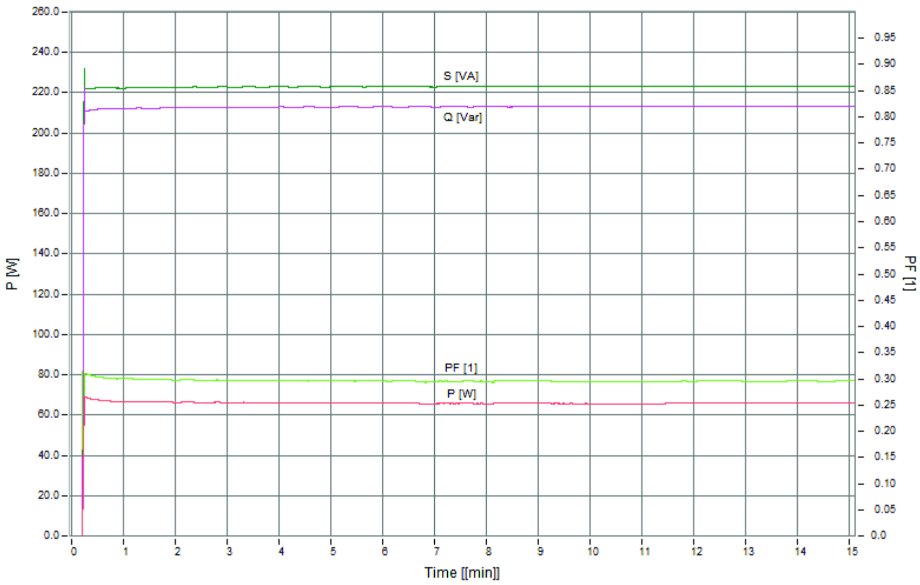


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 230.15	[V]	*****	0.00^0
I L1 = 1.24	[A]	*****	71.70

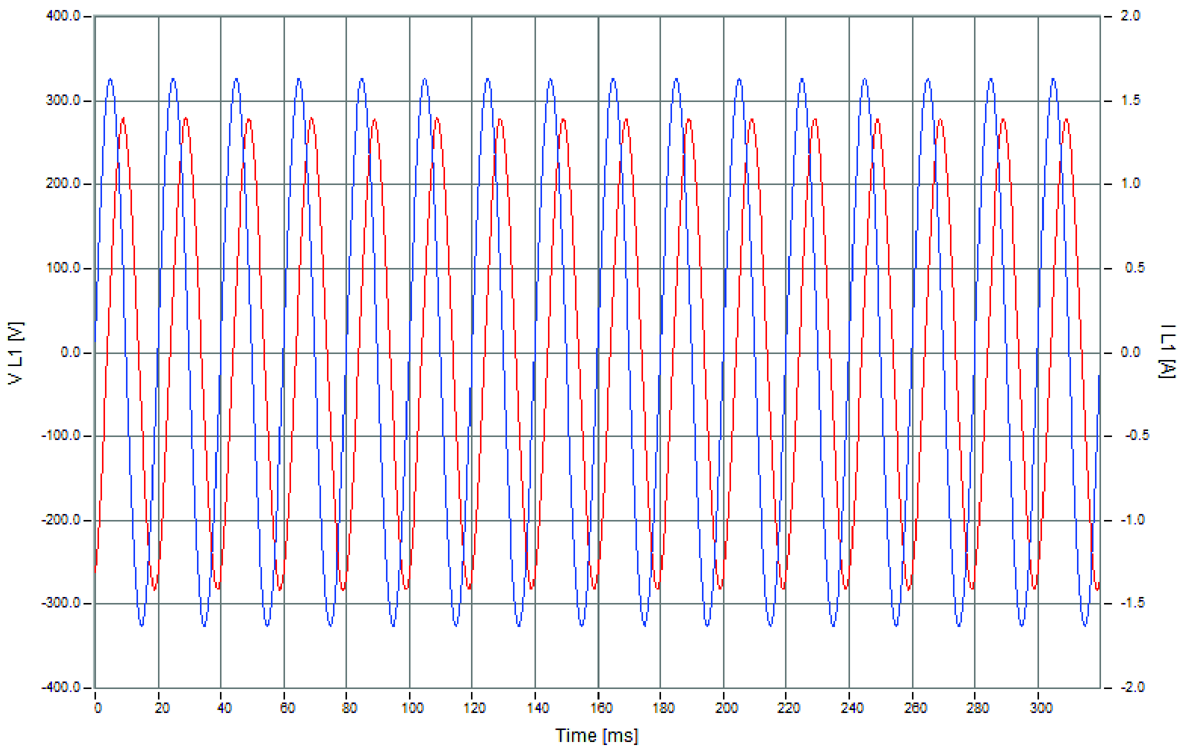


Figure 5. Current and voltage signal curve - 230 V

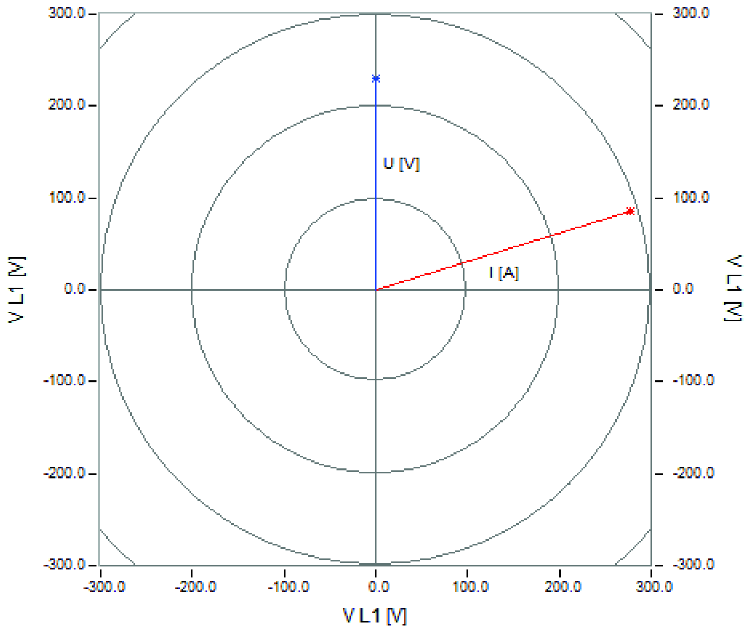


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

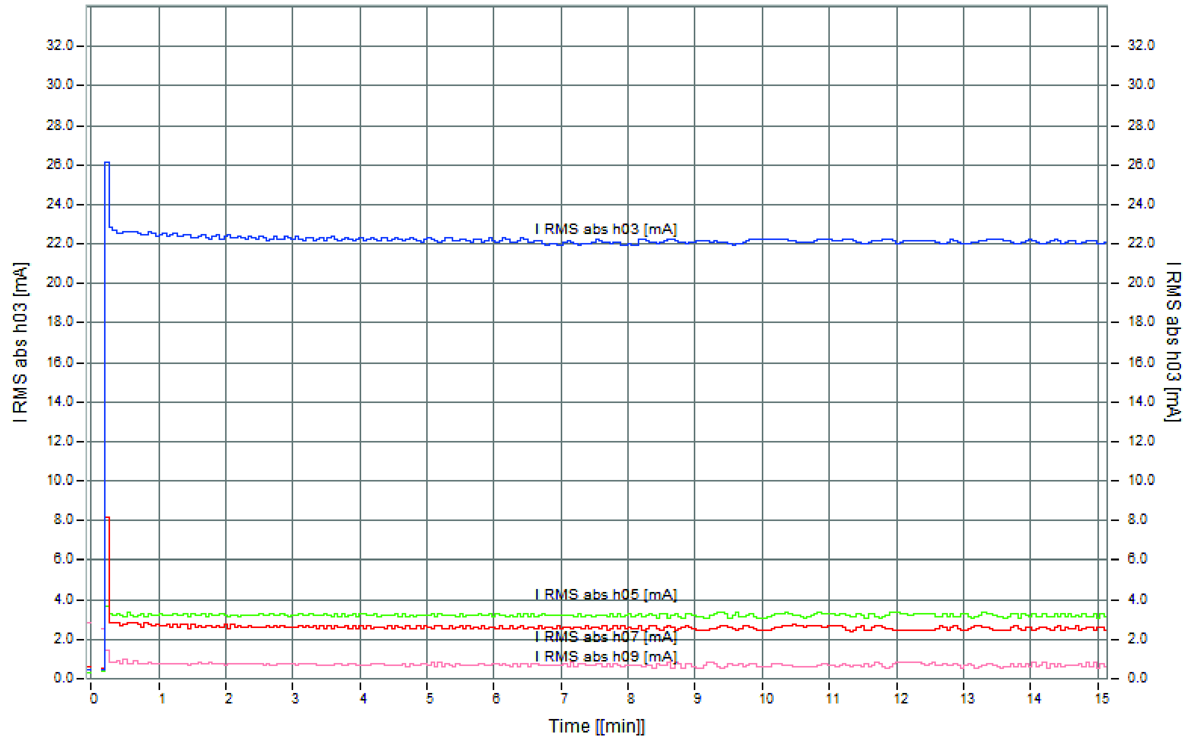


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

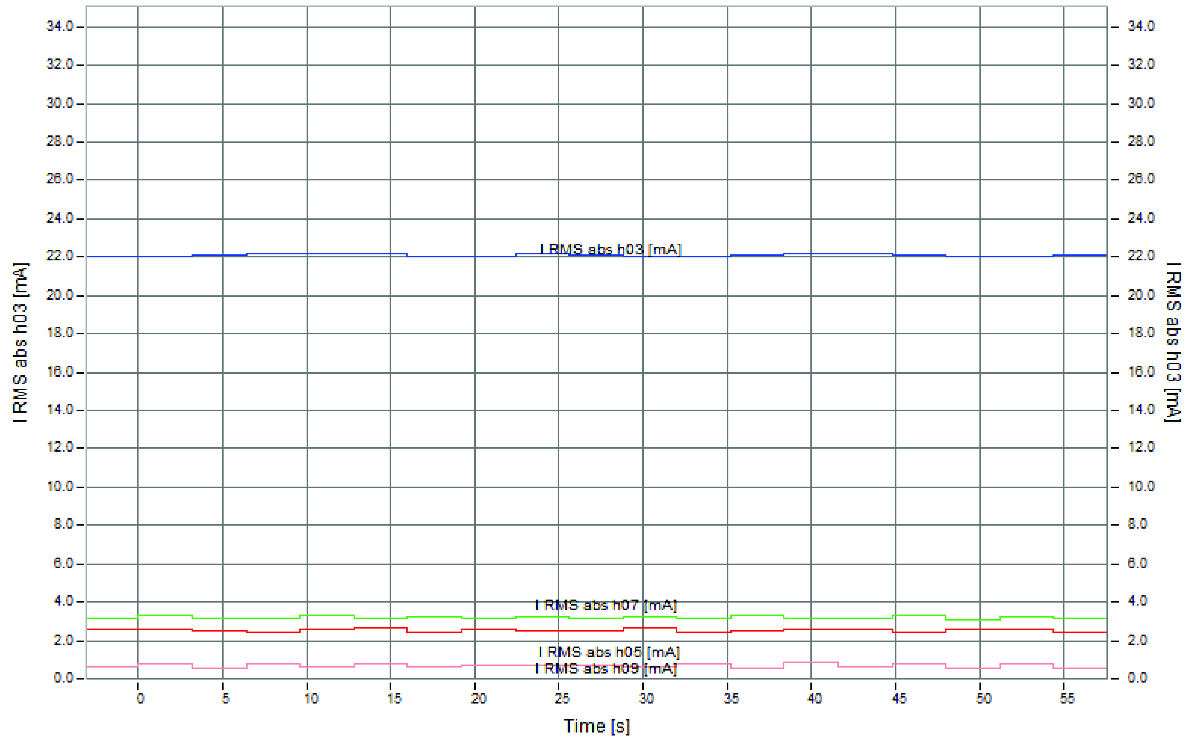


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

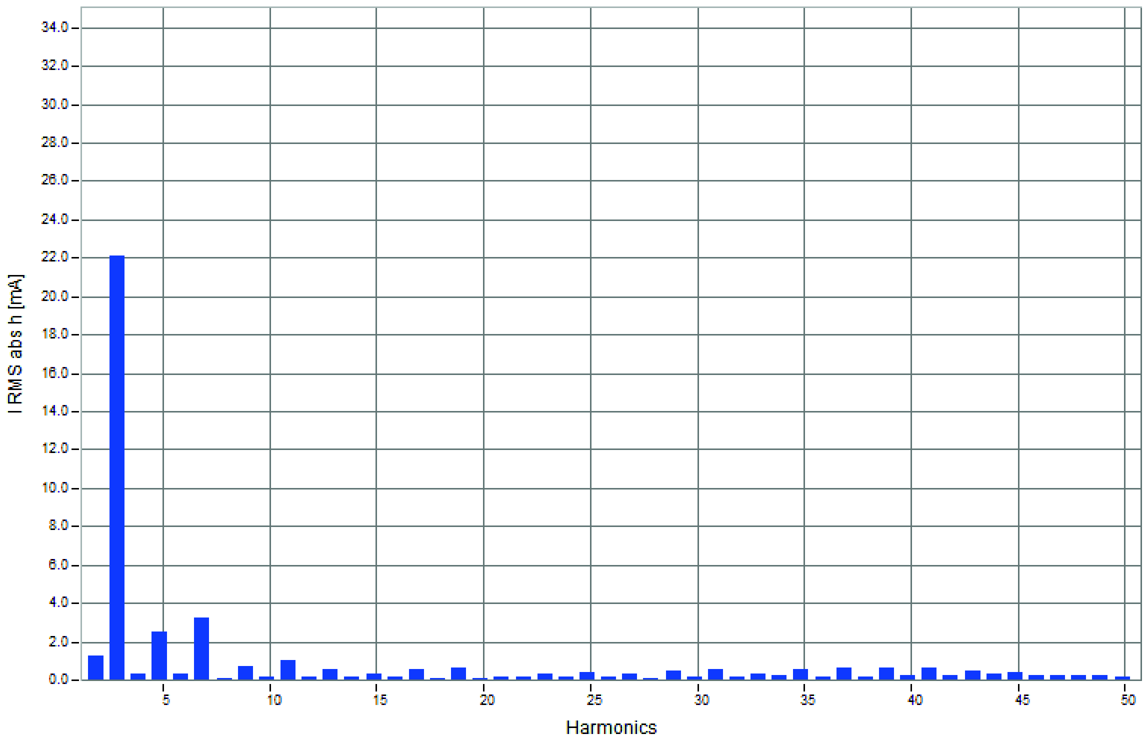


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.33\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.33\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 190.24 V
Current: I = 0.76 A
Active Power = 47.08 W
Reactive Power = 136.98 var
Apparent Power = 144.90 VA
Power Factor = 0.32

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

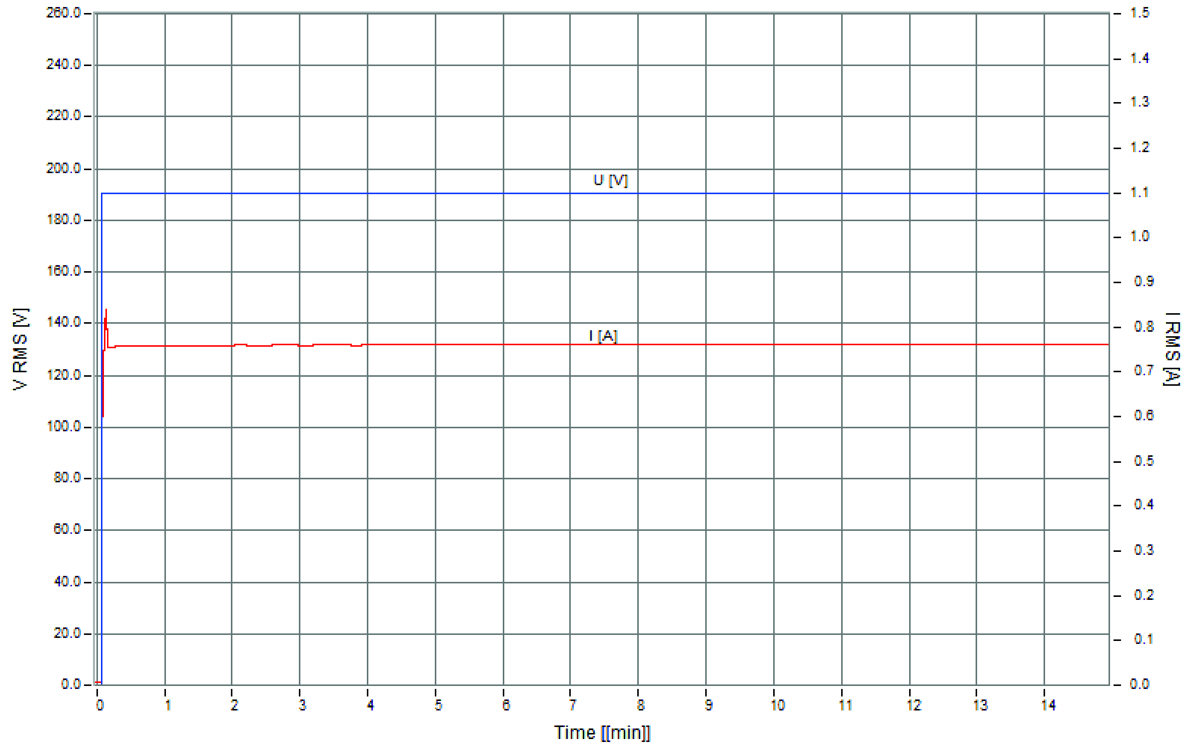


Figure 10. Root Mean Square of voltage and current - 190 V

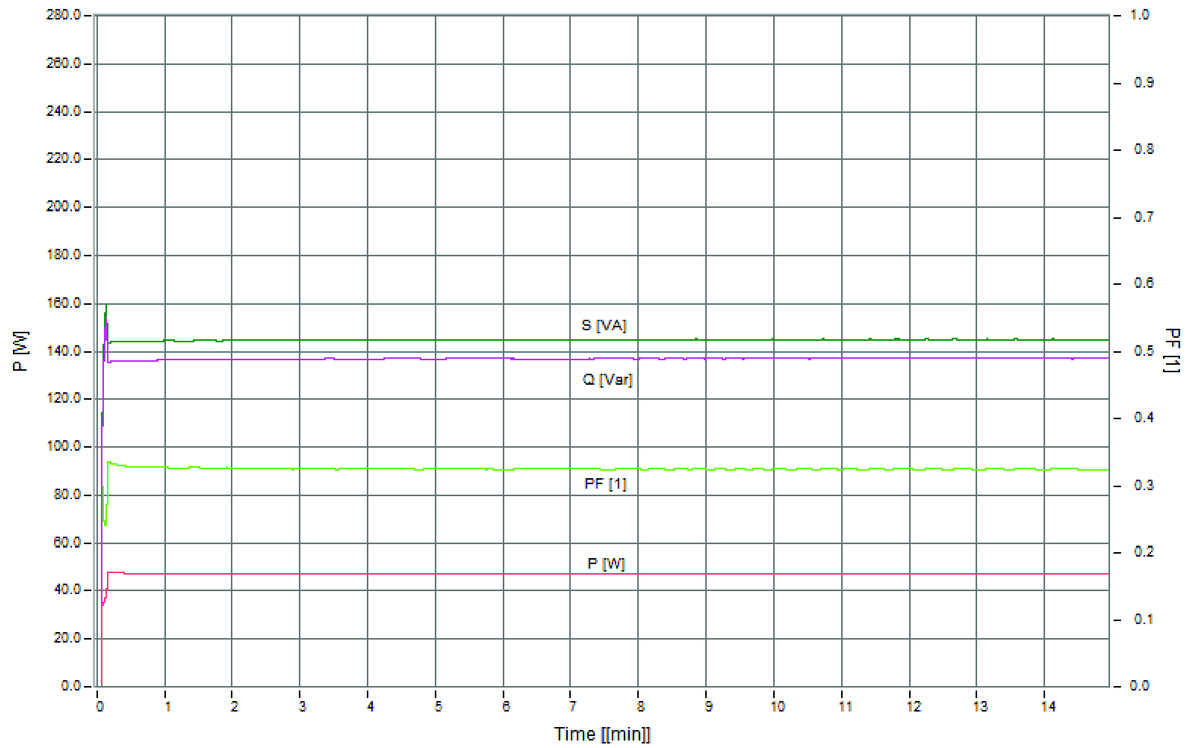


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 190.26	[V]	*****	0.00^0
I L1 = 0.75	[A]	*****	71.02^0

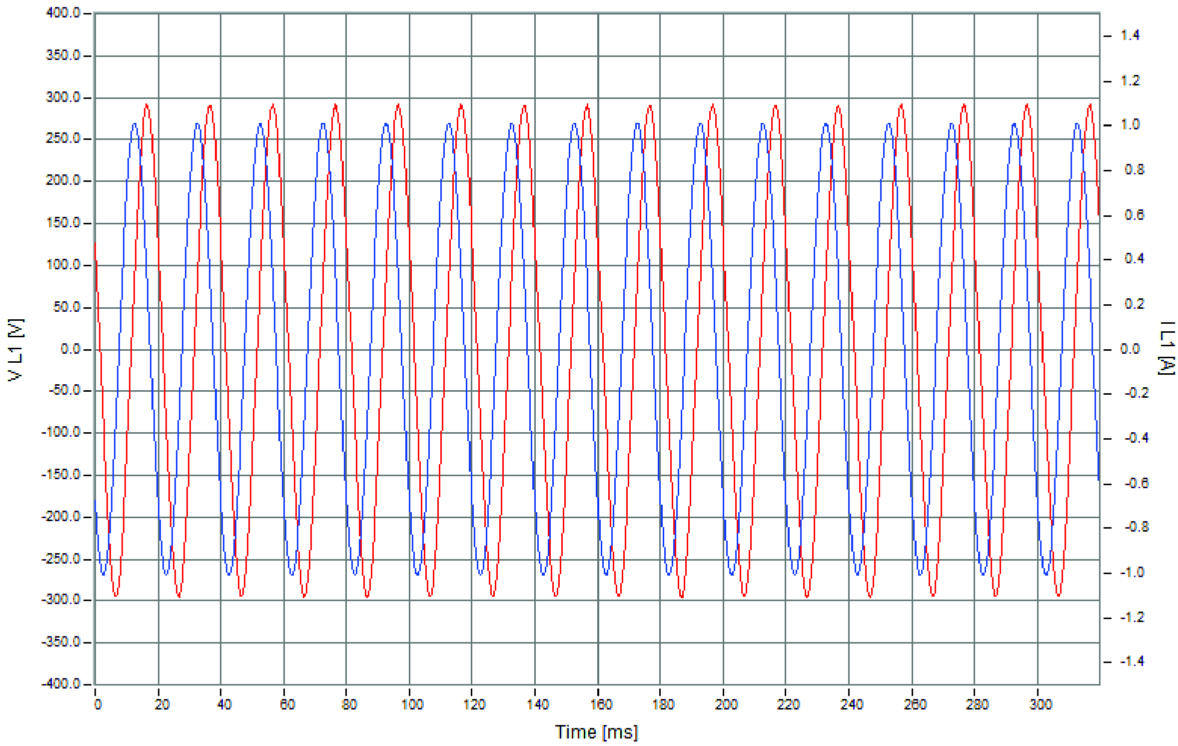


Figure 12. Current and voltage signal curve - 190 V

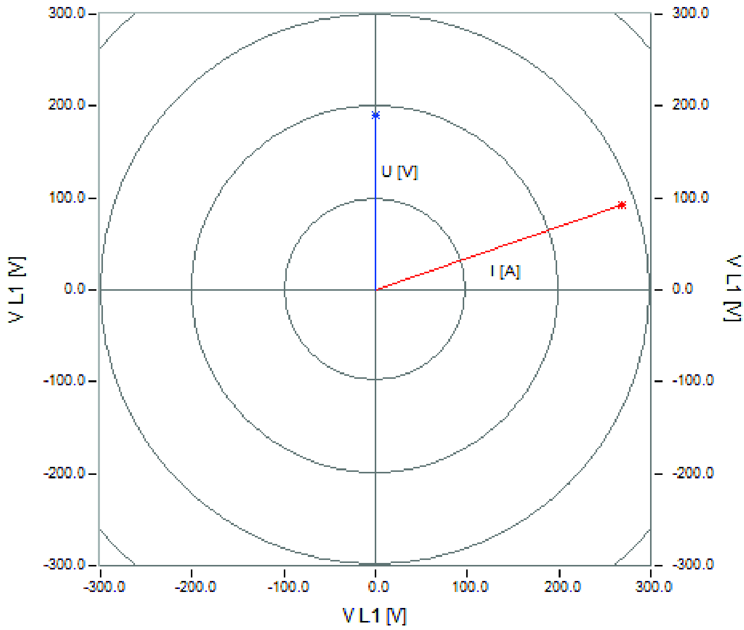


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

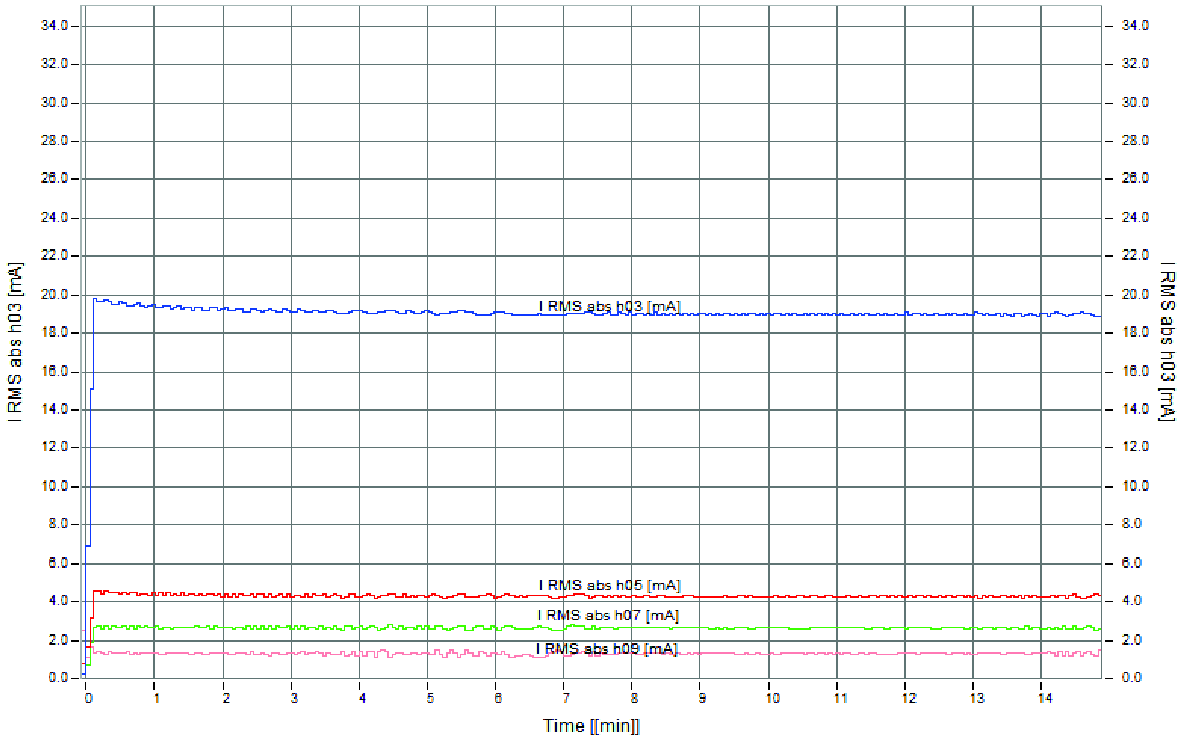


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

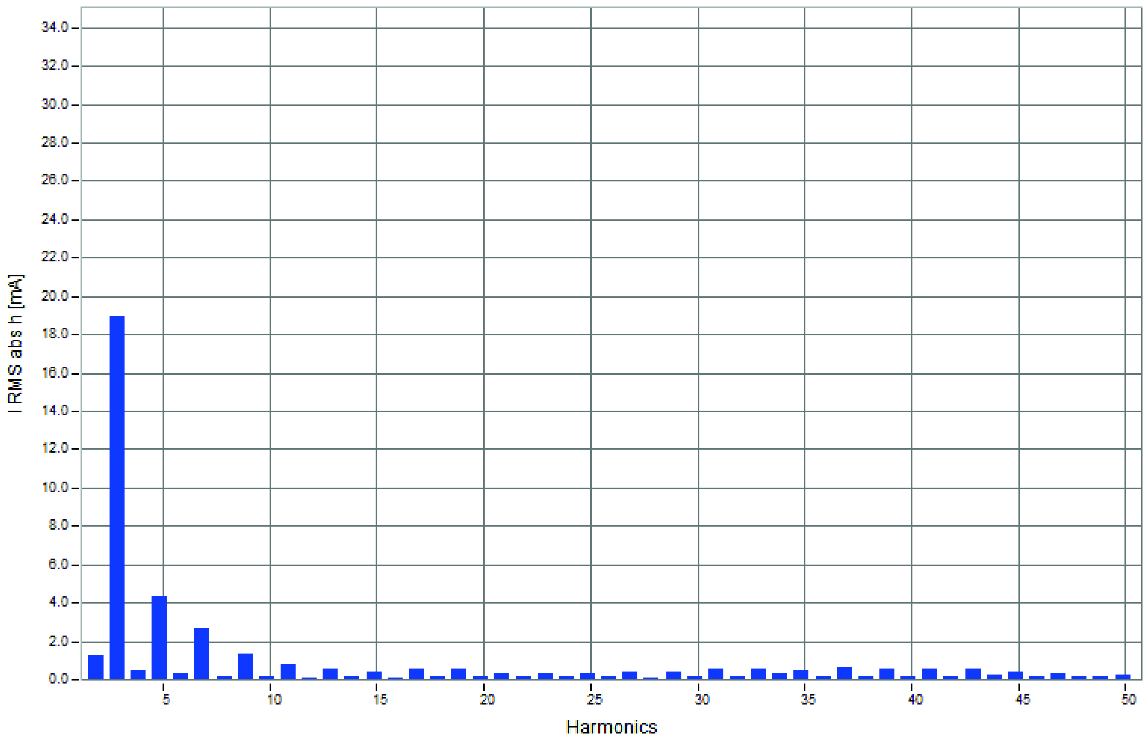


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.60\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.60\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 200.26 V
Current: I = 0.81 A
Active Power = 51.69 W
Reactive Power = 154.76 var
Apparent Power = 163.22 VA
Power Factor = 0.31

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

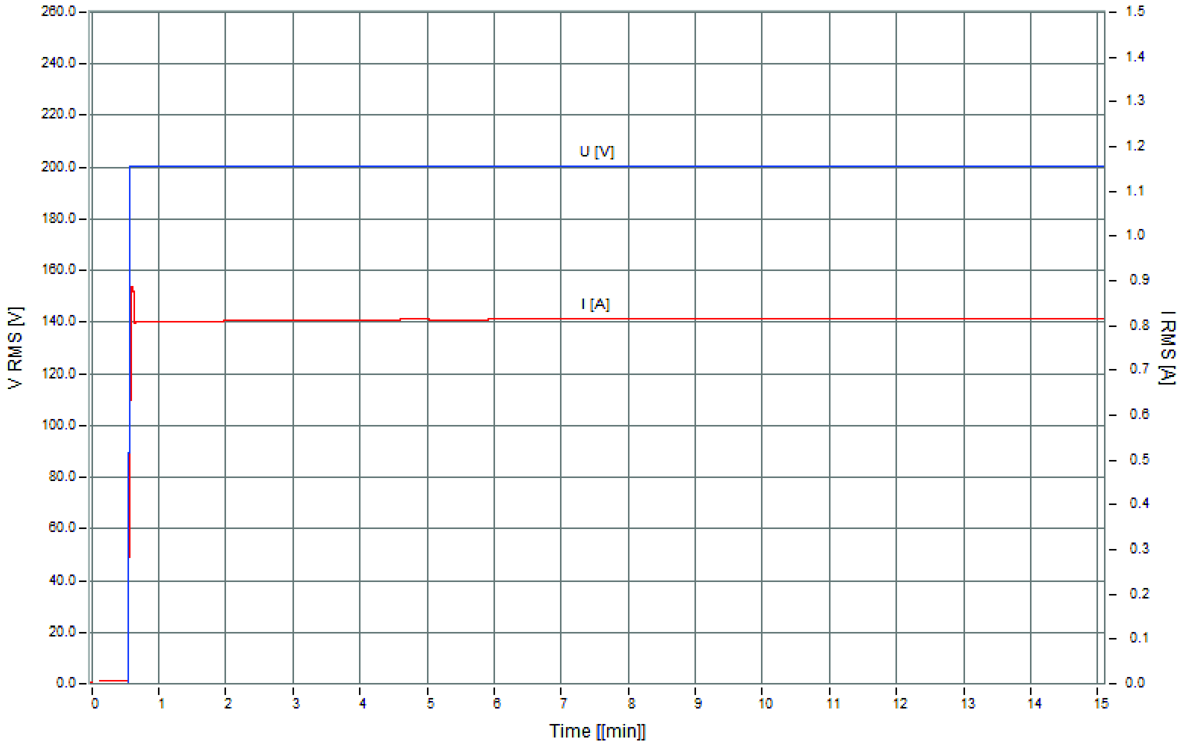


Figure 16. Root Mean Square of voltage and current - 200 V

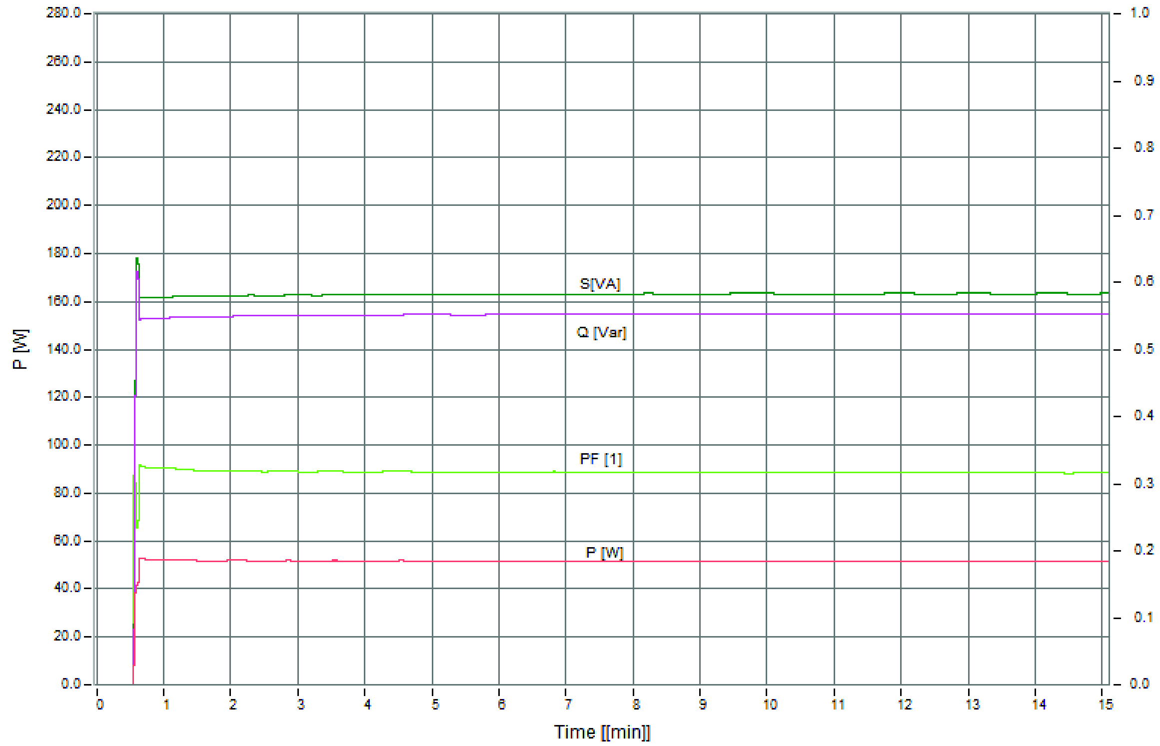


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 200.25	[V]	*****	0.00^0
I L1 = 0.81	[A]	*****	71.52^0

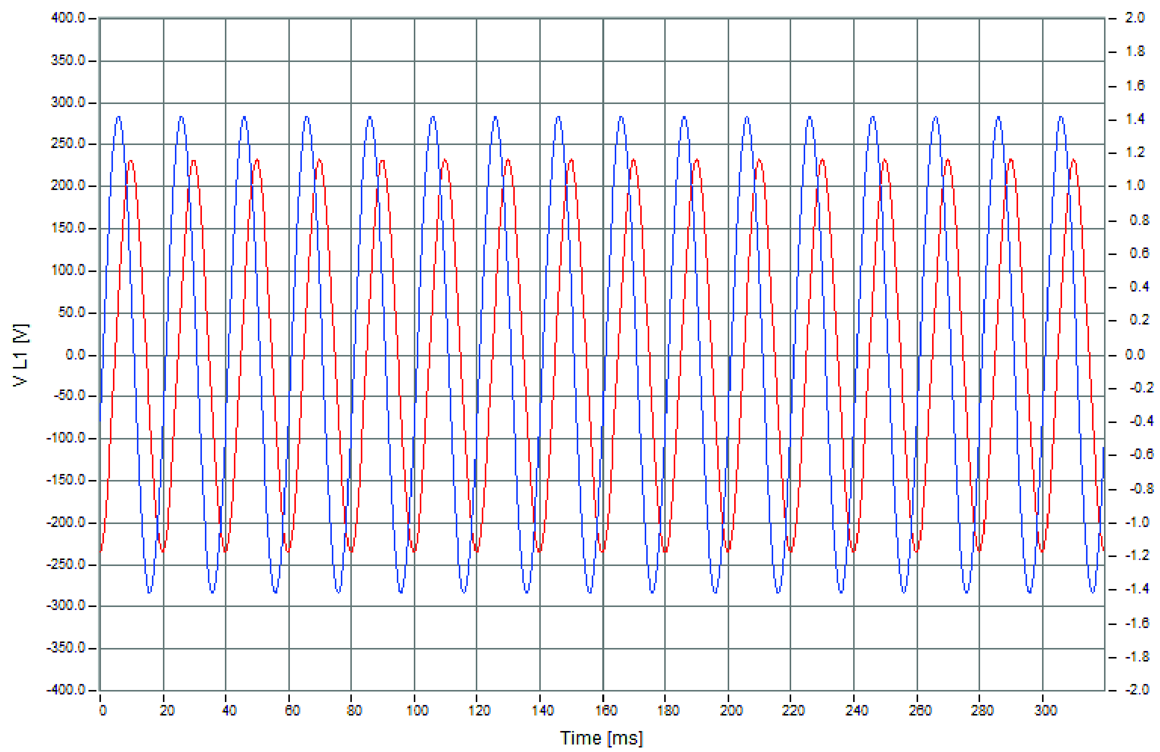


Figure 18. Current and voltage signal curve - 200 V

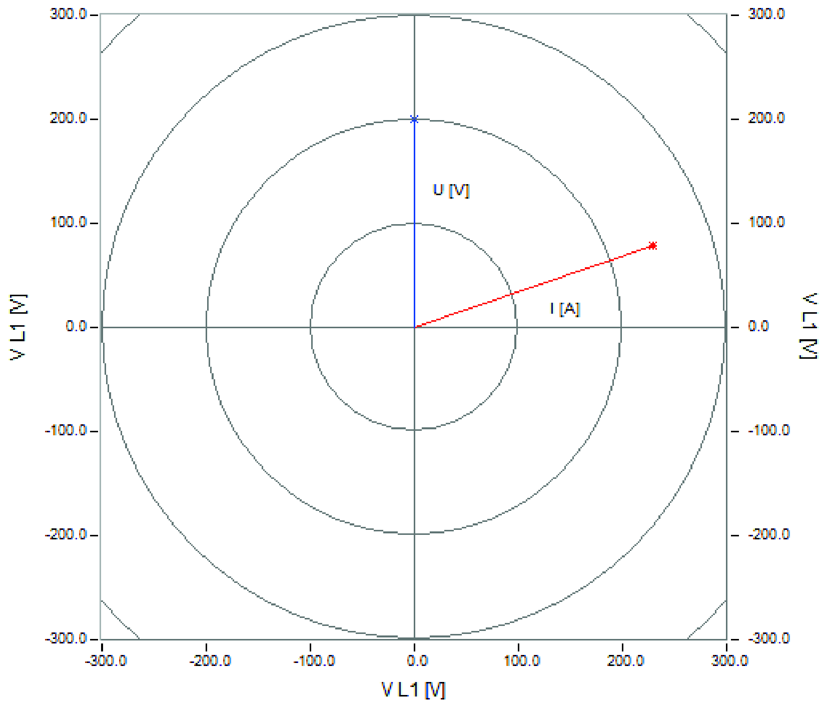


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

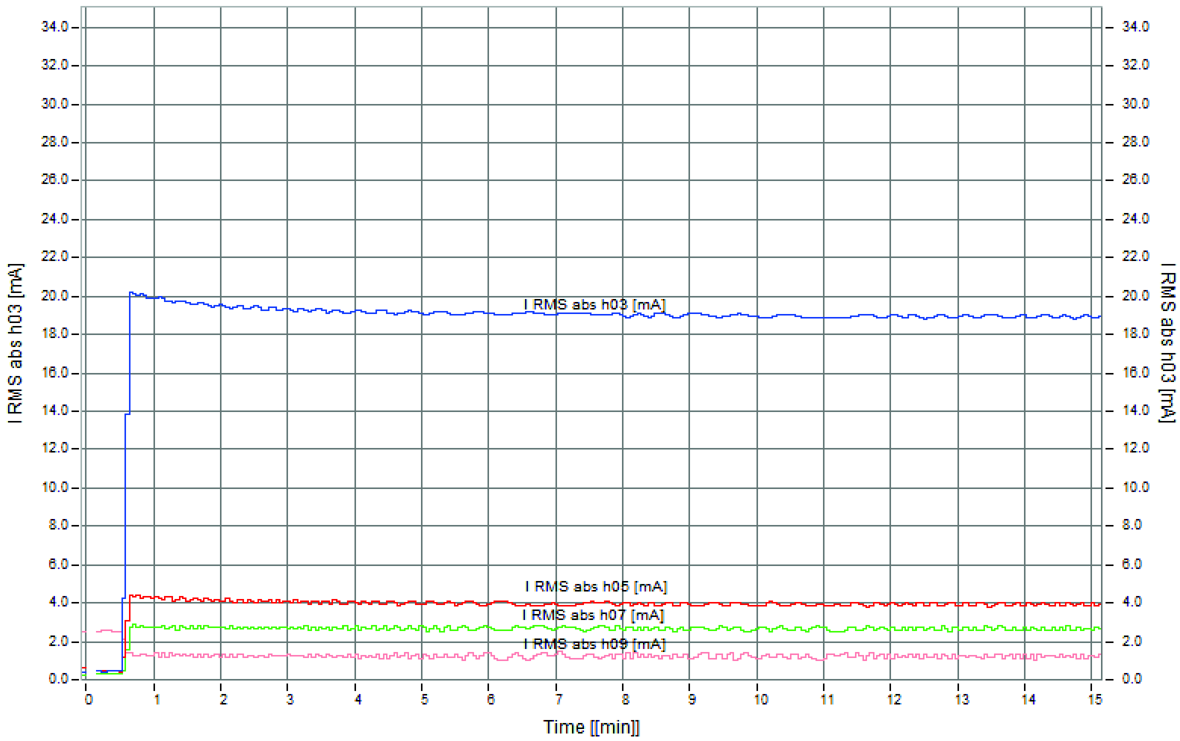


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

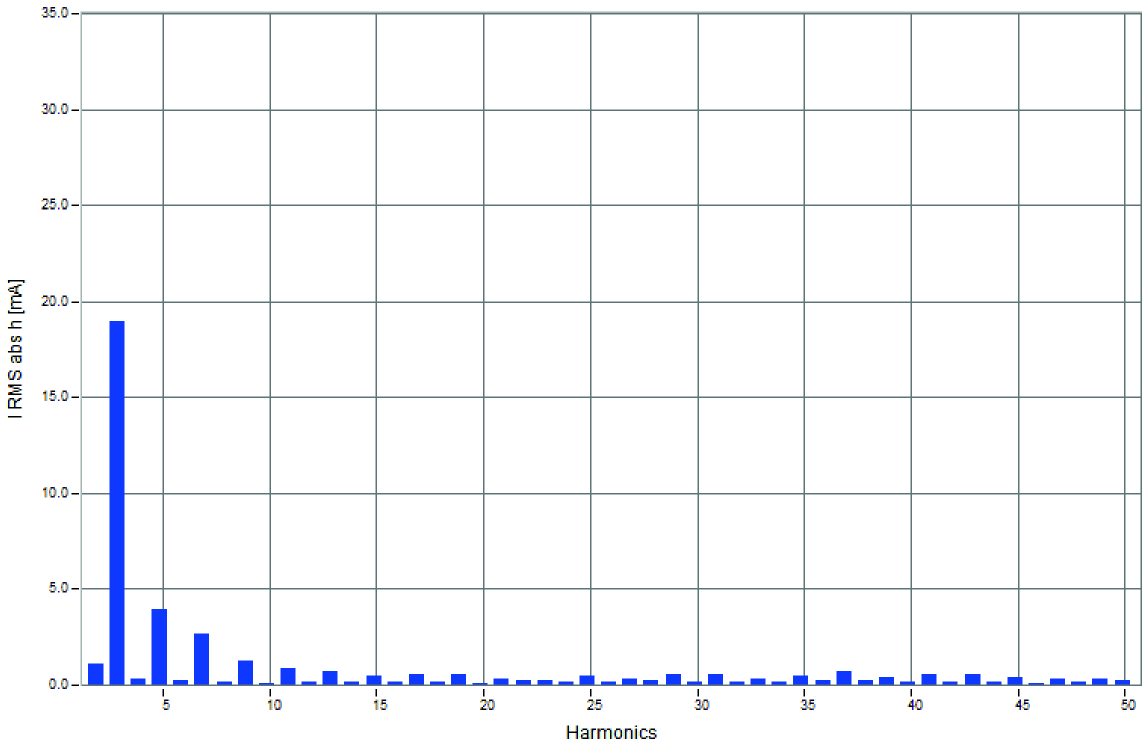


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.42\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.42\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:

Voltage: U = 210.29 V
Current: I = 0.86A
Active Power = 56.26 W
Reactive Power = 173.33 var
Apparent Power = 182.29 VA
Power Factor = 0.30

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

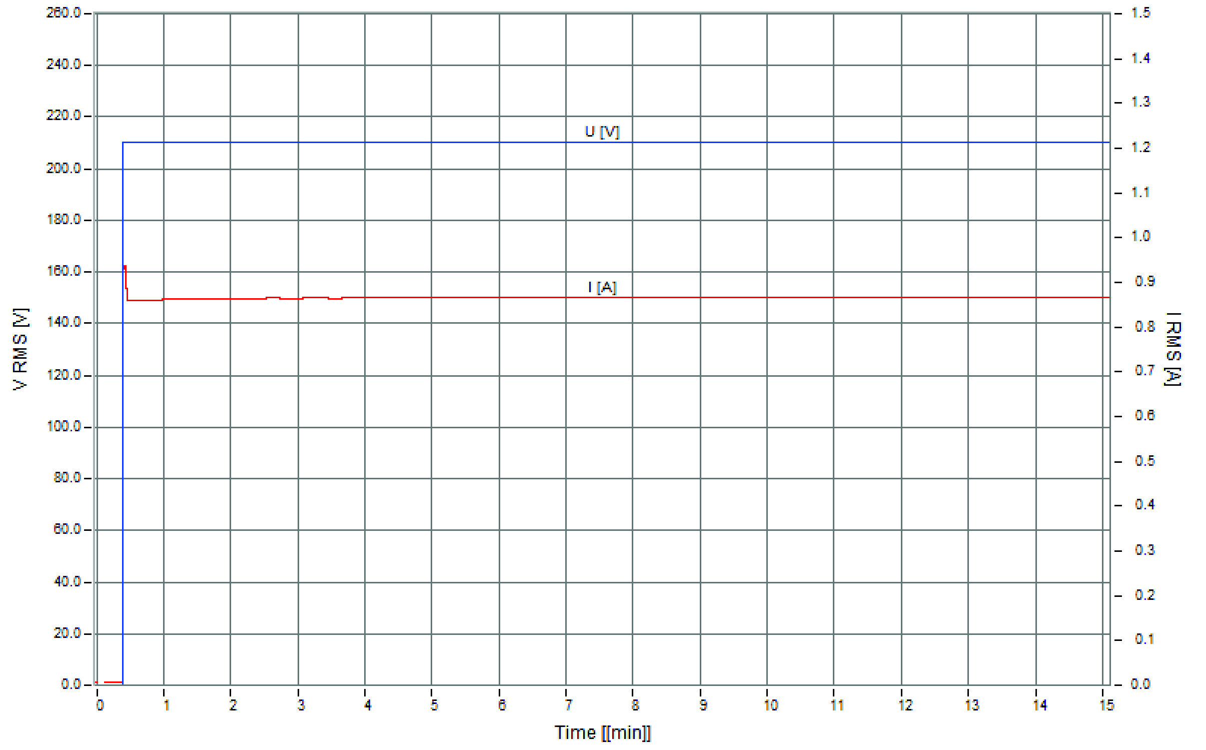


Figure 22. Root Mean Square of voltage and current - 210 V

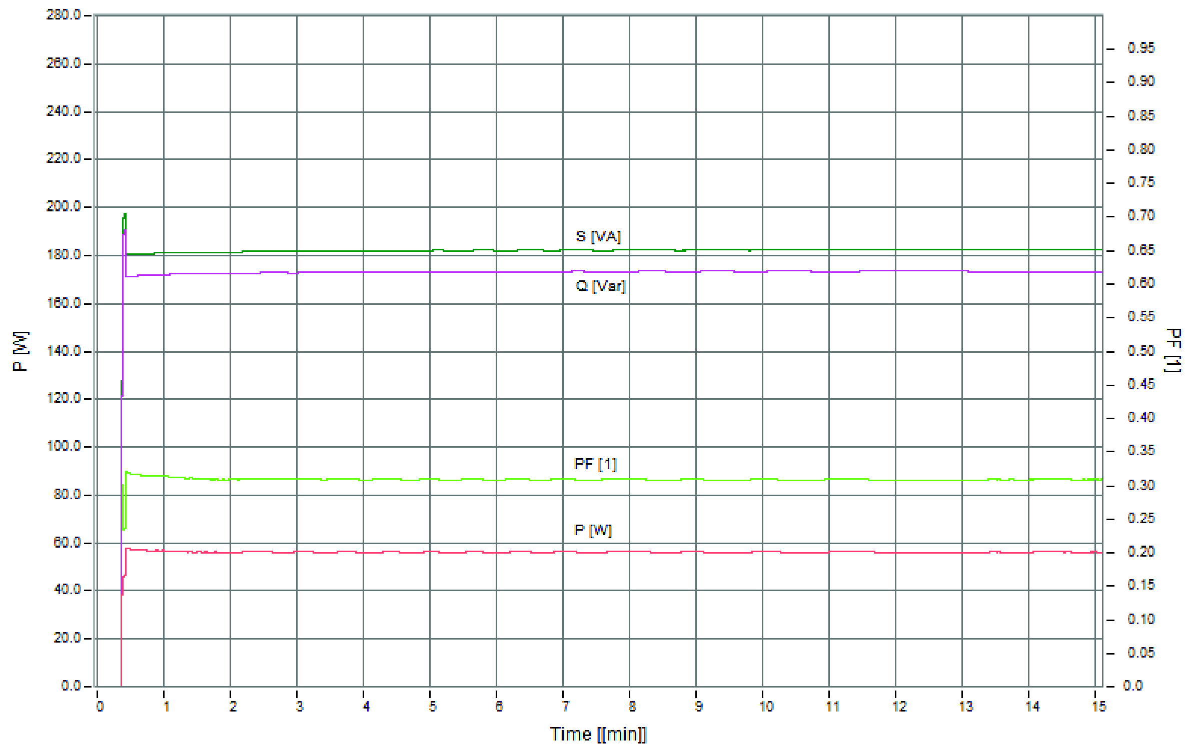


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 210.31	[V]	*****	0.00^0
I L1 = 0.85	[A]	*****	71.64^0

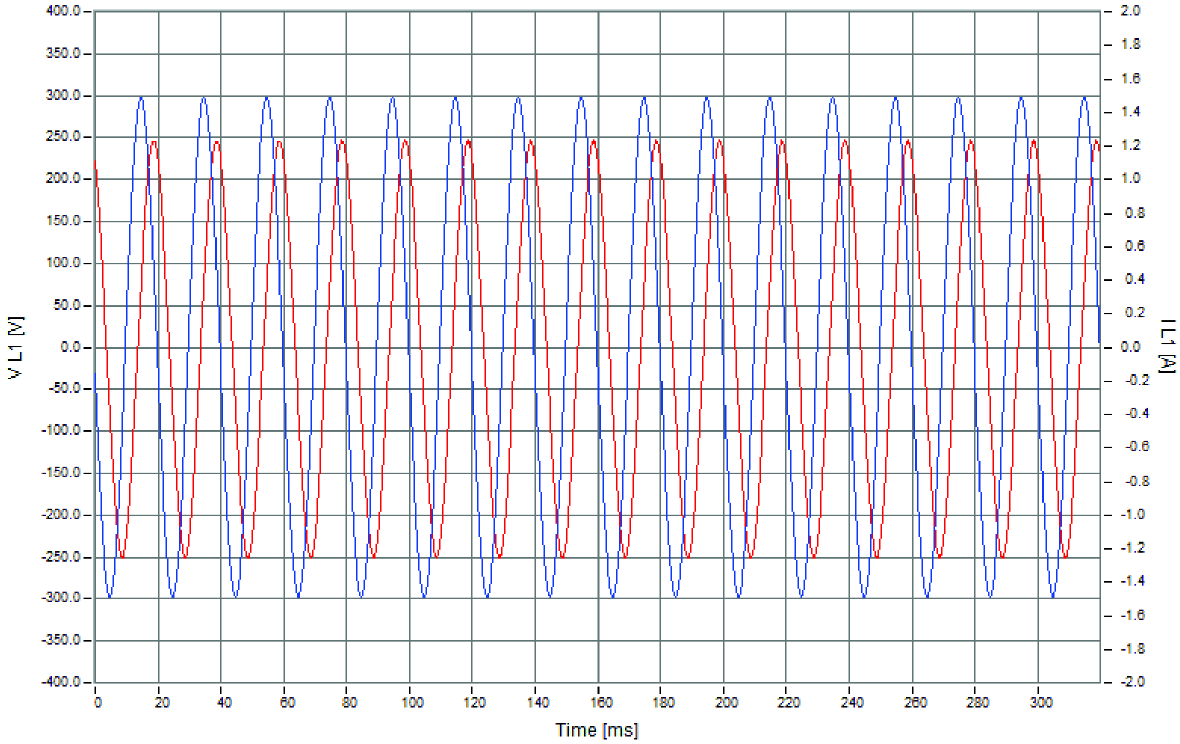


Figure 24. Current and voltage signal curve - 210 V

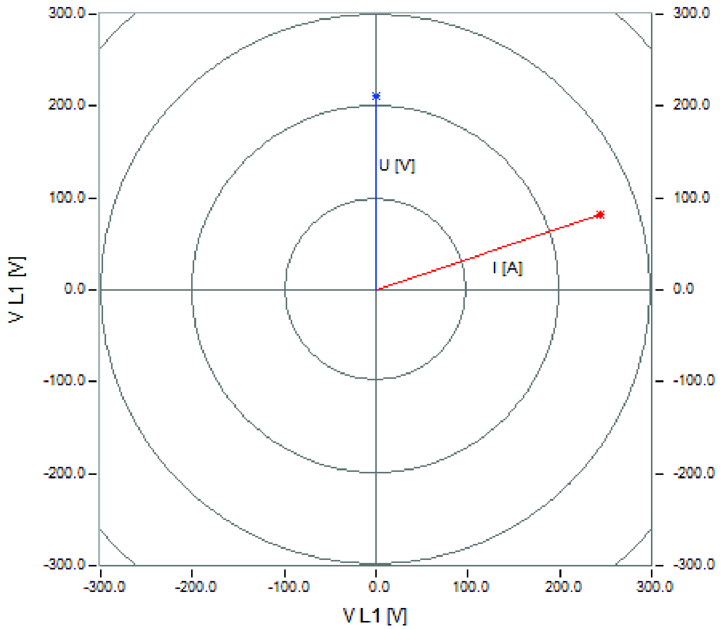


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

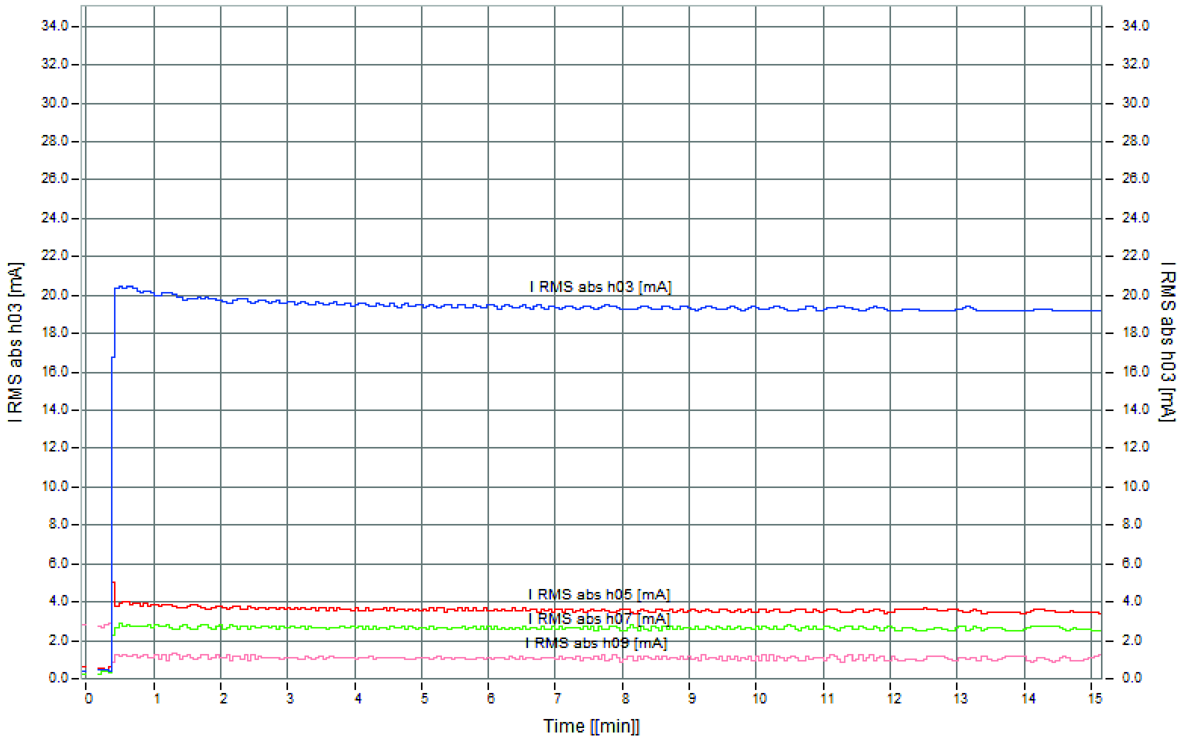


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

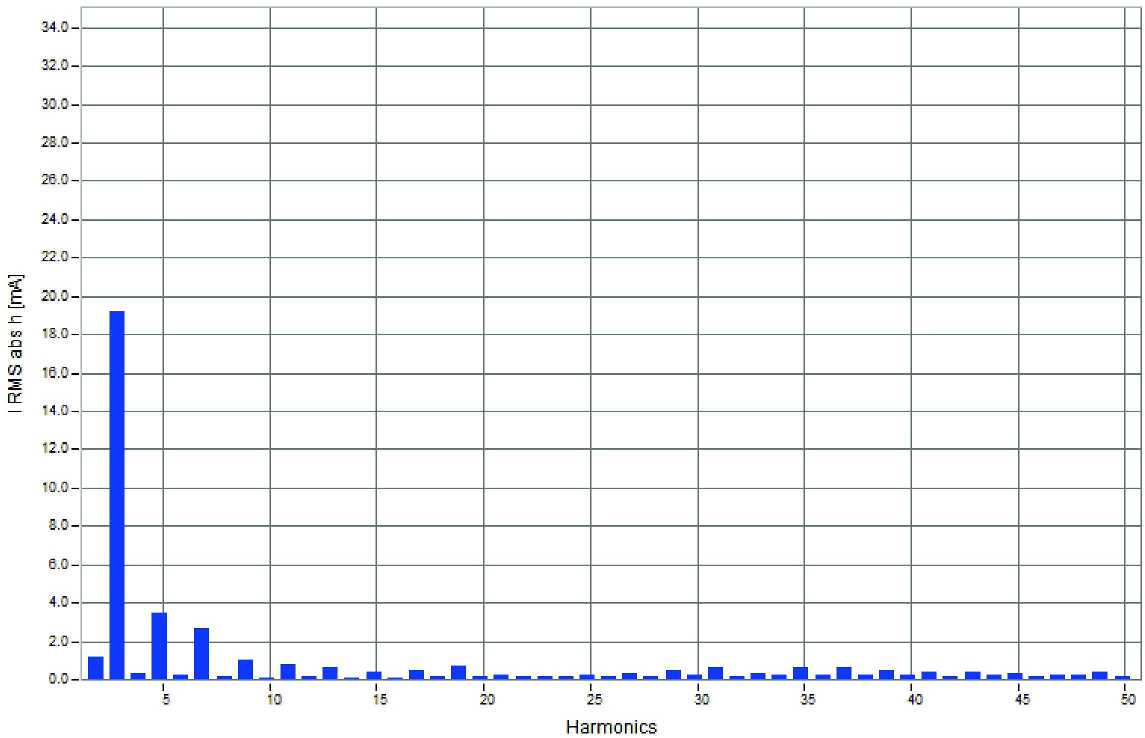


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.29\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.29\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 220.32 V

Current: I = 0.91 A

Active Power = 60.96 W

Reactive Power = 192.73 var

Apparent Power = 202.1 VA

Power Factor = 0.3

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

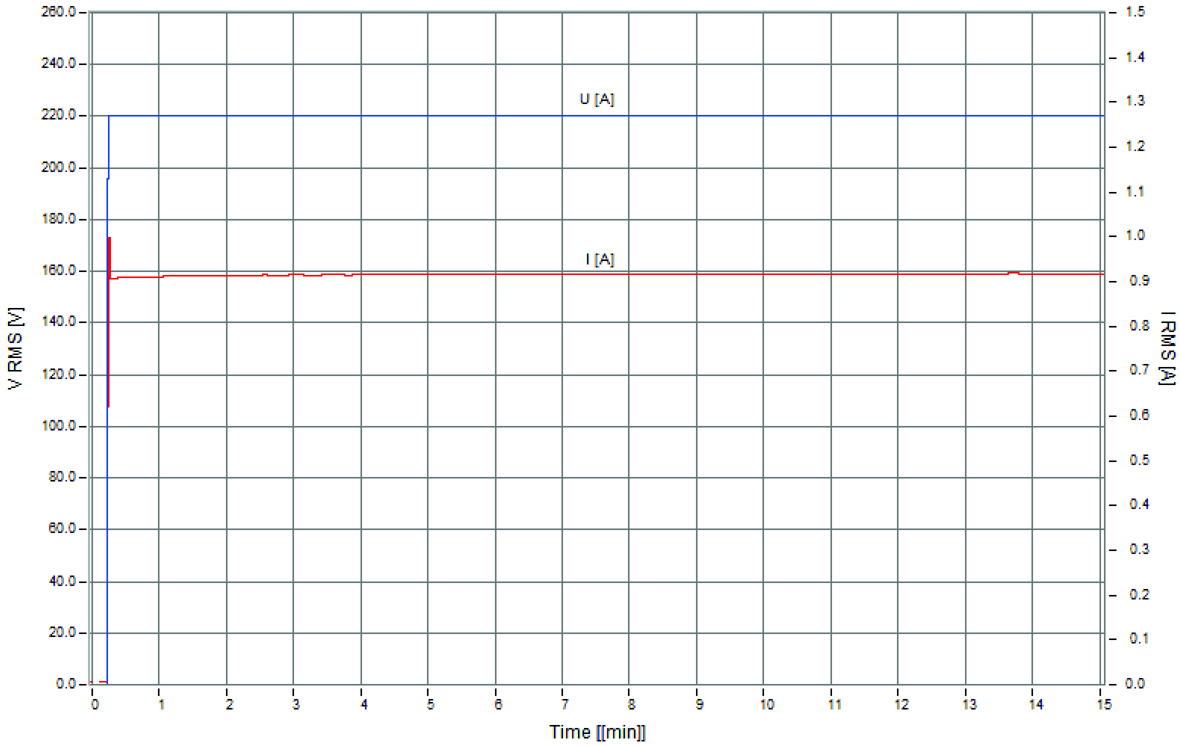


Figure 28. Root Mean Square of voltage and current - 220 V

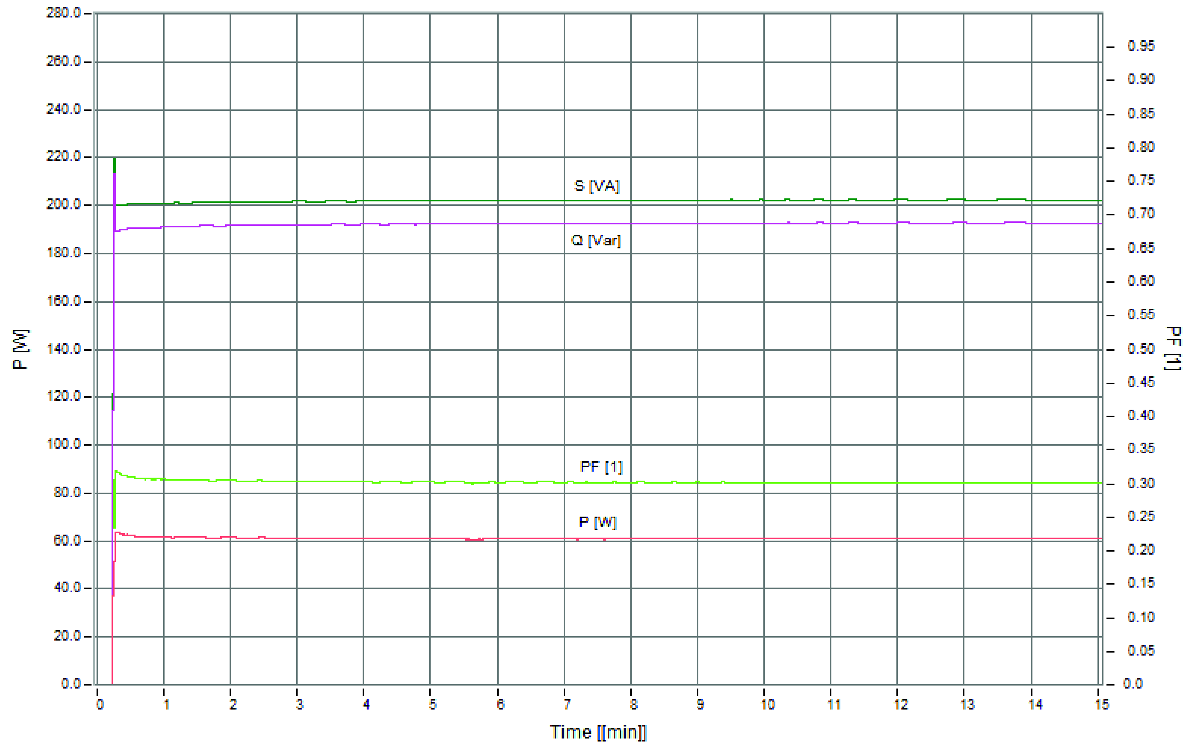


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 220.32	[V]	*****	0.00^0
I L1 = 0.91	[A]	*****	72.49^0

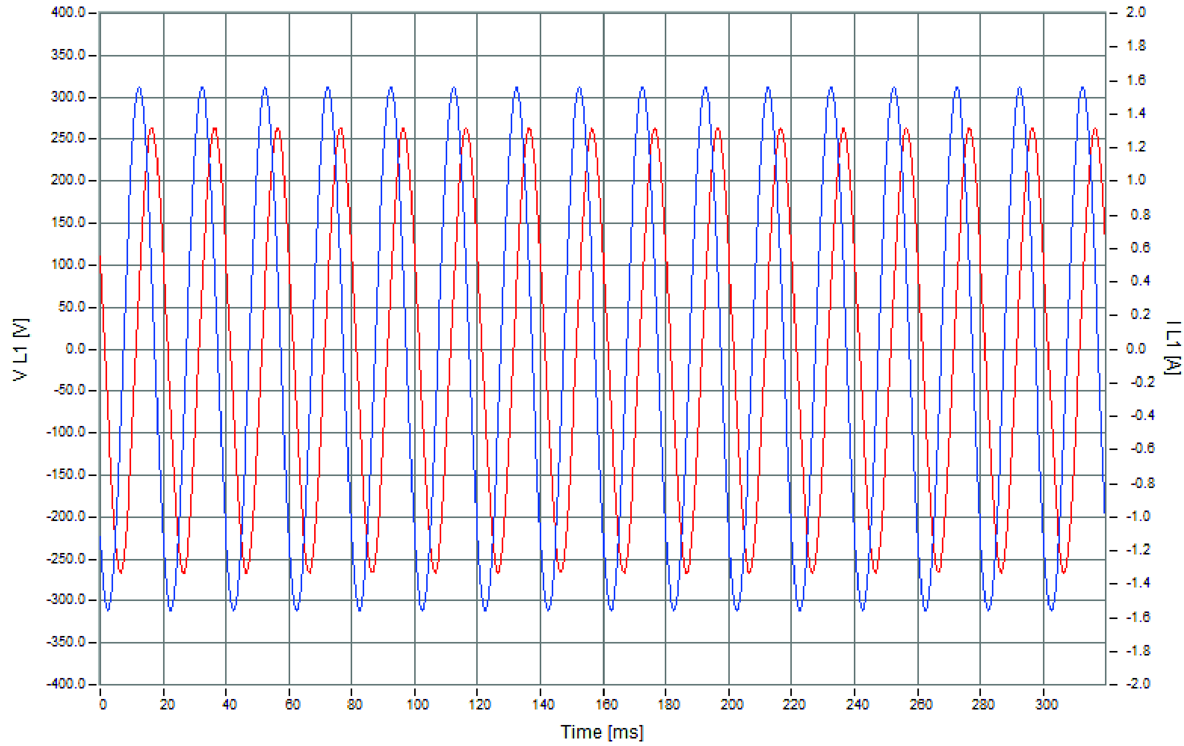


Figure 30. Current and voltage signal curve - 220 V

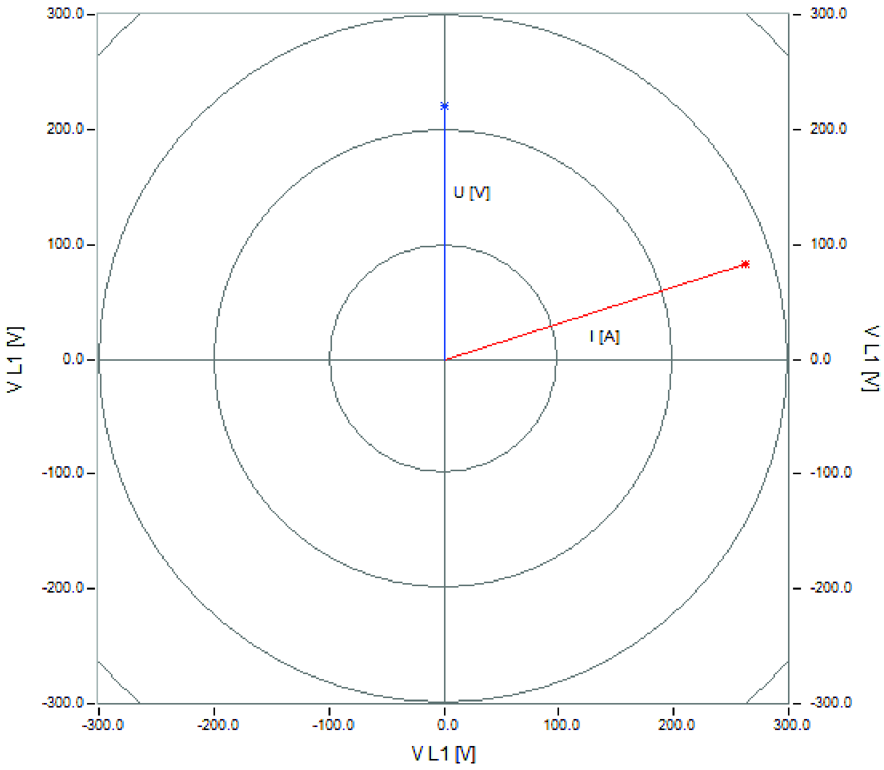


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

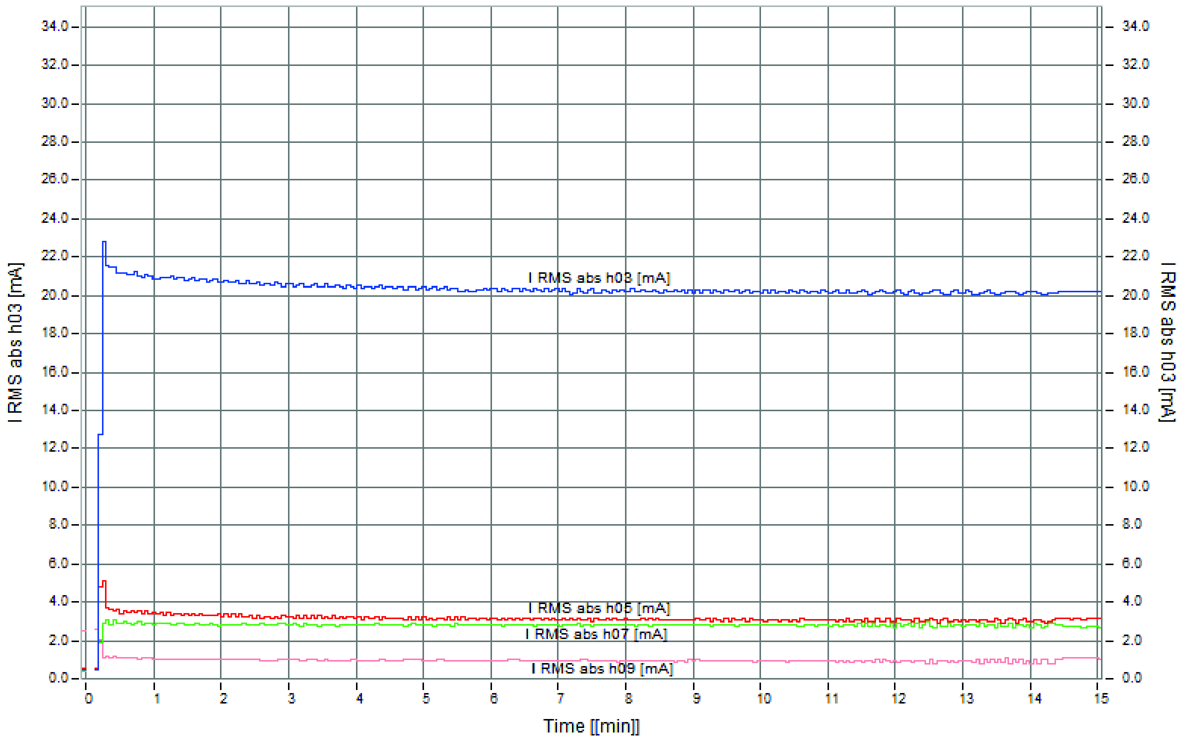


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

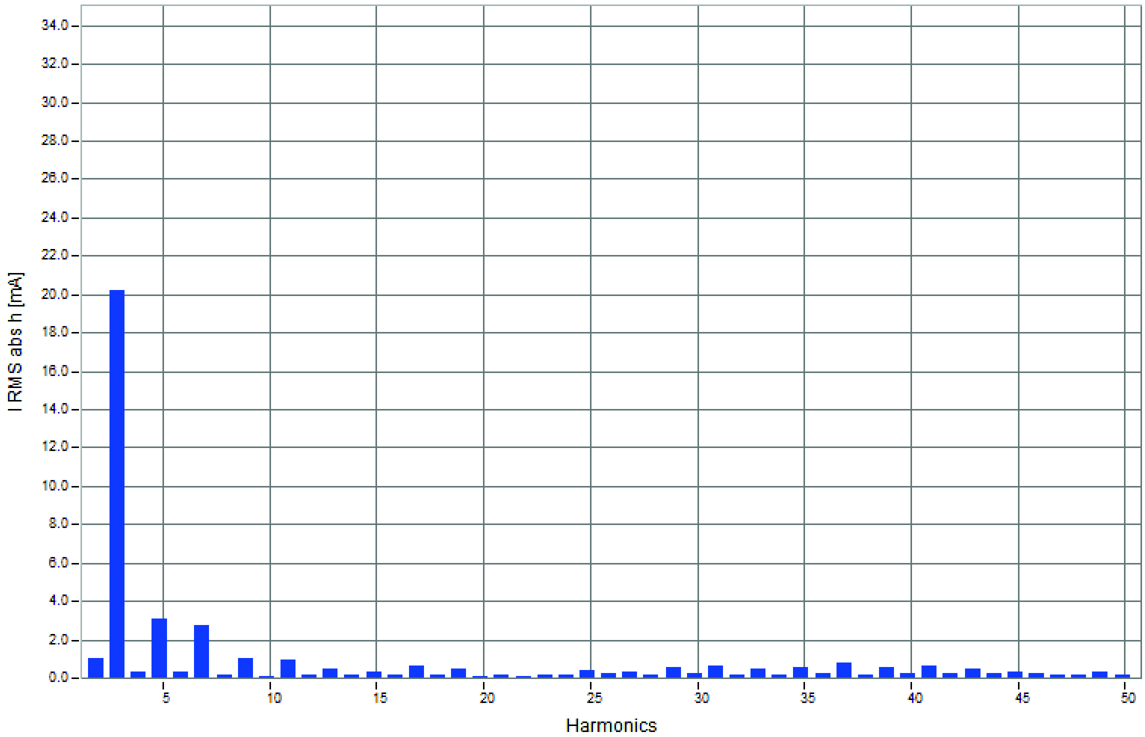


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.27\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.27\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 240.40 V
Current: I = 1.02 A
Active Power = 71.16 W
Reactive Power = 234.3 var
Apparent Power = 245.56 VA
Power Factor = 0.28

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

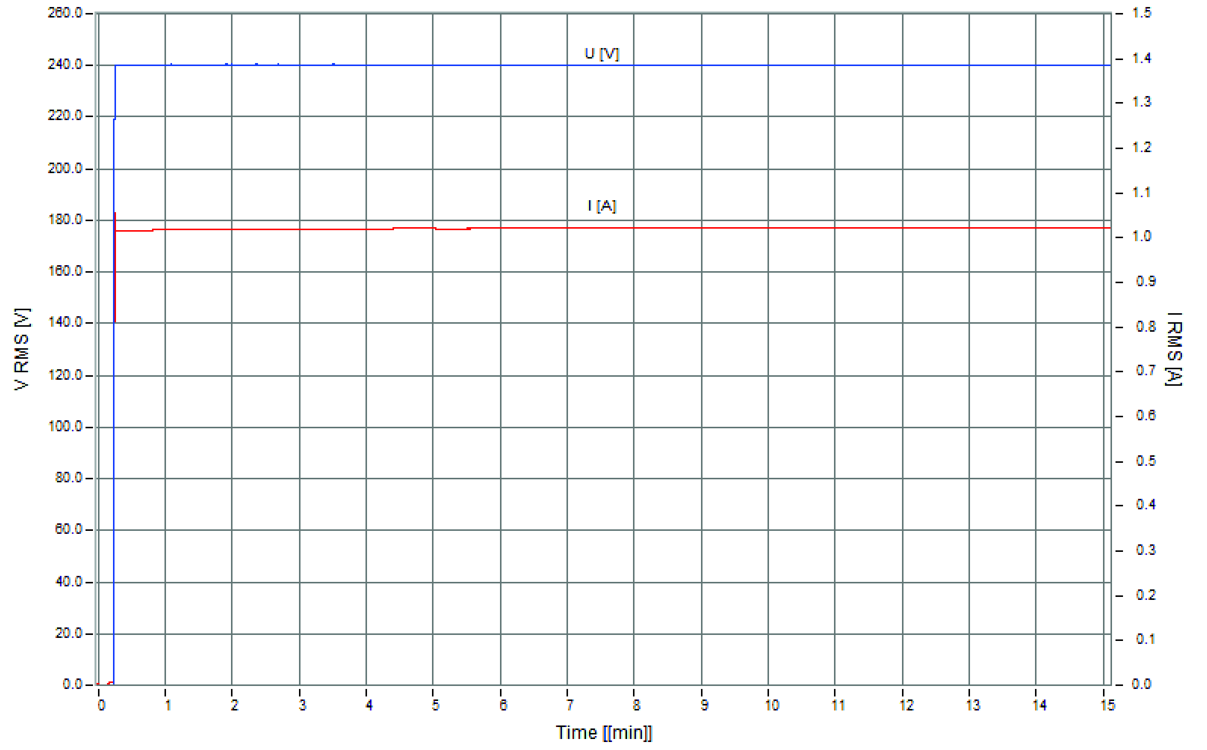


Figure 34. Root Mean Square of voltage and current - 240 V

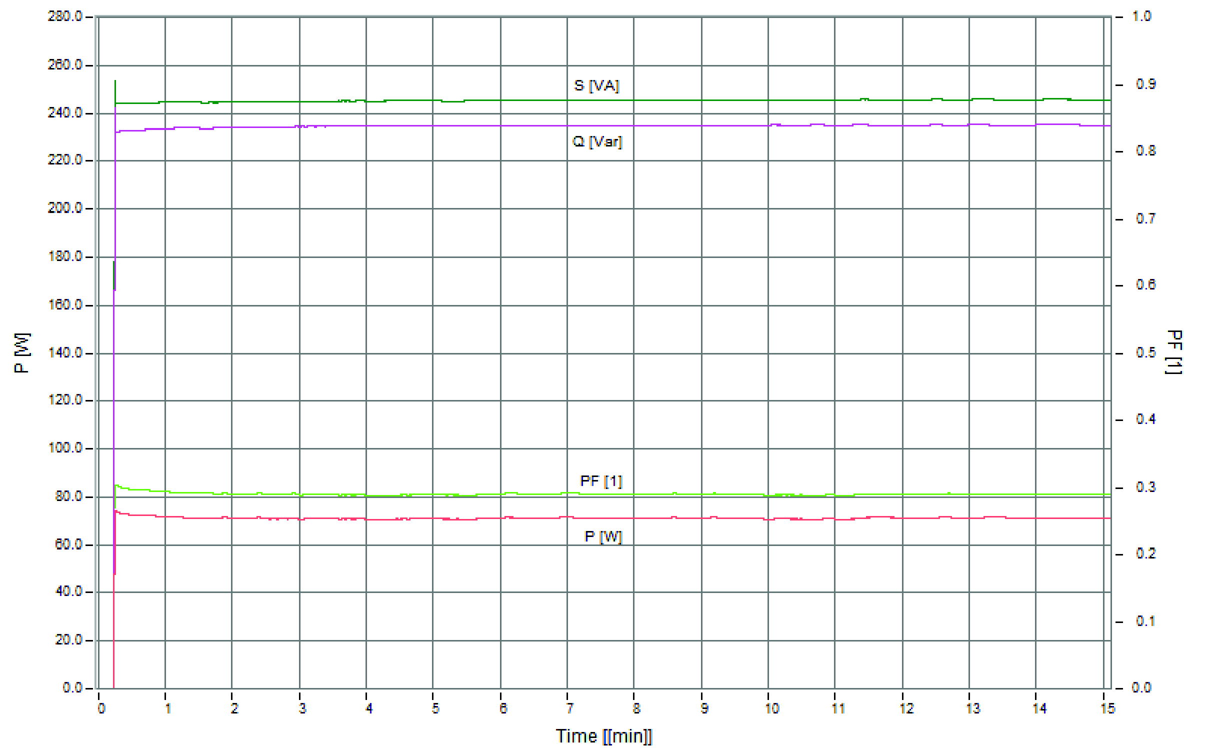


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 240.42	[V]	*****	0.00^0
I L1 = 1.01	[A]	*****	72.22^0

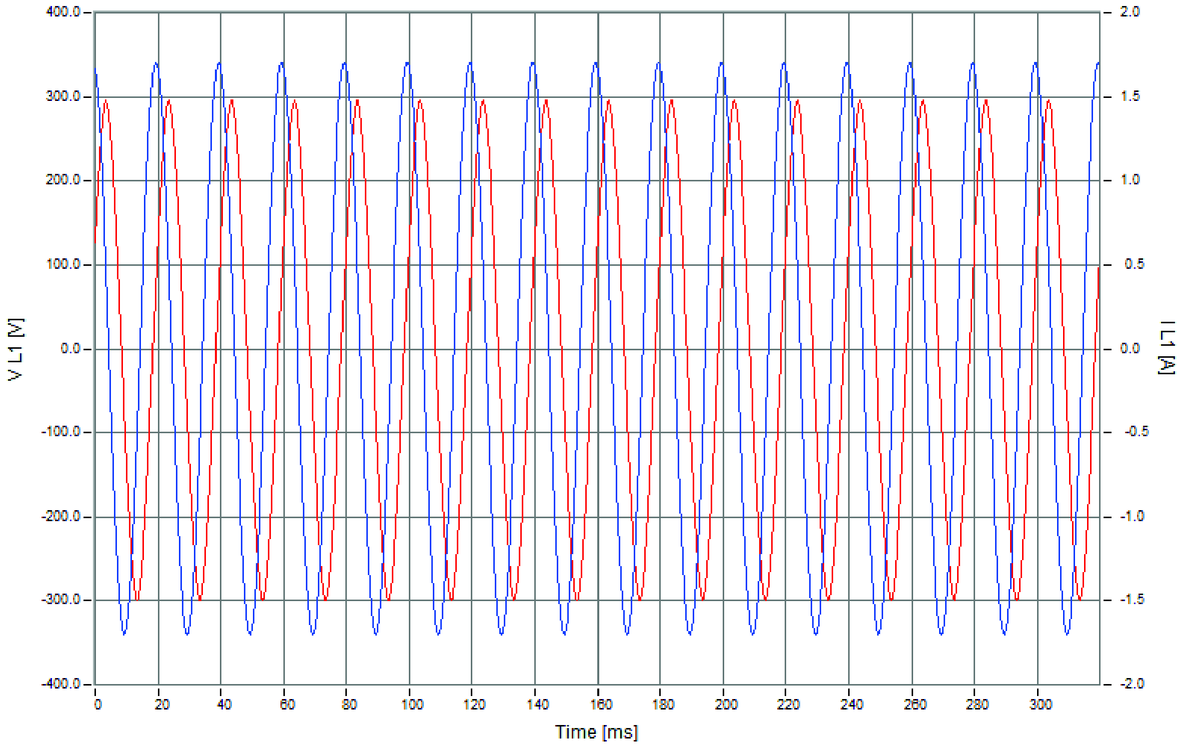


Figure 36. Current and voltage signal curve - 240 V

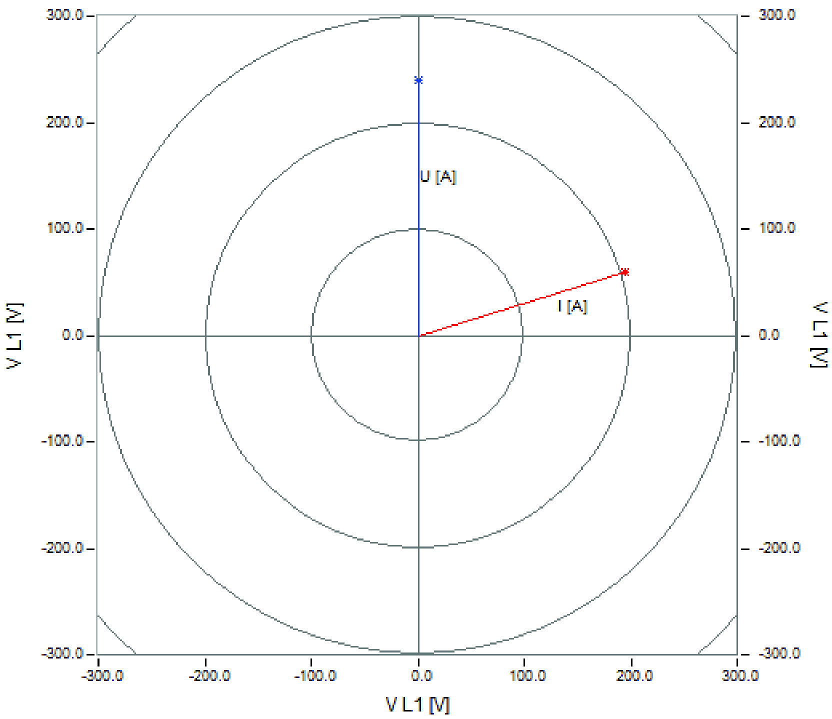


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

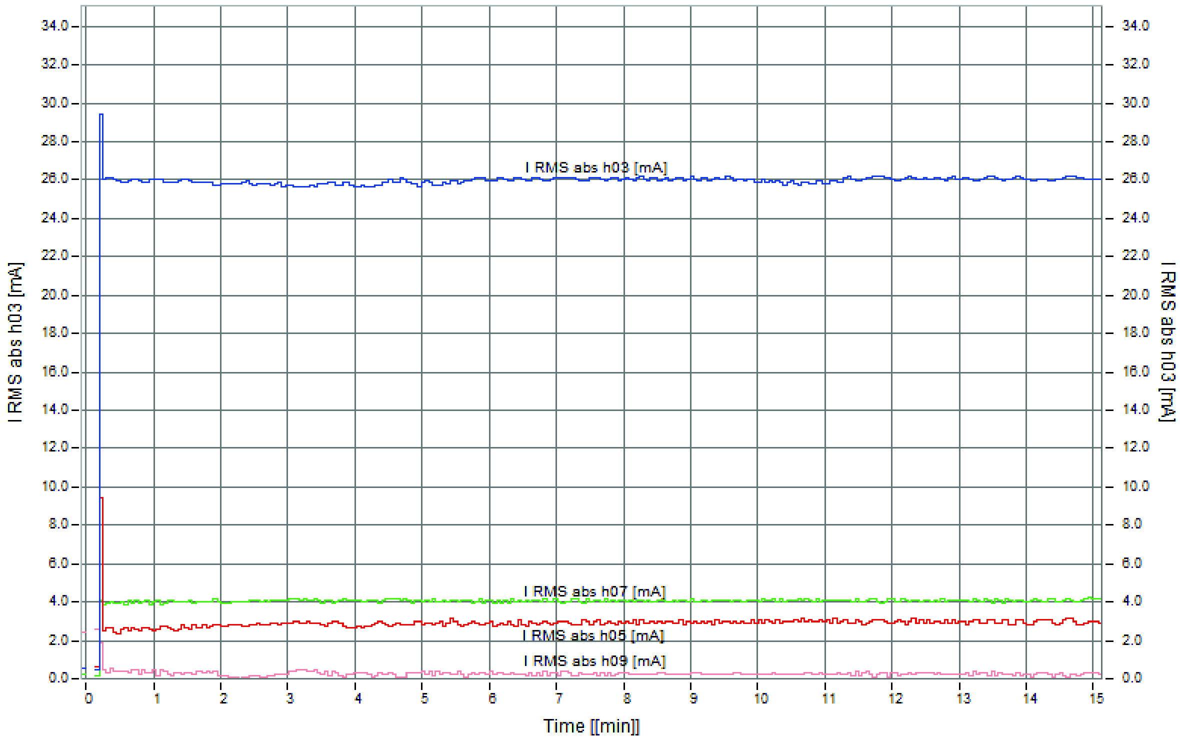


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

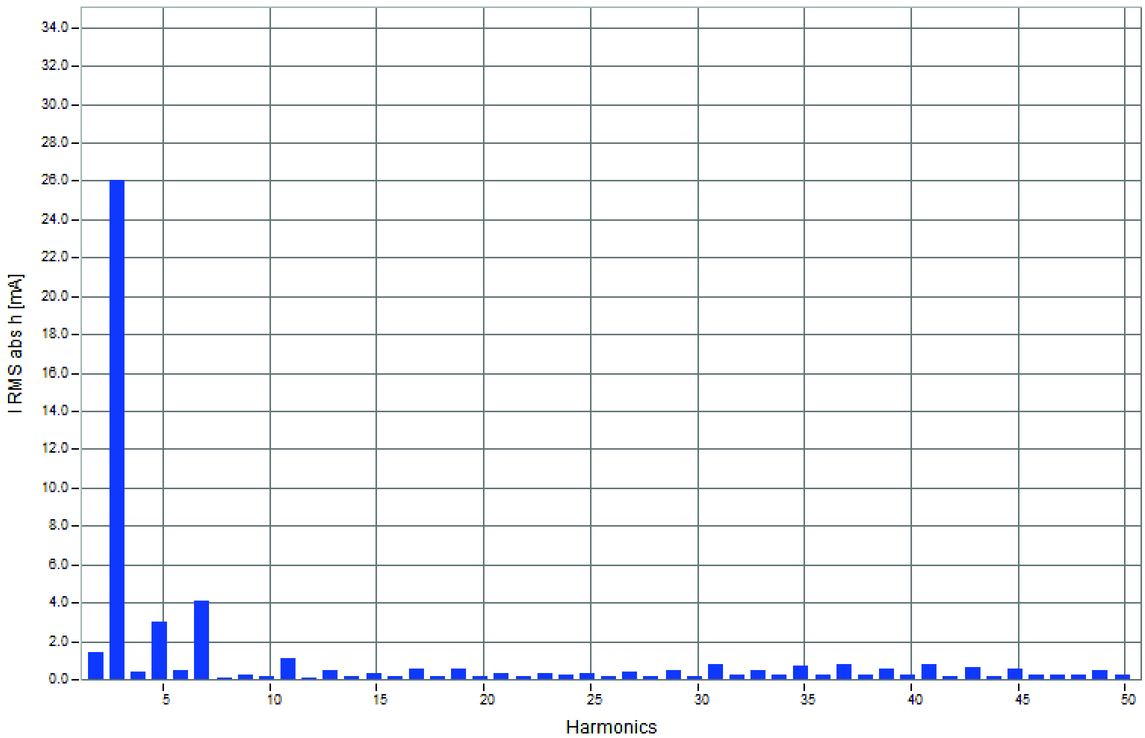


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.61\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.61\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:

Voltage: U = 250.43 V
Current: I = 1.07 A
Active Power = 75.97 W
Reactive Power = 258.28 var
Apparent Power = 269.37 VA
Power Factor = 0.28

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

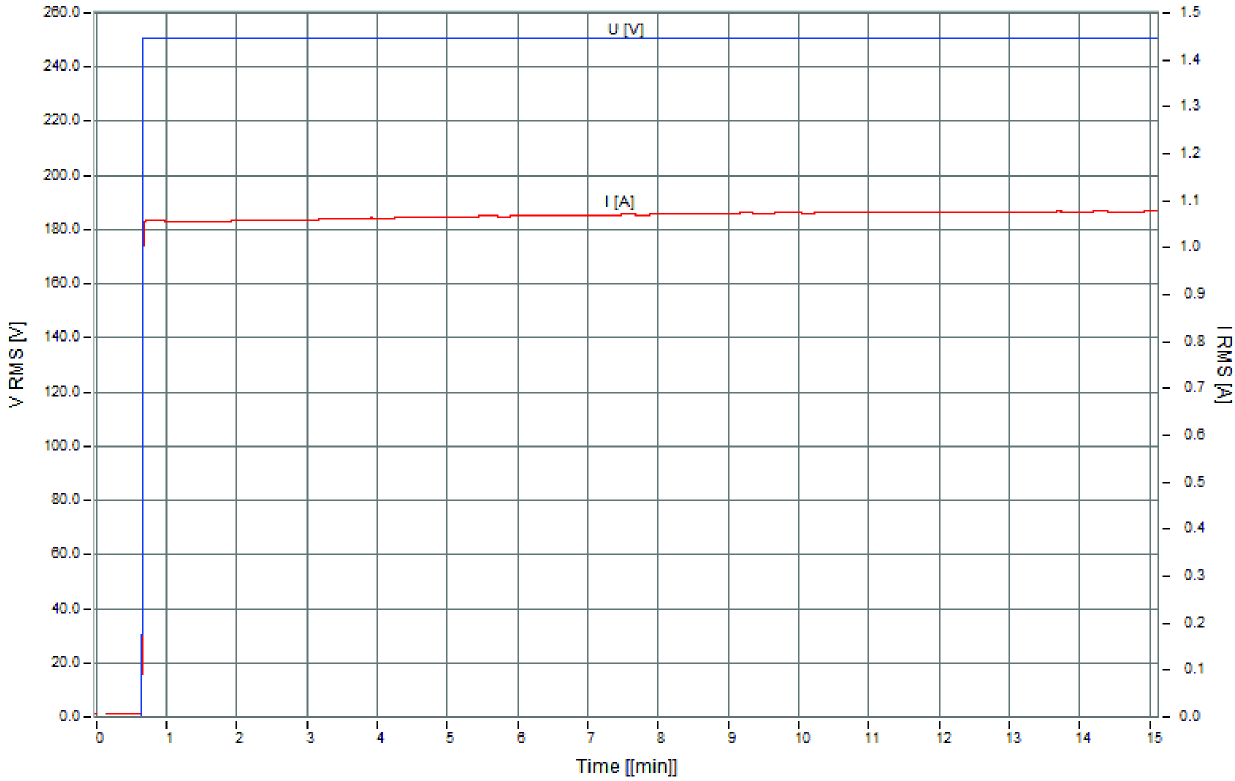


Figure 40. Root Mean Square of voltage and current - 250 V

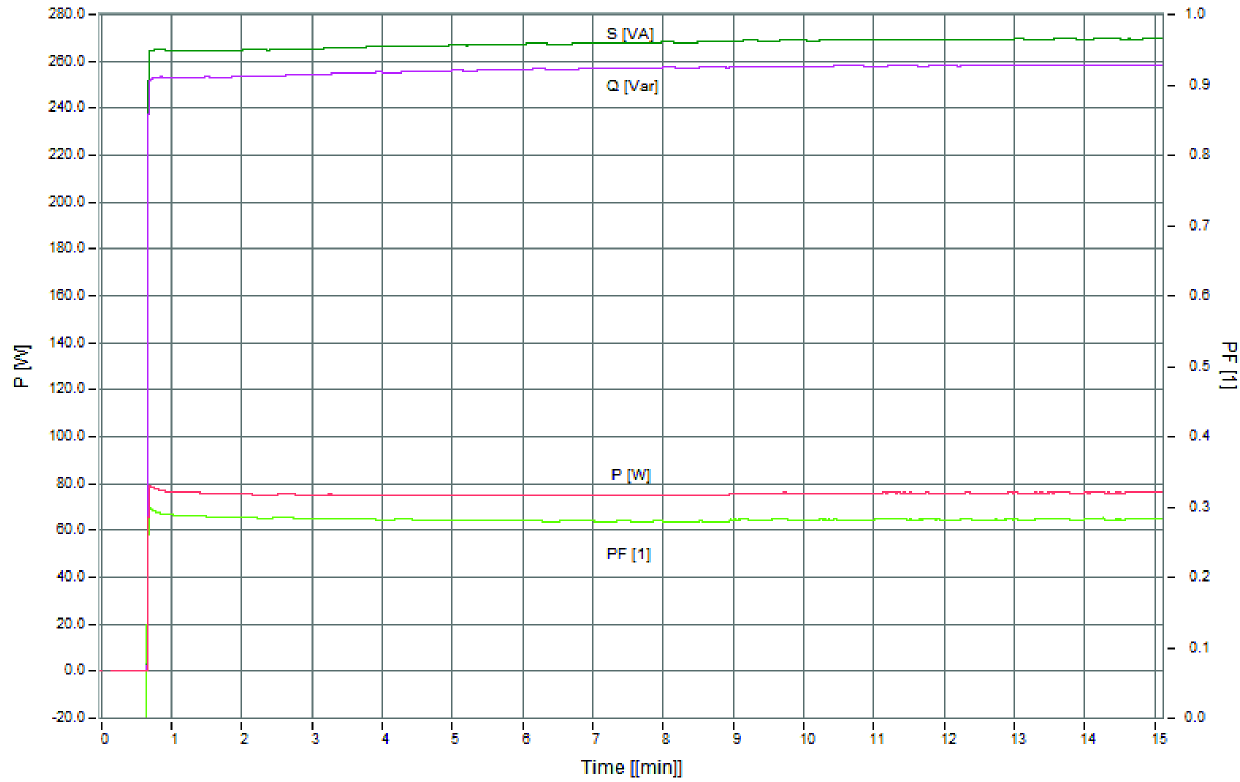


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 250.45	[V]	*****	$0,00^0$
I L1 = 1.06	[A]	*****	73.68^0

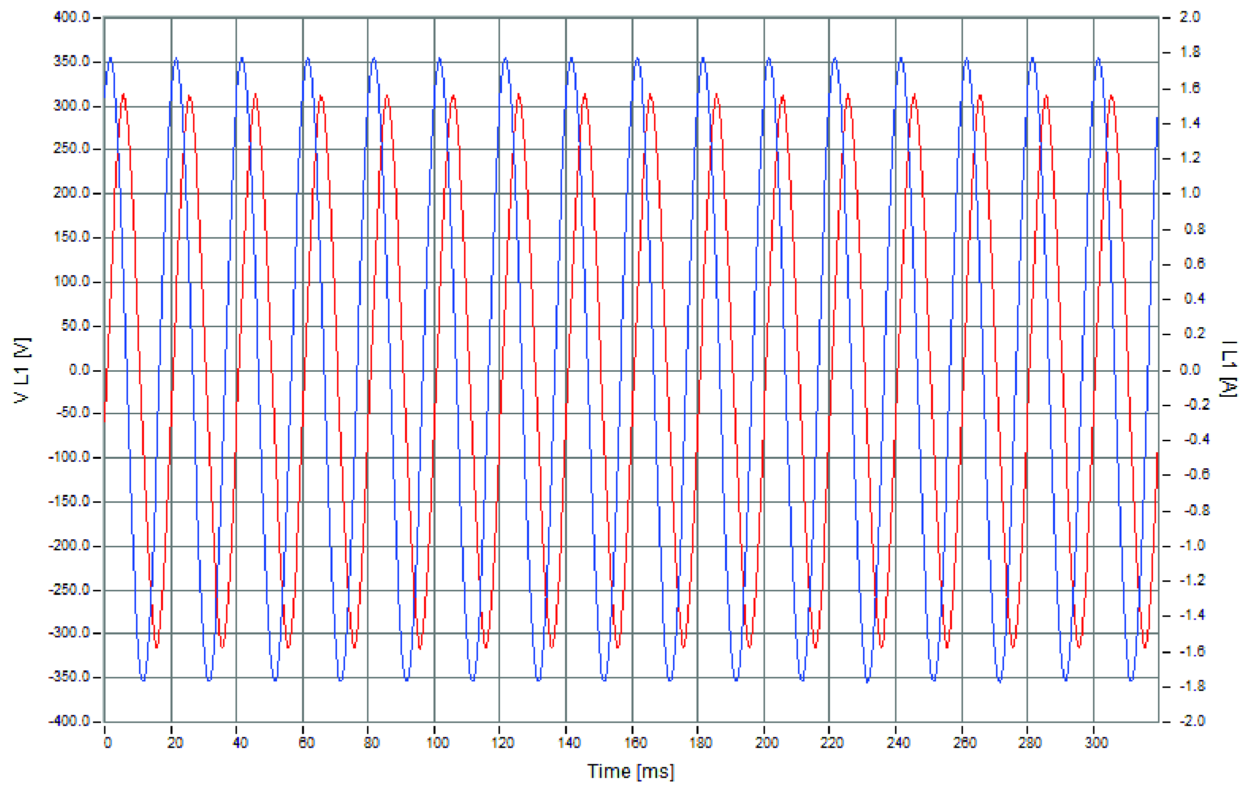


Figure 42. Current and voltage signal curve - 250 V

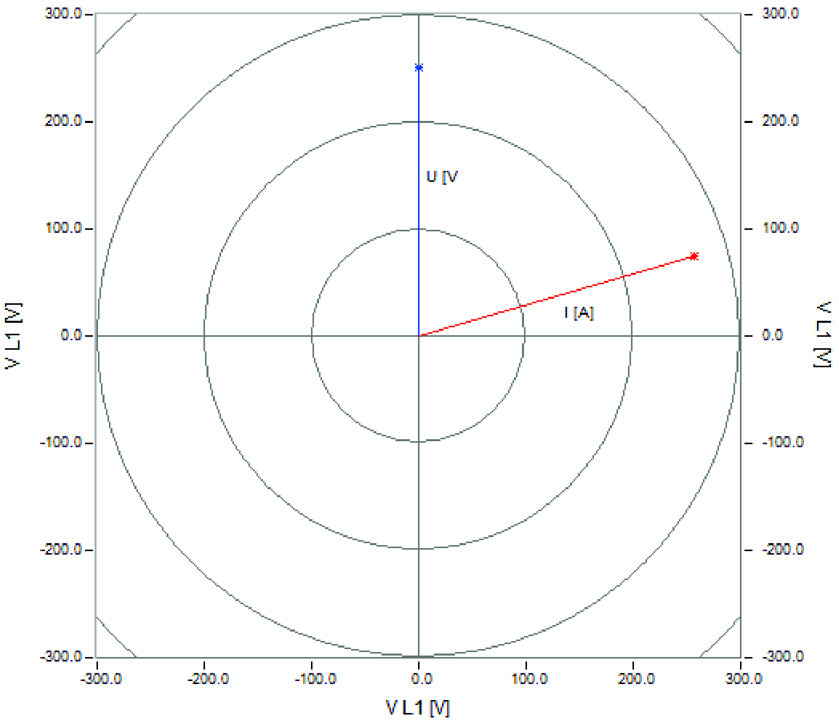


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

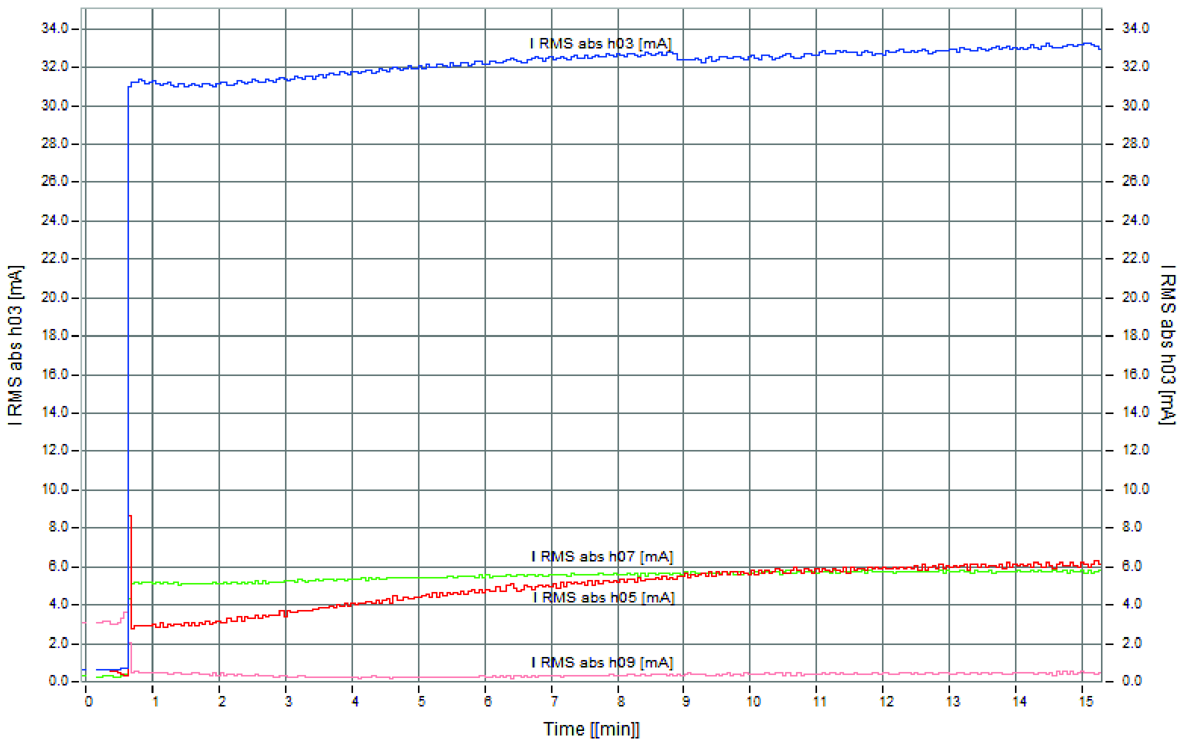


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

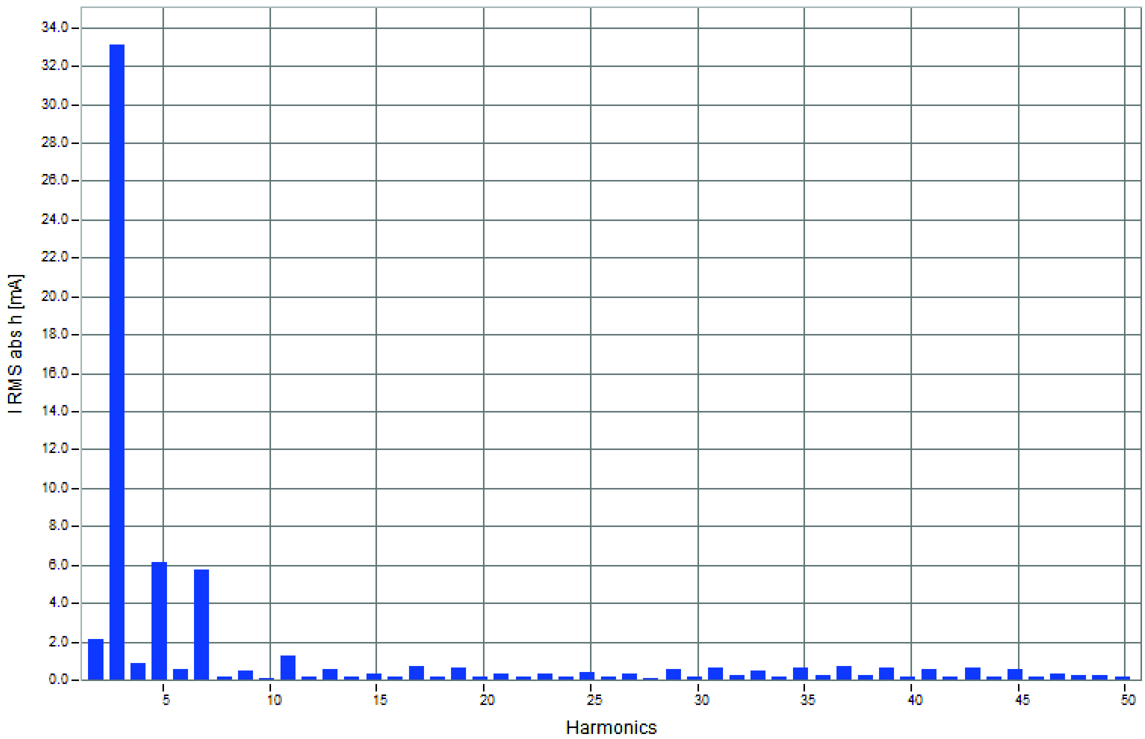


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.19\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.19\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results concernin the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 3.19%, for the maximum voltage, 1.09 p.u.. The minimum THD, 2.27%, is measured for the voltage 0.96 p.u.. Further increase of the voltage, 1.04 p.u., causes a slight increase of the THD, 2.61%.

In **outside at 0.3^{0}C** , TDH reached the maximum value 3.08% for voltage 1.09 p.u. and the minimum value 2.52 % is measured for the nominl voltage.

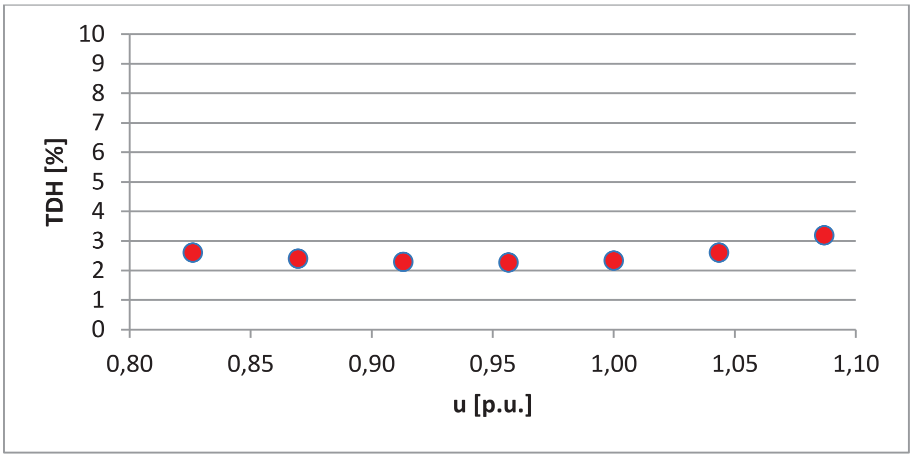


Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature

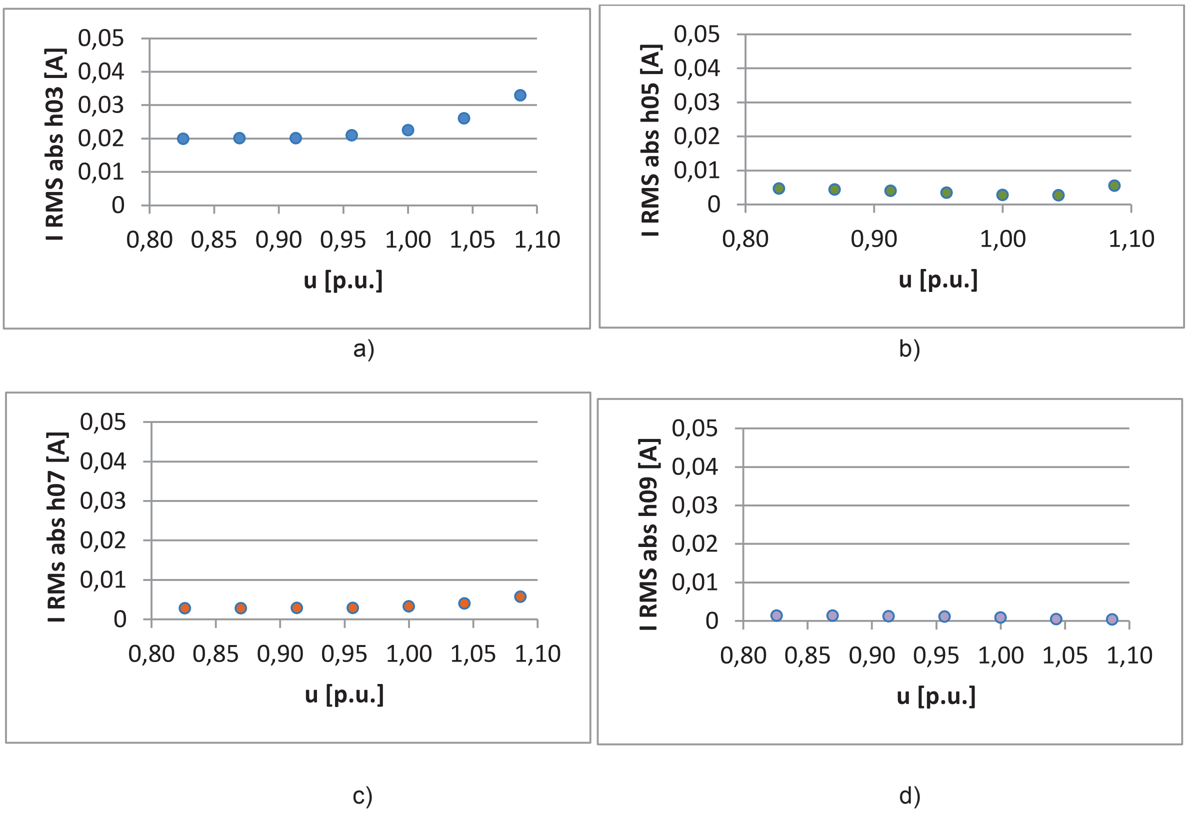


Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which have a parabolic behaviour with a minimum of 0.01mA by voltage 0.82 p.u.. Figures 47. b) and d) shows the 5th and the 7th harmonic respectively. In both cases the harmonic values are increasing with the voltage increase. Figure 47. c) shows 9th harmonic which decreases marginally with the voltage increase.

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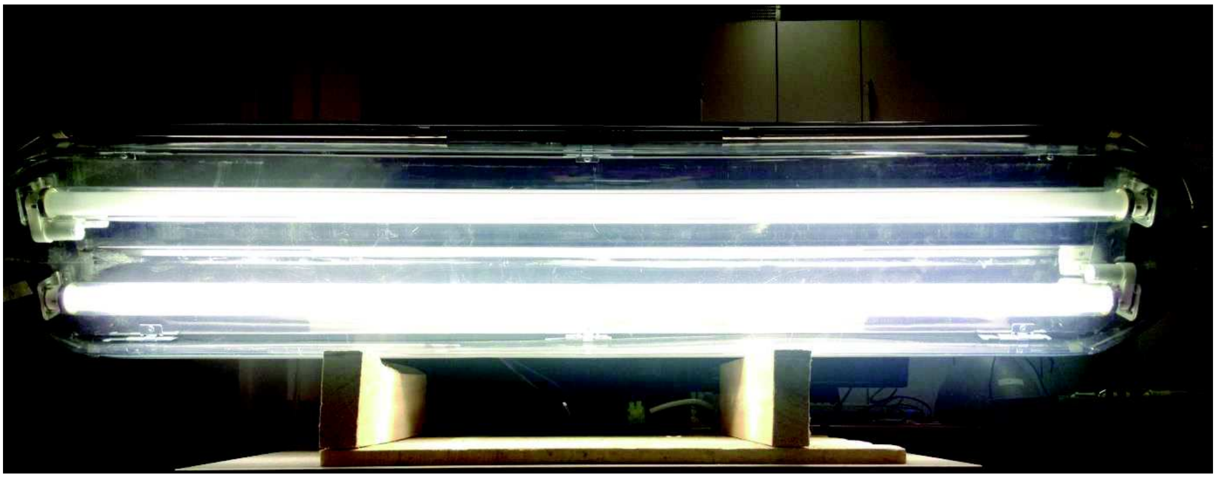
A - 1040 Wien

MEASUREMENT PROTOCOL 3

Conventional lamps-new
1XLight source: NARVA
Ballast: TRIDONIC ATCO



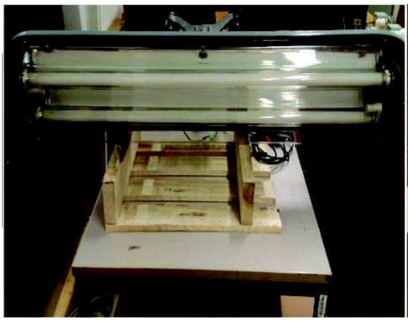
Vienna 27.January 2016

1. Content

2. List of figures

3. Light type

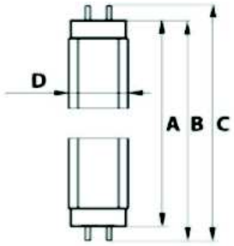
Conventional lamps
1 X NARVA fluorescent lamp
NARVA starter: BSt65
Status: new



4. Technical data

NARVA Fluorescent Lamp: LT - T8/T12 36 W COLOURLUX plus ET.XL
Voltage: 220-240 V
Real power : 36 W

Size A (max., mm)	1.199,4
Size B (min., mm)	1.204,1
Size B (max., mm)	1.206,5
Size C (max., mm)	1.213,6
Size D (max., mm)	38,0



NARVA starter: BSt65
Voltage: 220 V – 240 V
Power: 4 W – 65.80 W

TRIDONIC ATCO ballast- ETAWATT 36
Voltage: 230 V
Frequency: 50 Hz

5. Measurement

5.1. Schema

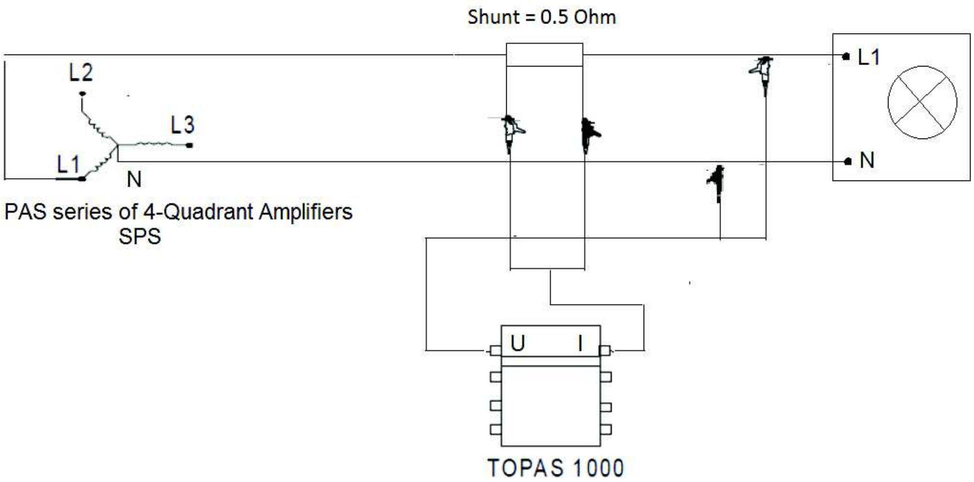


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside **Temperature**: 21.9^{0}C
Voltage range: 190-250 V **Shunt:** 0.5 Ω
Measurement interval: 15 min

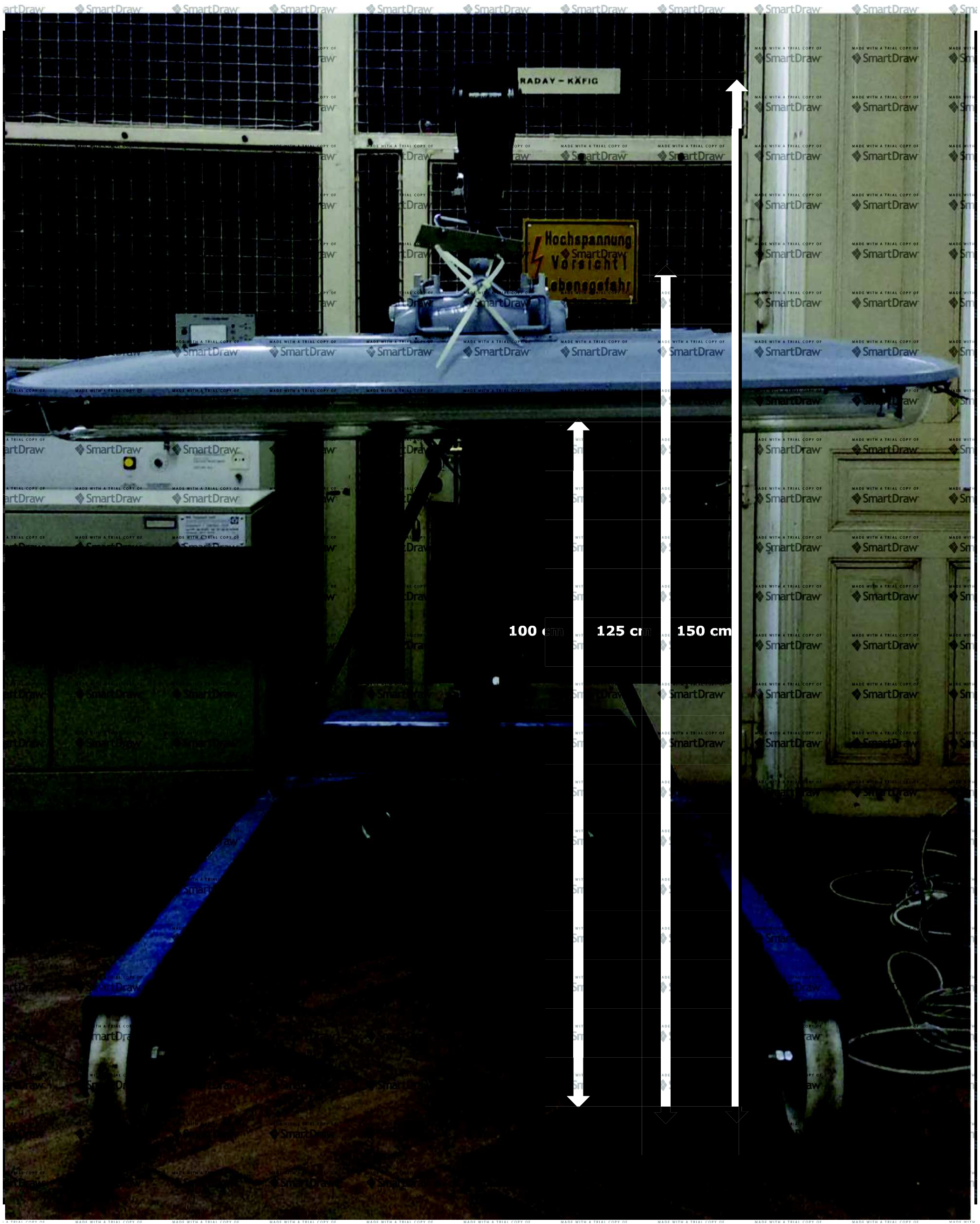


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement

Voltage: U = 230.25 V

Current: I = 0.76 A

Active Power = 62.81 W

Reactive Power = 165.25 var

Apparent Power = 176.86 VA

Power Factor = 0.35

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

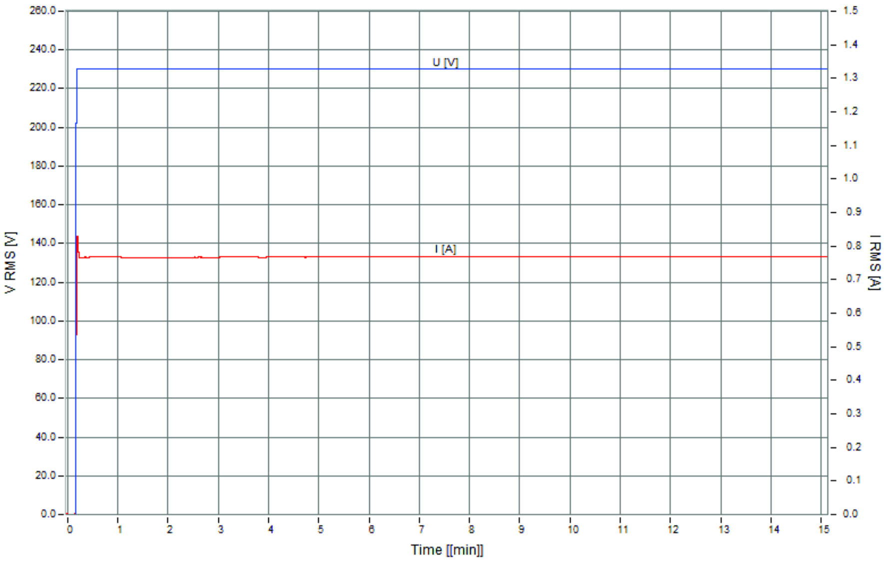


Figure 3. Root Mean Square of voltage and current - 230 V

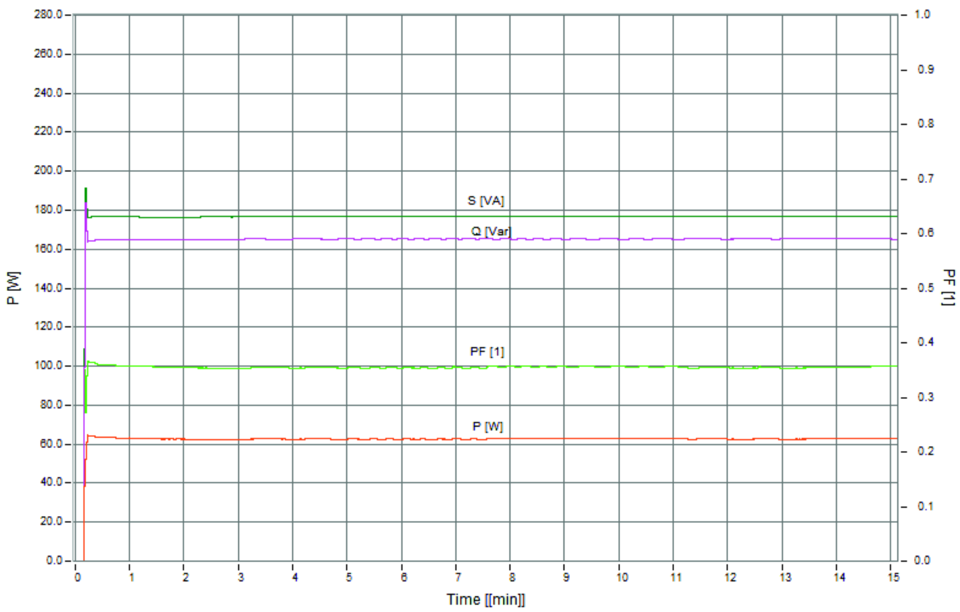


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 230.25	[V]	*****	0.00^0
I L1 = 0.76	[A]	*****	69.20

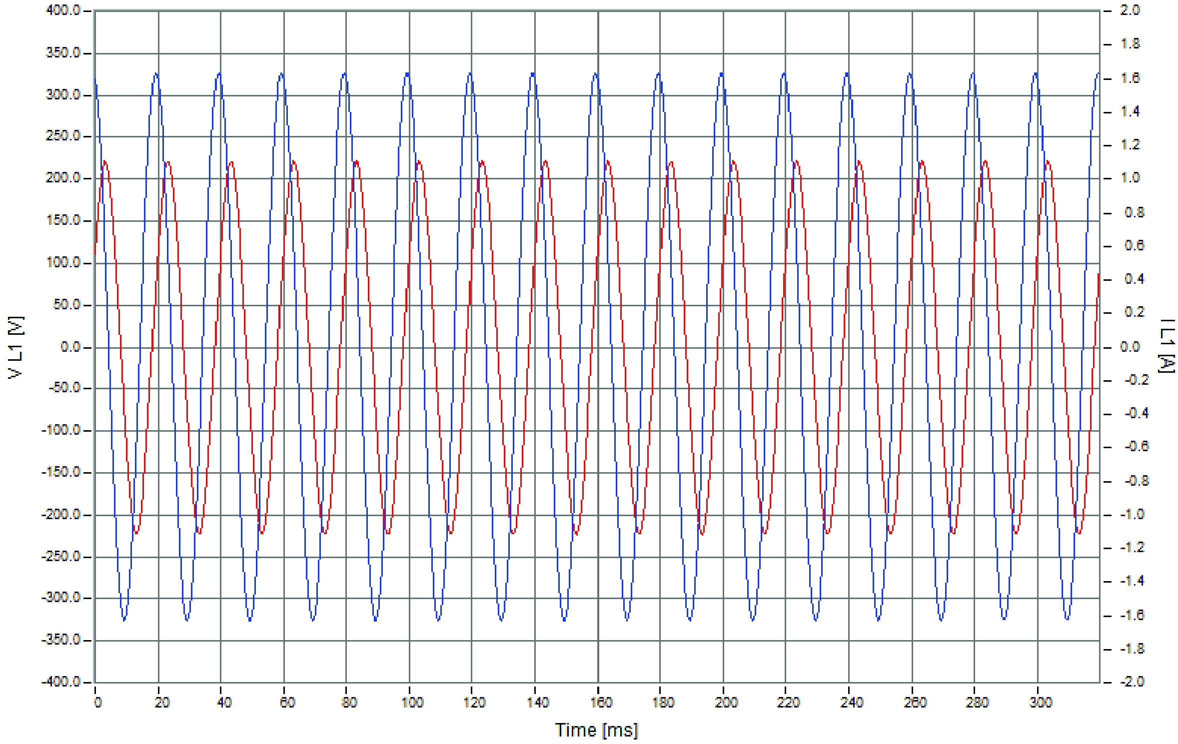


Figure 5. Current and voltage signal curve - 230 V

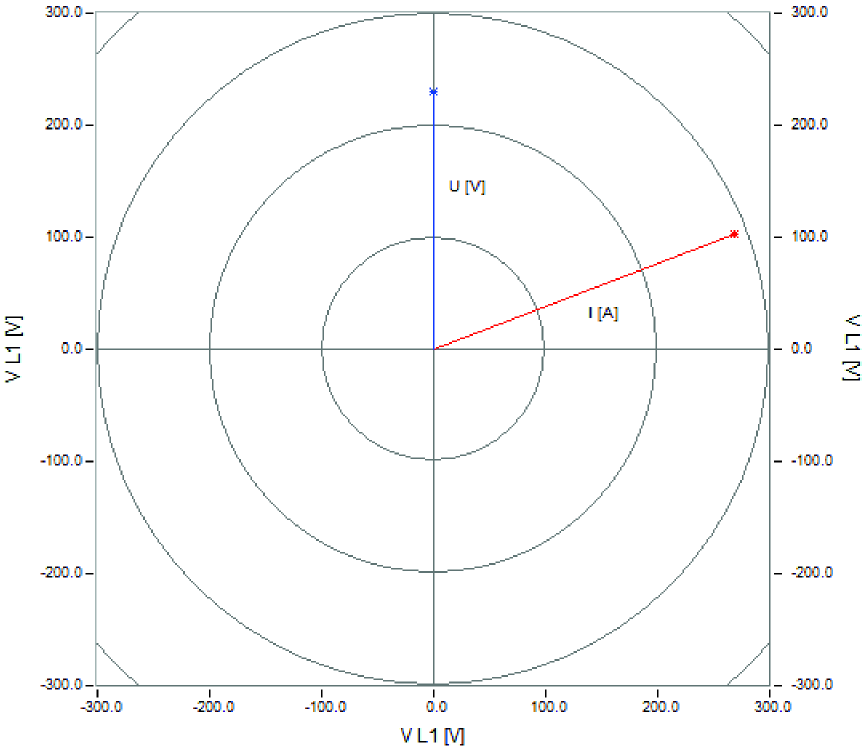


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

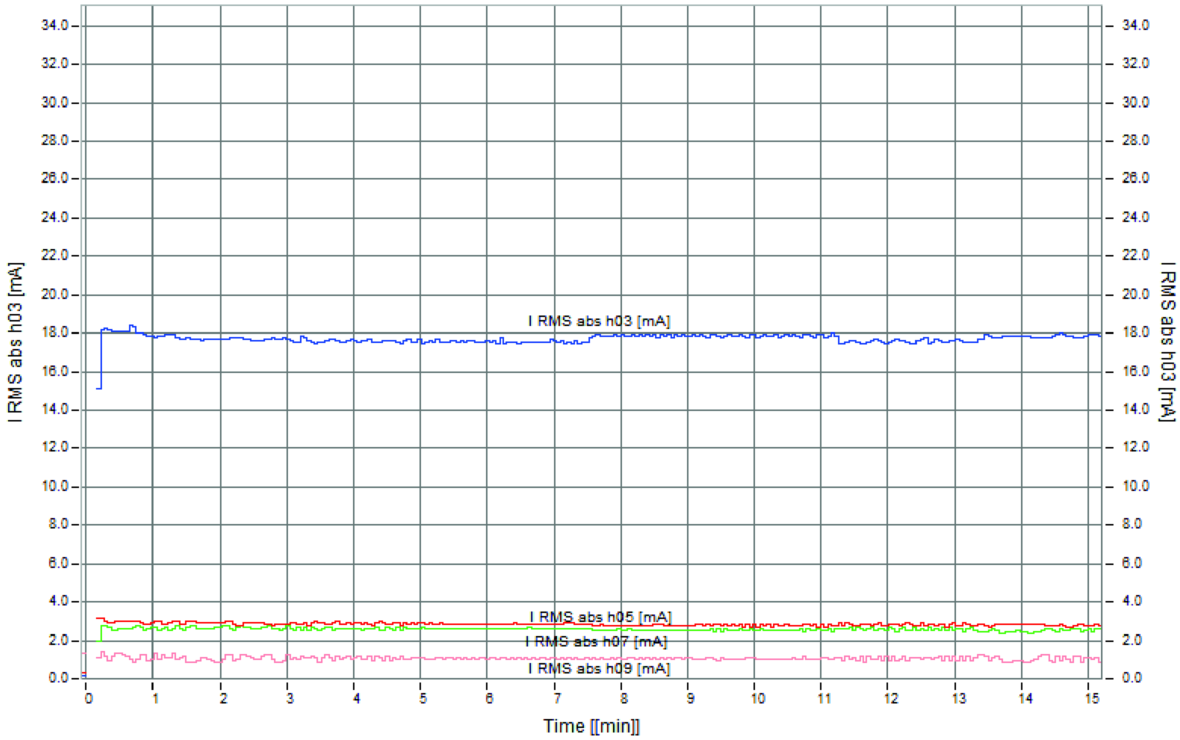


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

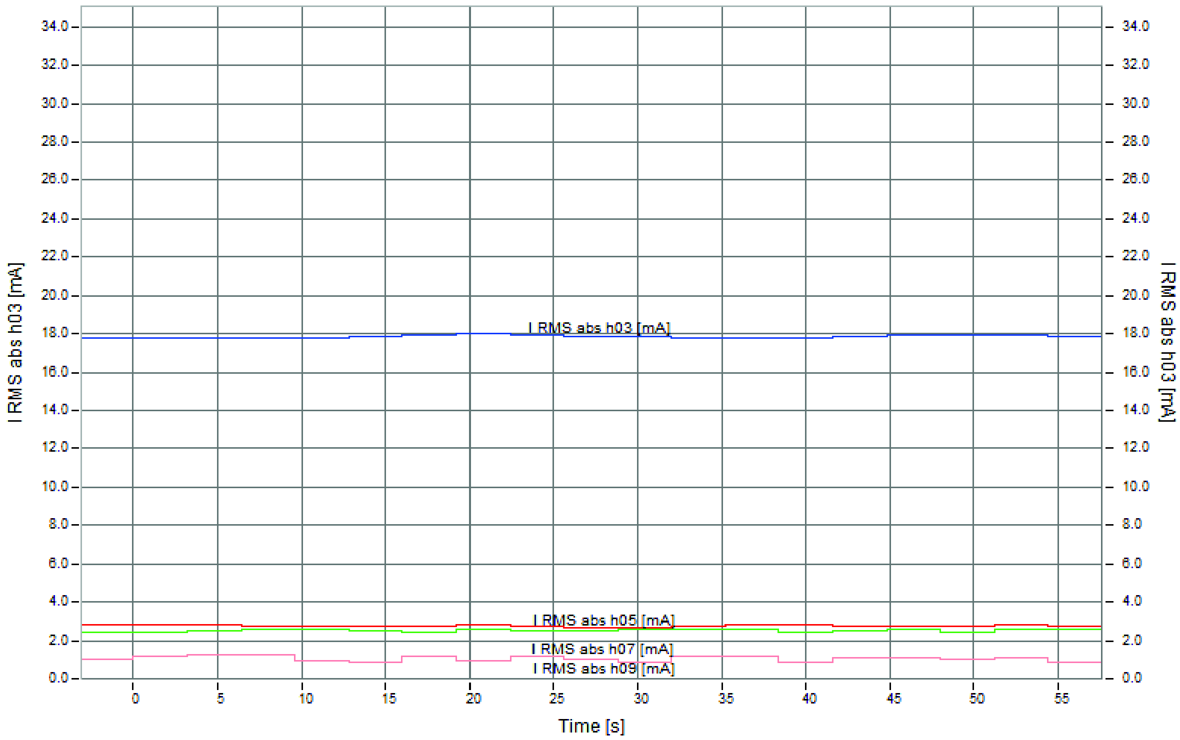


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

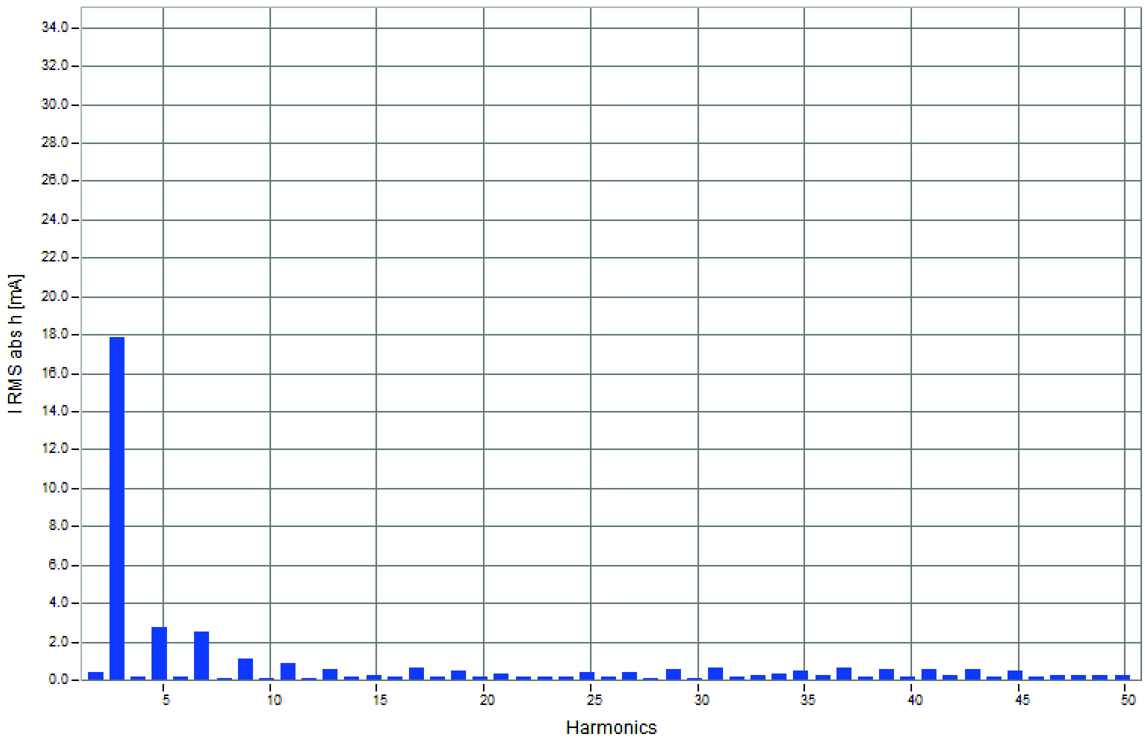


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.39\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.39\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 190.18 V
Current: I = 0.60 A
Active Power = 47.36 W
Reactive Power = 105.1 var
Apparent Power = 114.13 VA
Power Factor = 0.38

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

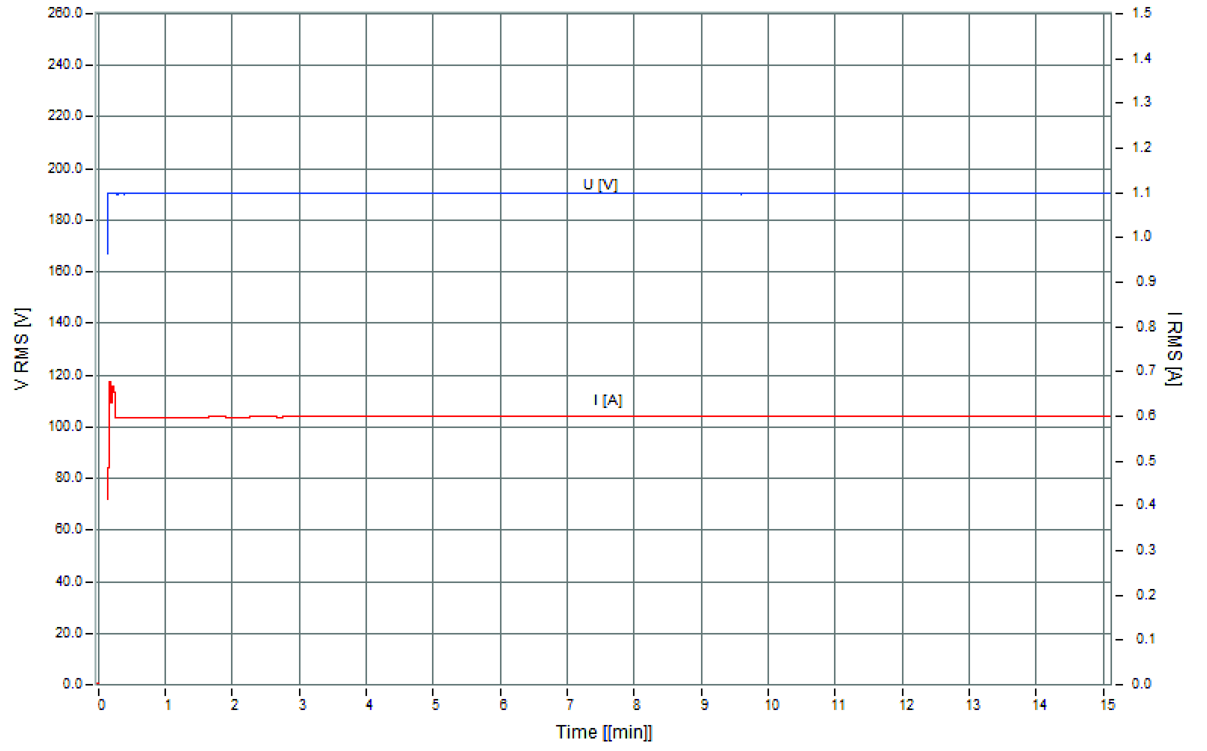


Figure 10. Root Mean Square of voltage and current - 190 V

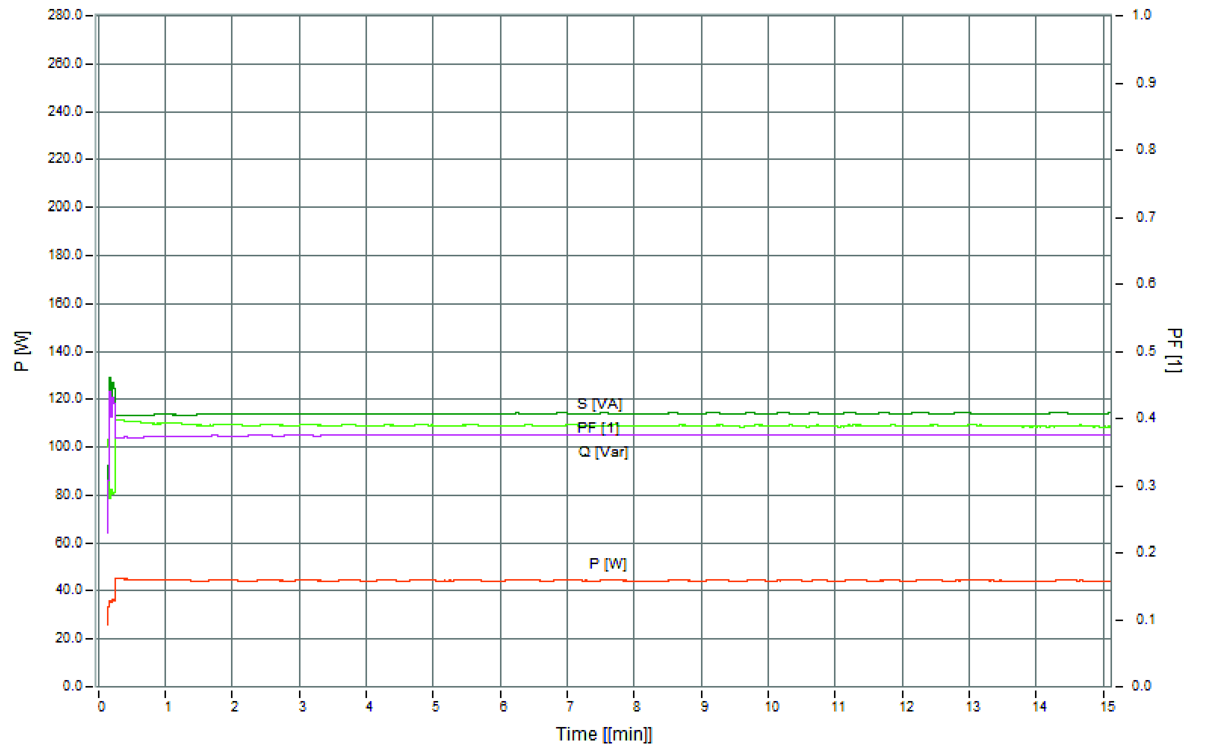


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 190.19	[V]	*****	0.00^0
I L1 = 0.60	[A]	*****	67.11^0

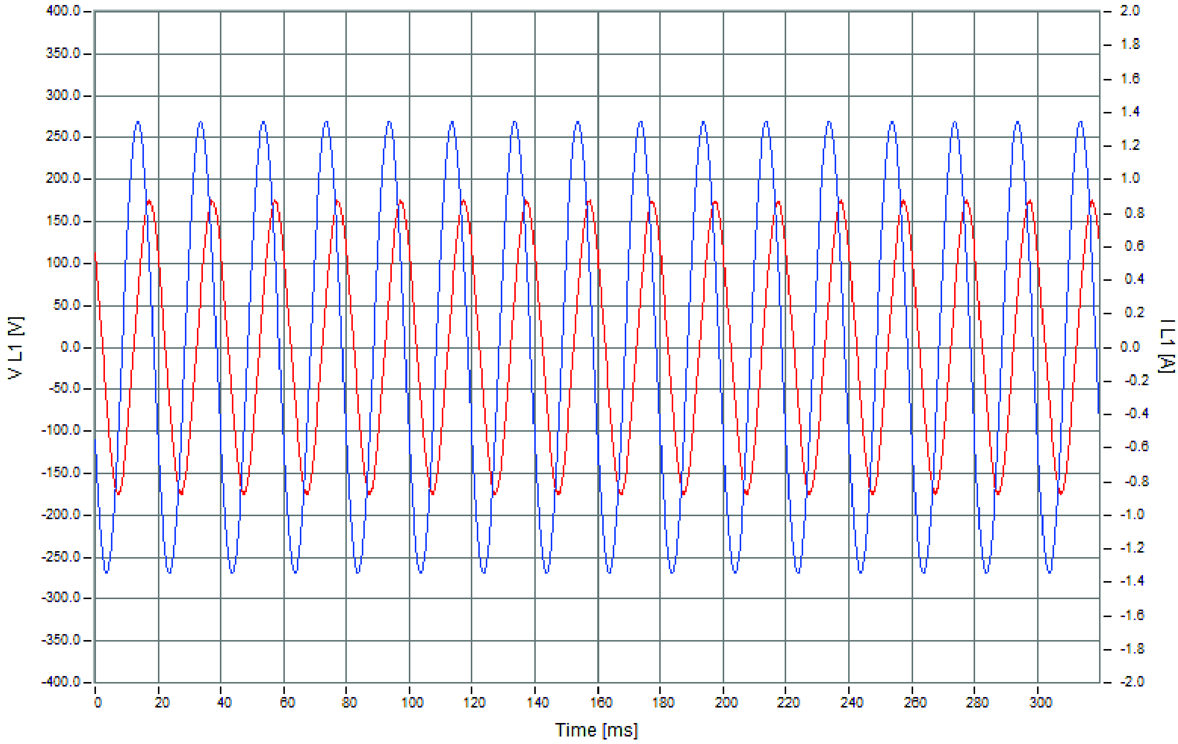


Figure 12. Current and voltage signal curve - 190 V

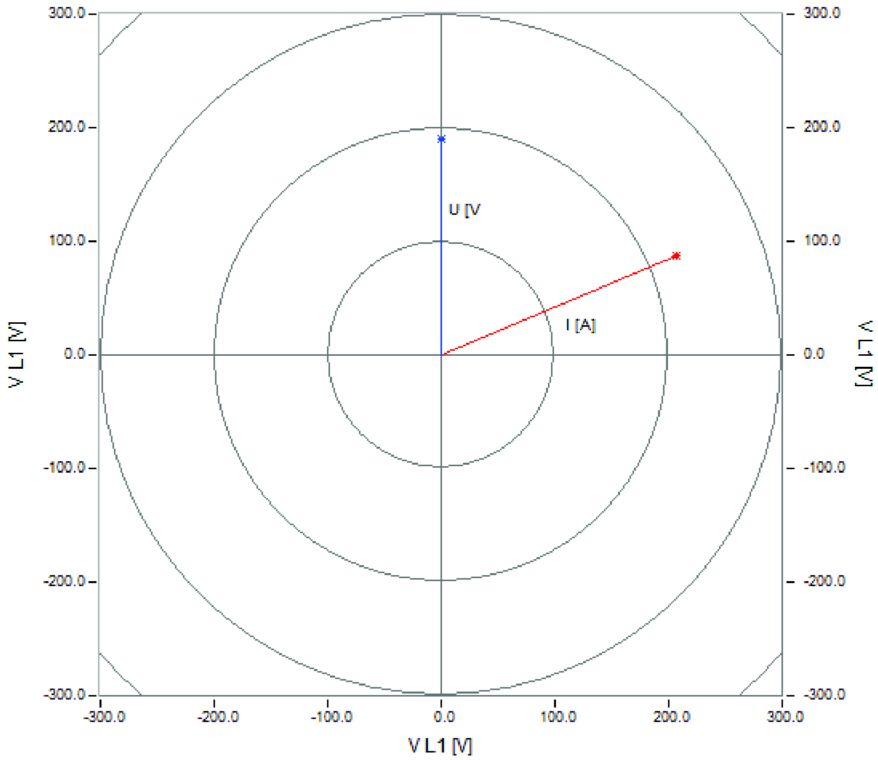


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

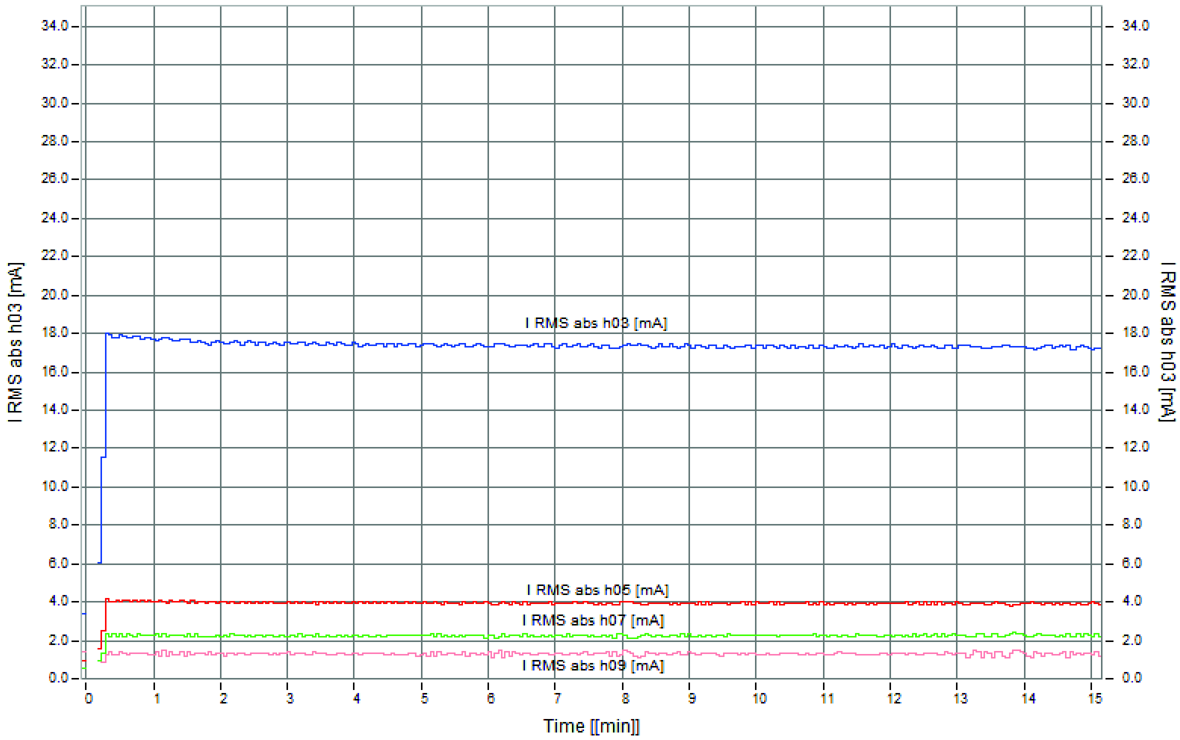


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

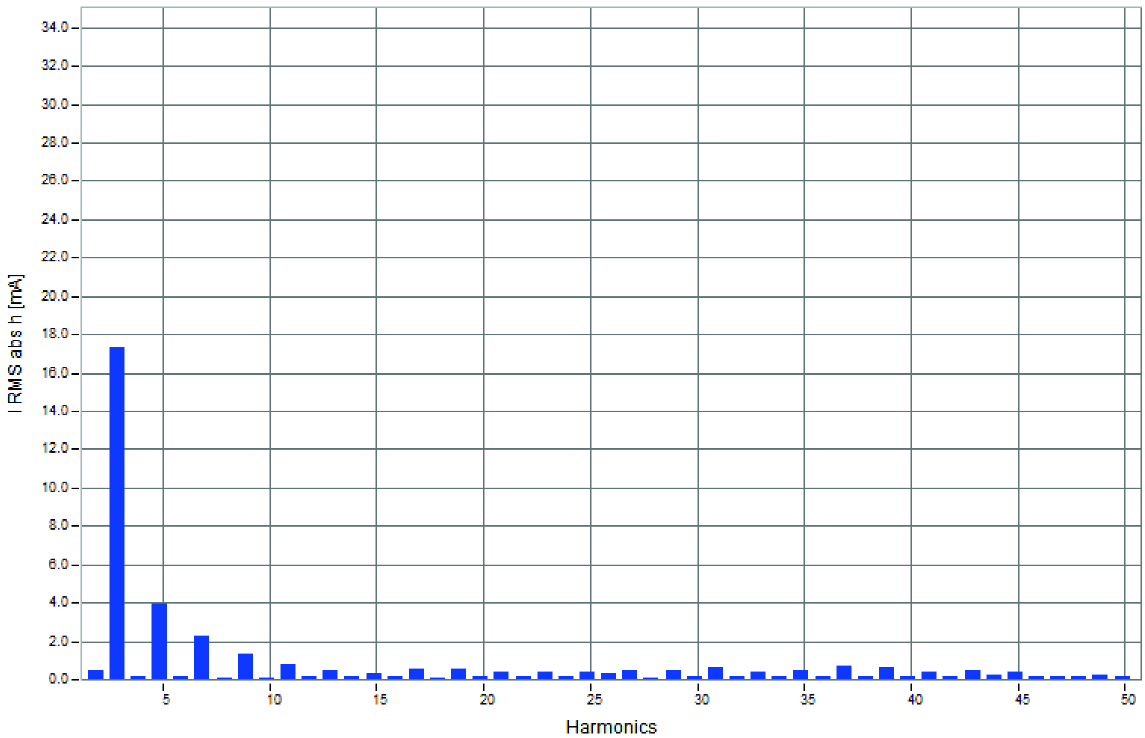


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.0\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.0\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 200.20 V
Current: I = 0.64 A
Active Power = 49.03 W
Reactive Power = 119.11 var
Apparent Power = 128.86 VA
Power Factor = 0.38

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

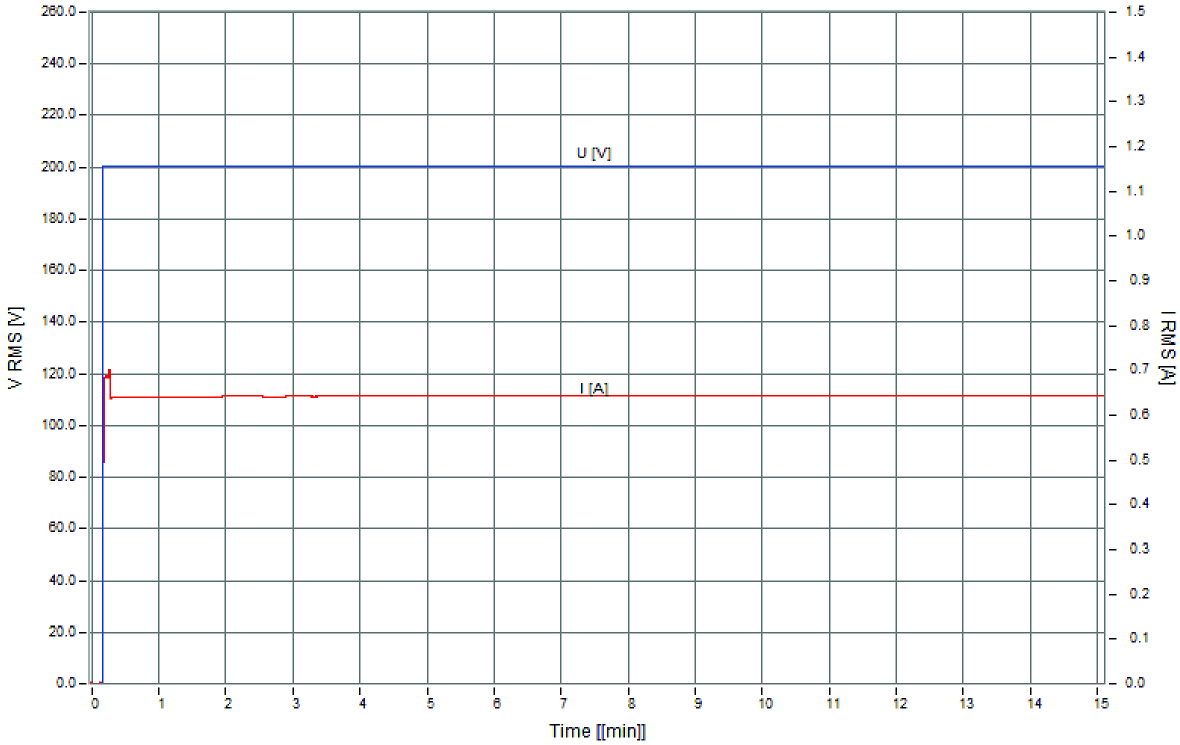


Figure 16. Root Mean Square of voltage and current - 200 V

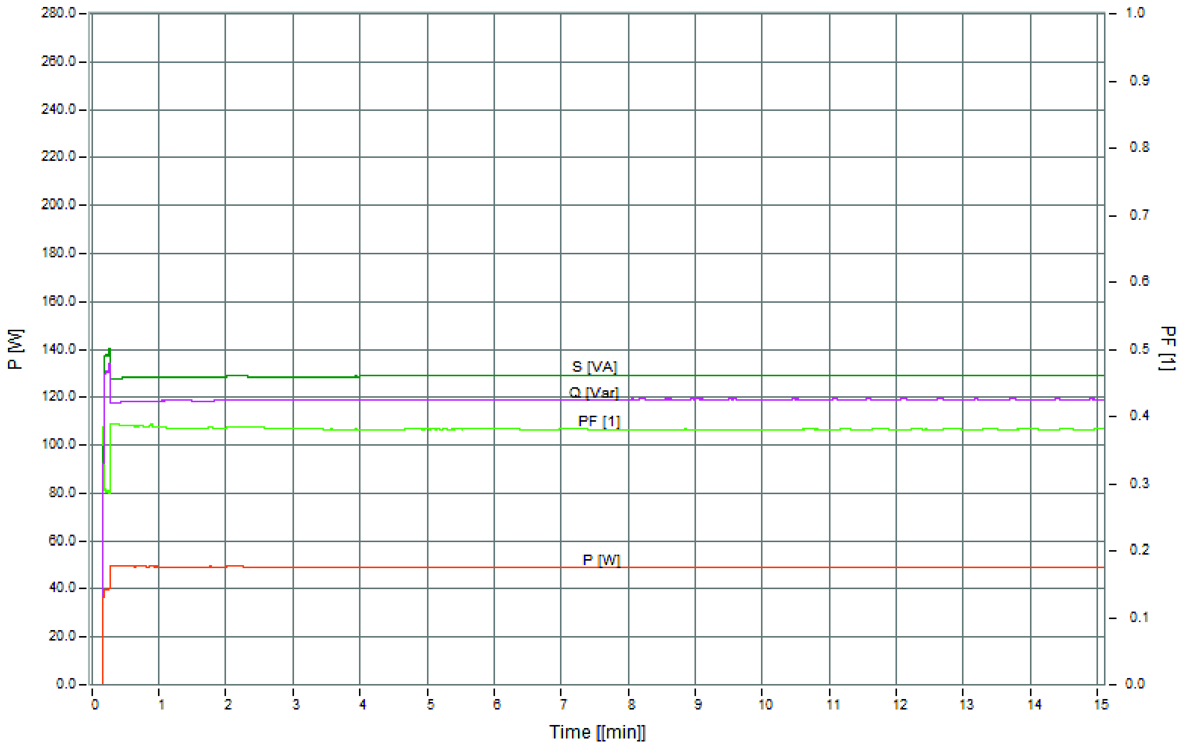


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 200.20 V	[V]	*****	0.00⁰
I L1 = 0.64 A	[A]	*****	67.67⁰

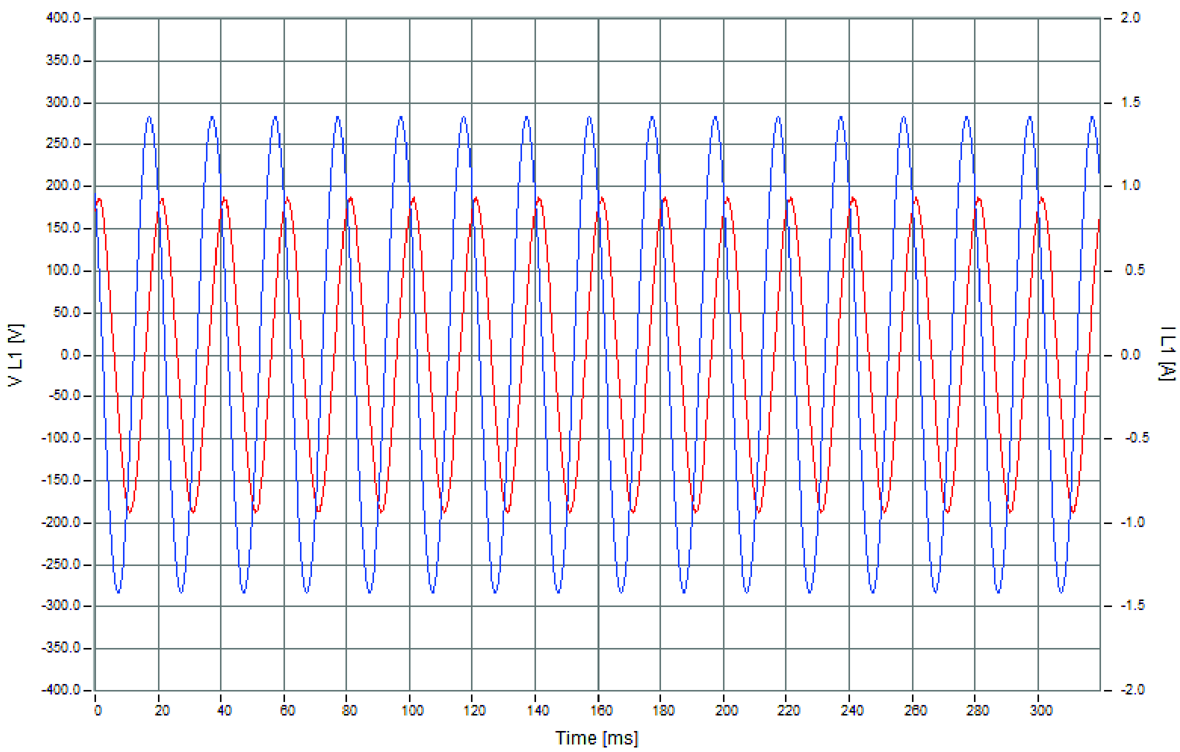


Figure 18. Current and voltage signal curve - 200 V

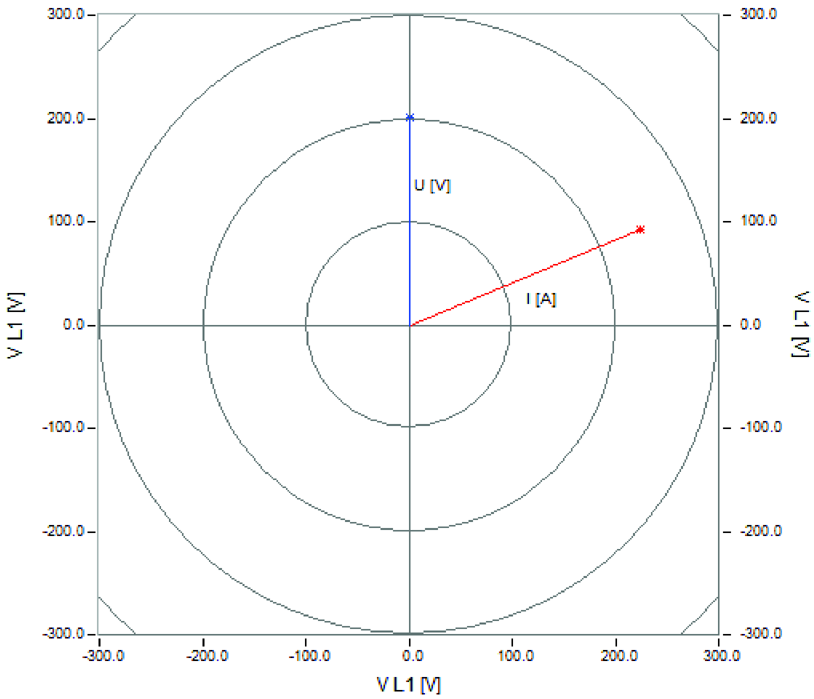


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

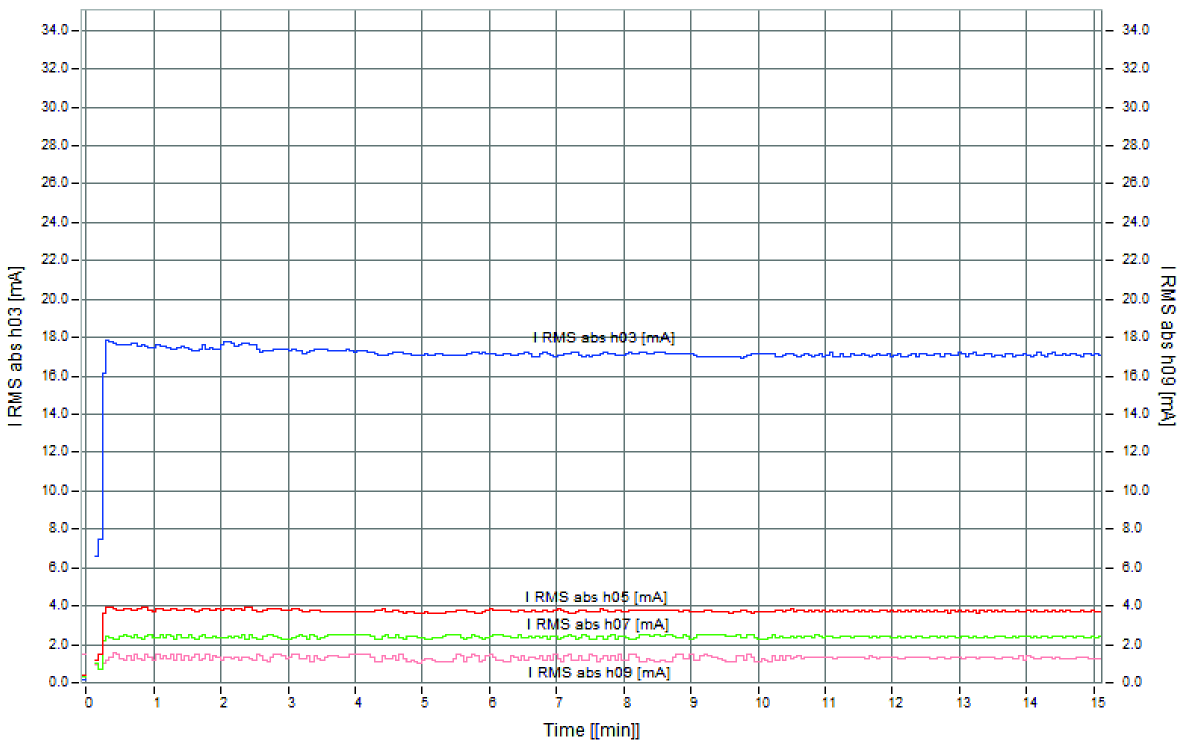


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

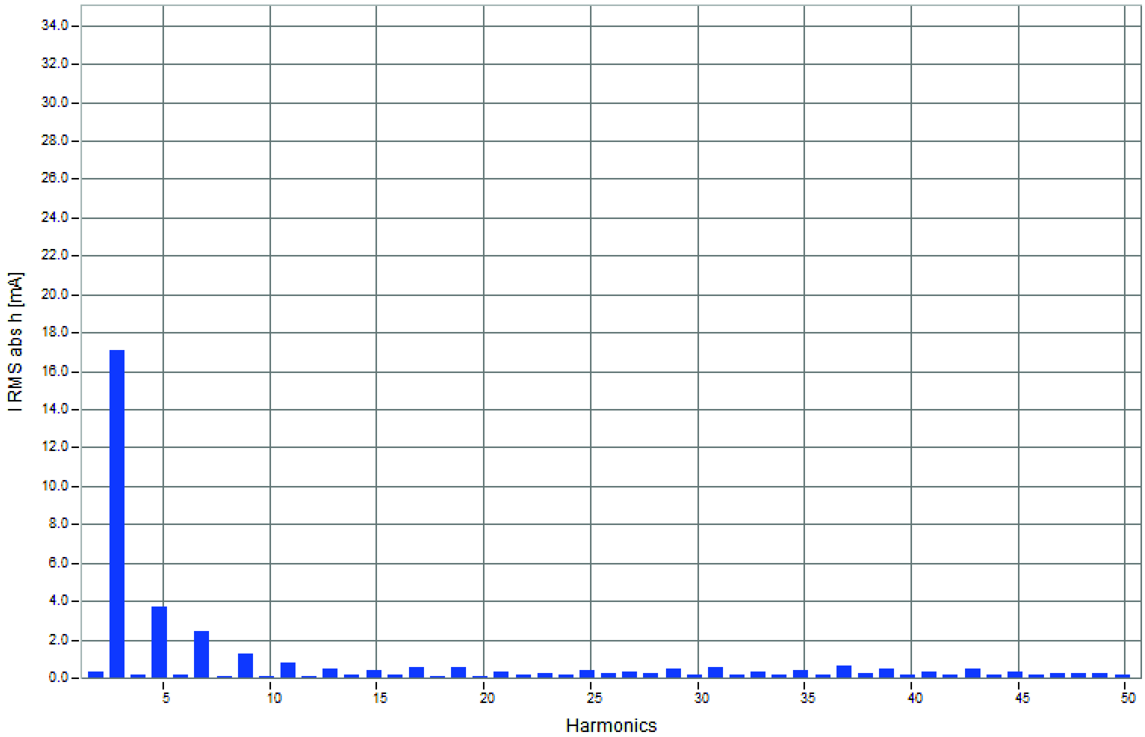


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.77\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.77\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:
Voltage: U = 210.19 V
Current: I = 0.68A
Active Power = 53.59 W
Reactive Power = 133.79 var
Apparent Power = 144.18 VA
Power Factor = 0.37

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

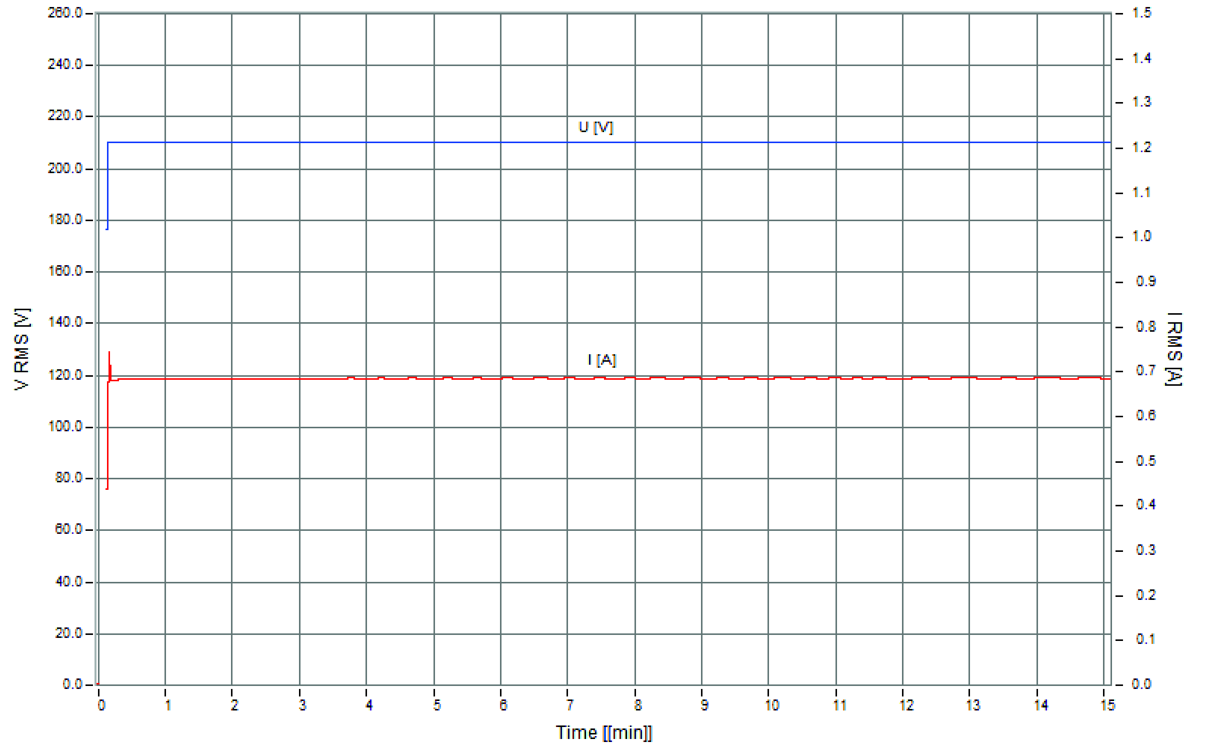


Figure 22. Root Mean Square of voltage and current - 210 V

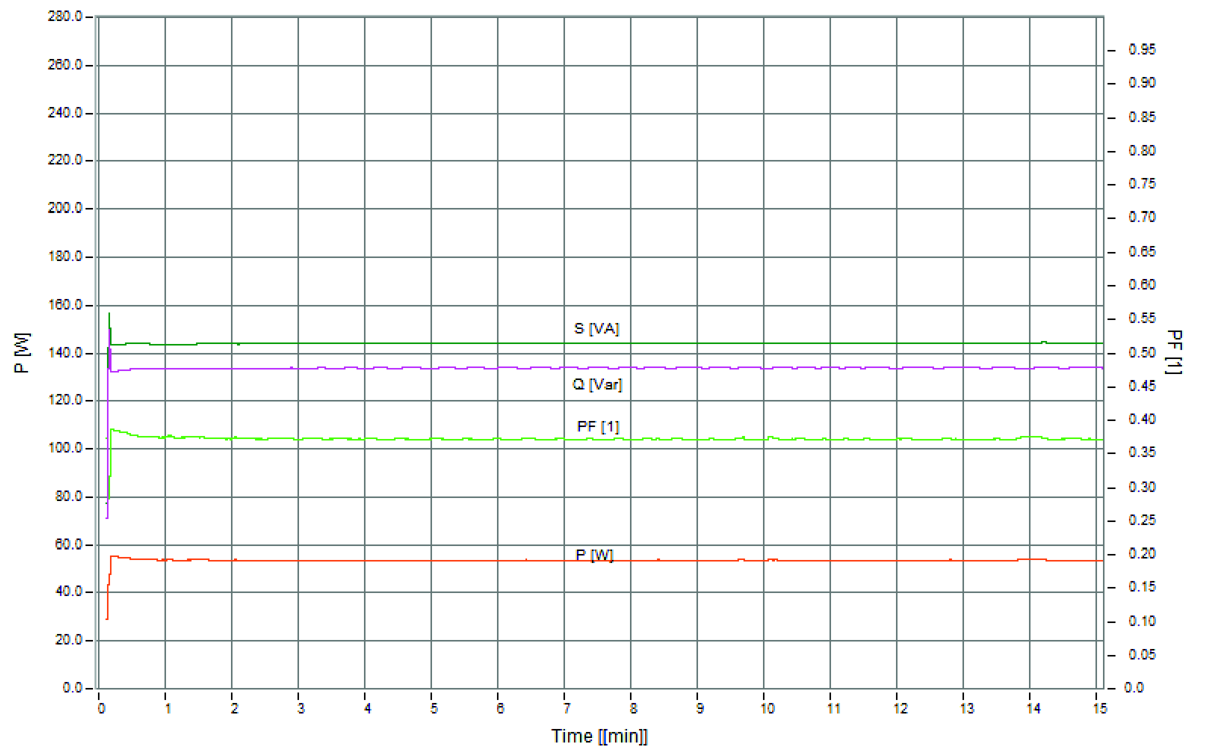


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 210.19	[V]	*****	0.00⁰
I L1 = 0.68	[A]	*****	68.22

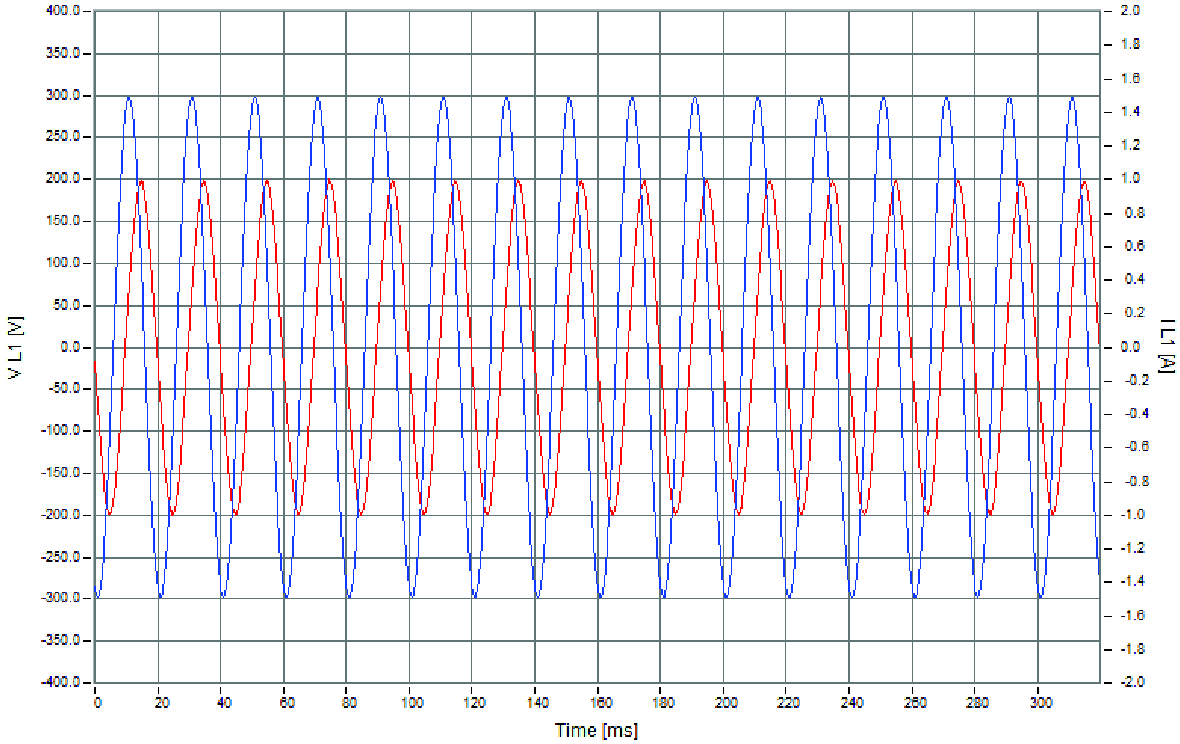


Figure 24. Current and voltage signal curve - 210 V

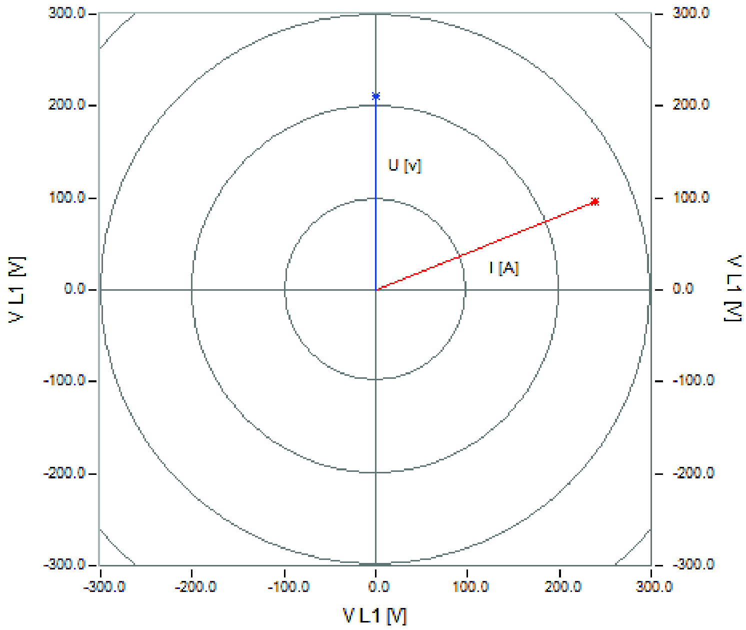


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

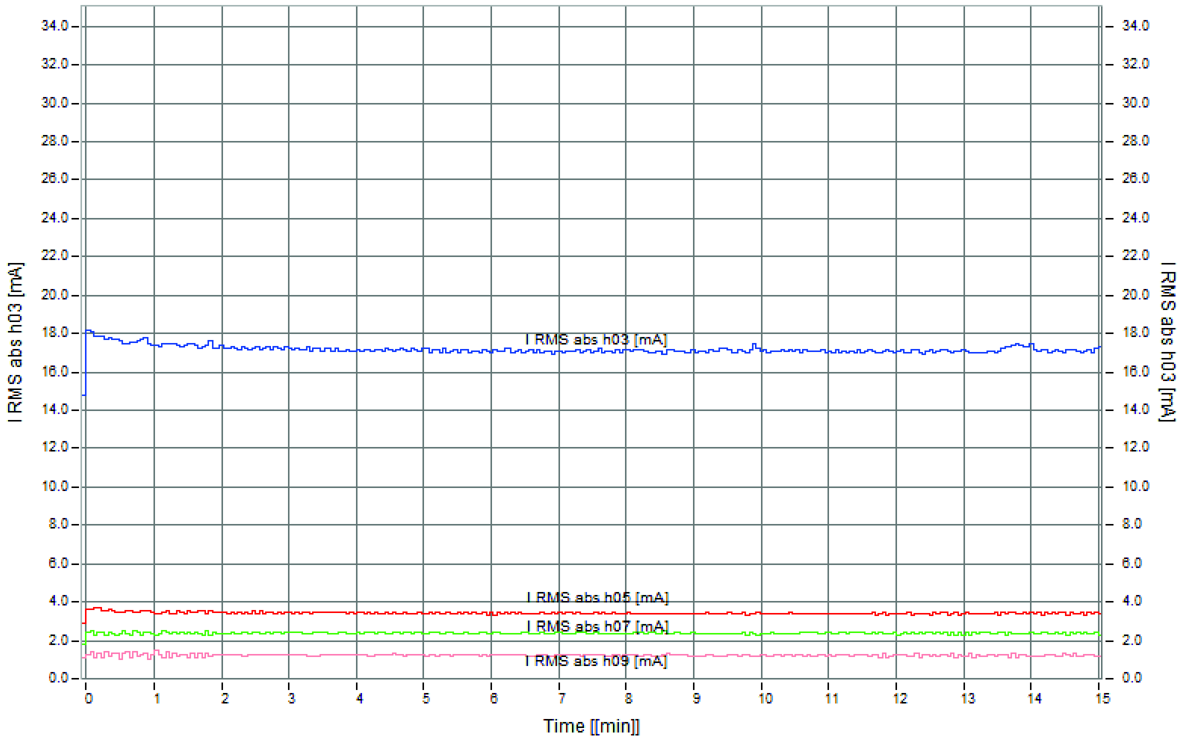


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

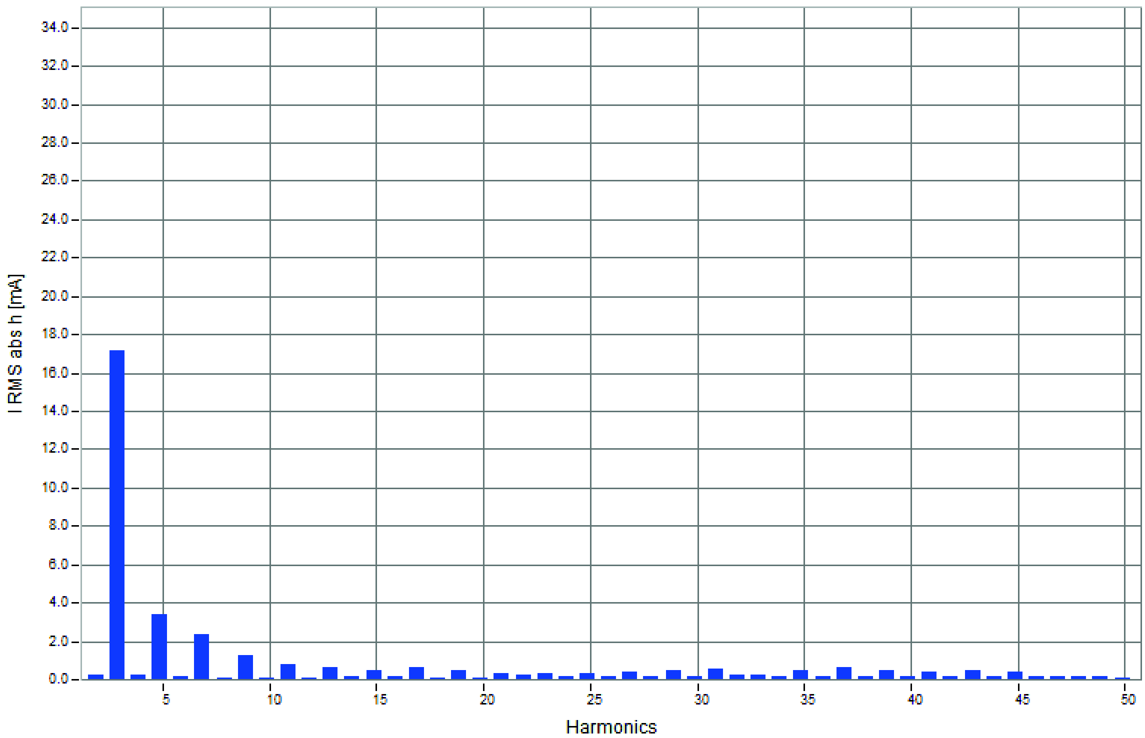


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.59\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.59\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 220.23 V

Current: I = 0.72 A

Active Power = 58.41 W

Reactive Power = 149.13 var

Apparent Power = 160.22 VA

Power Factor = 0.36

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

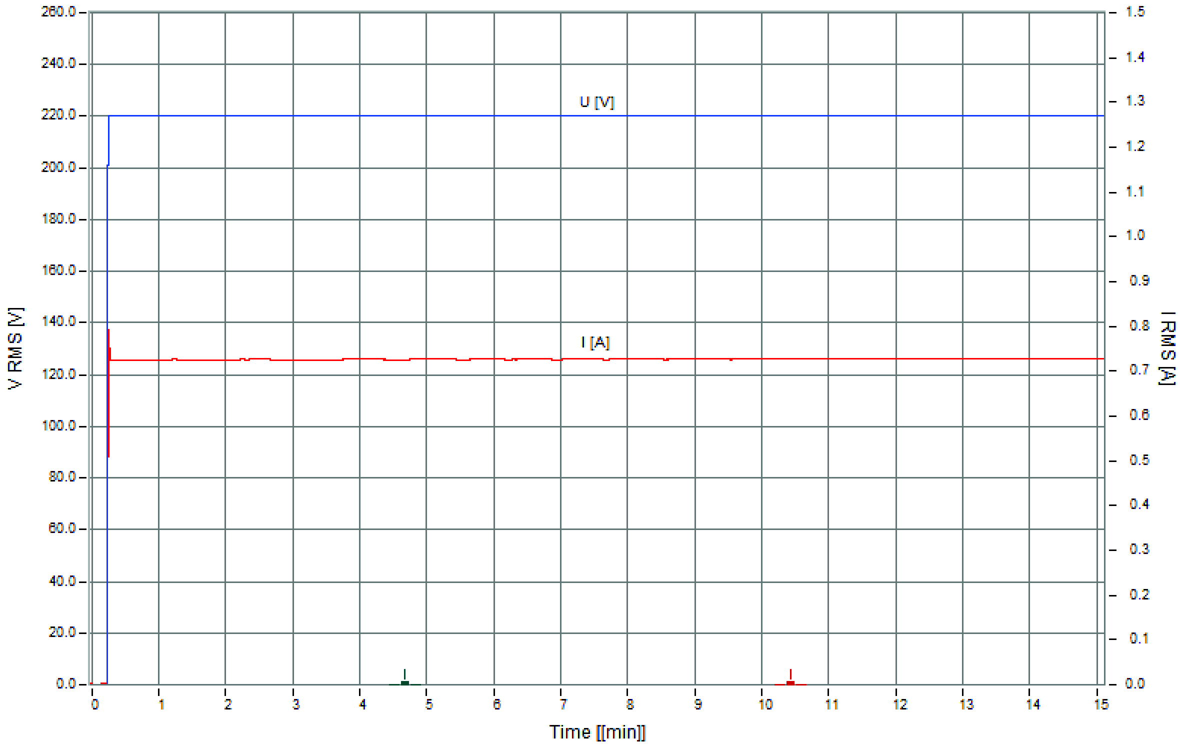


Figure 28. Root Mean Square of voltage and current - 220 V

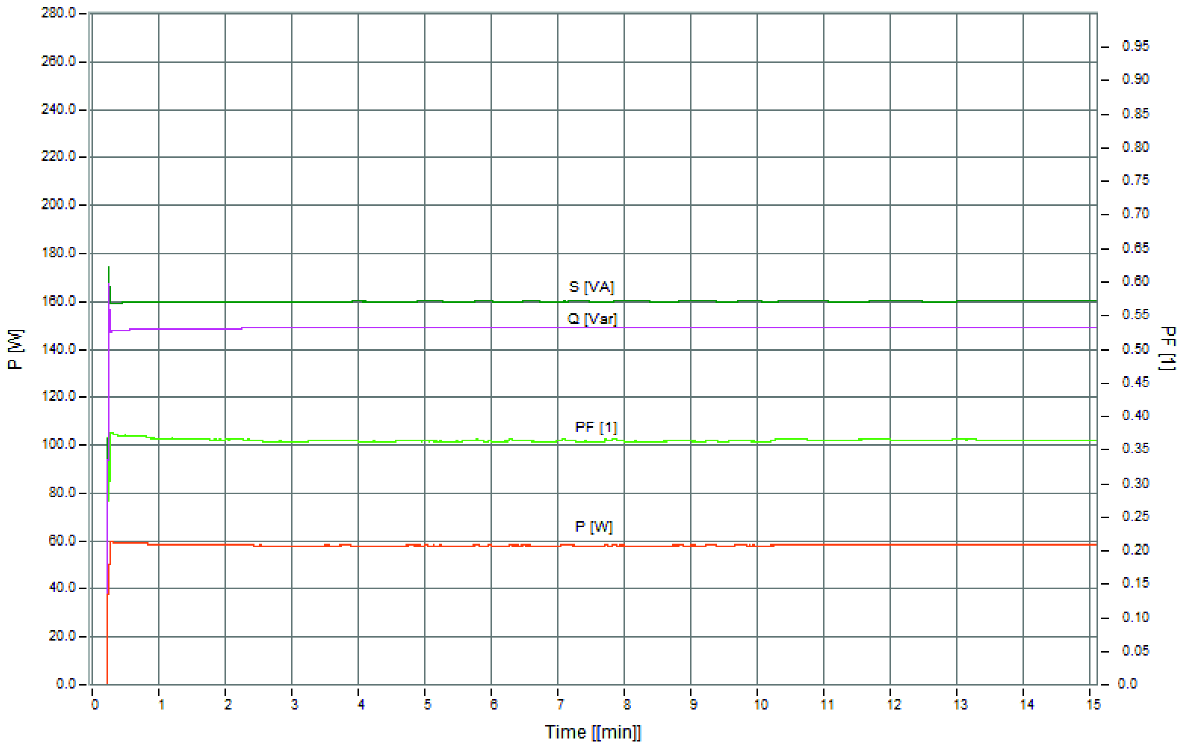


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 220.22	[V]	*****	0.00^0
I L1 = 0.72	[A]	*****	68.78^0

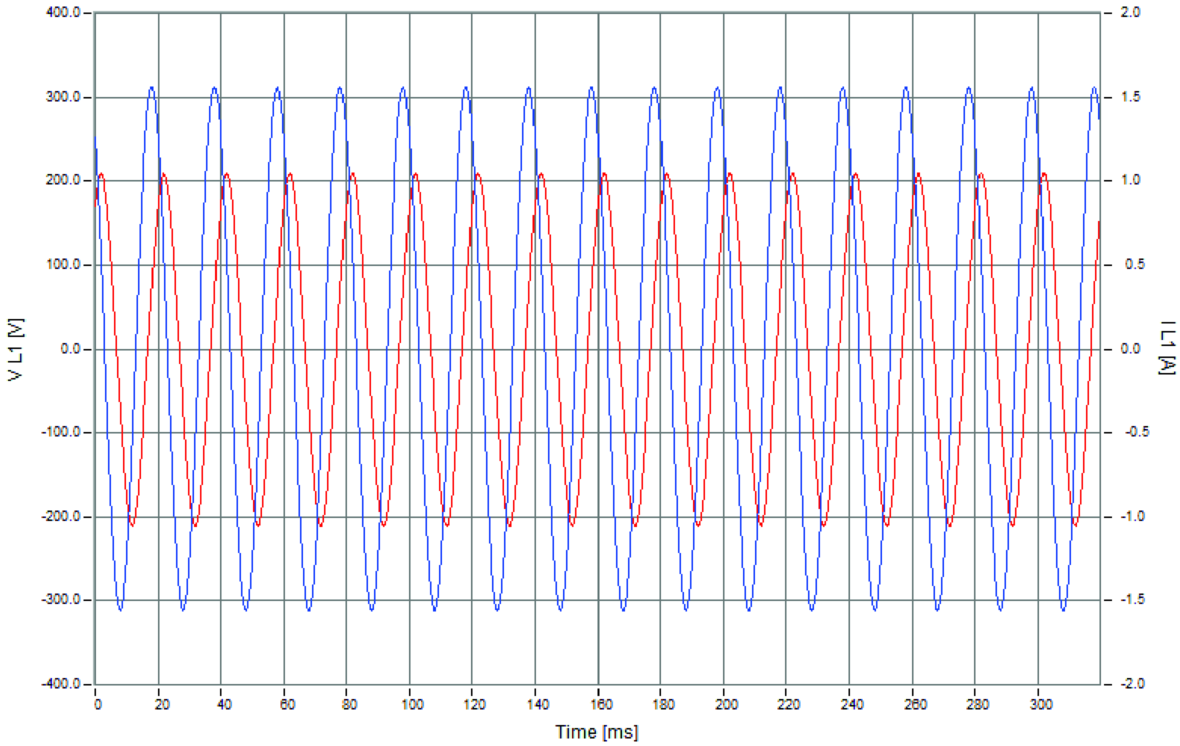


Figure 30. Current and voltage signal curve - 220 V

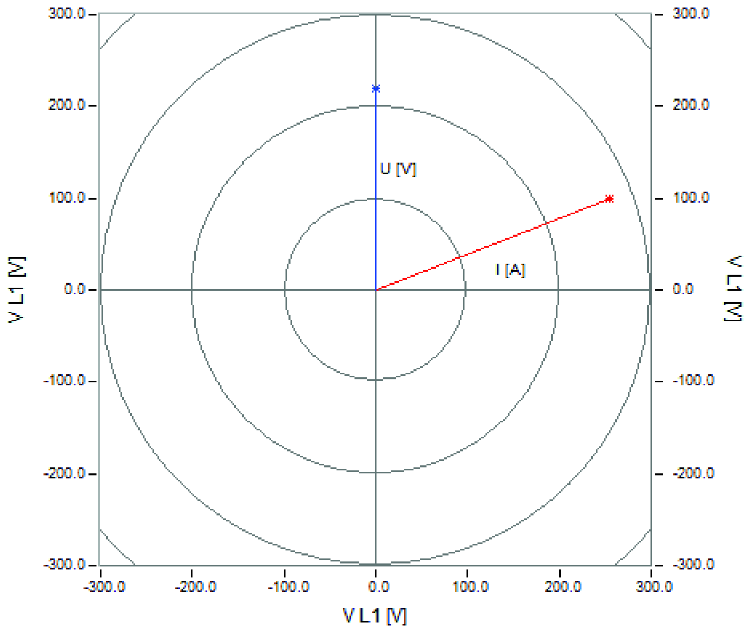


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

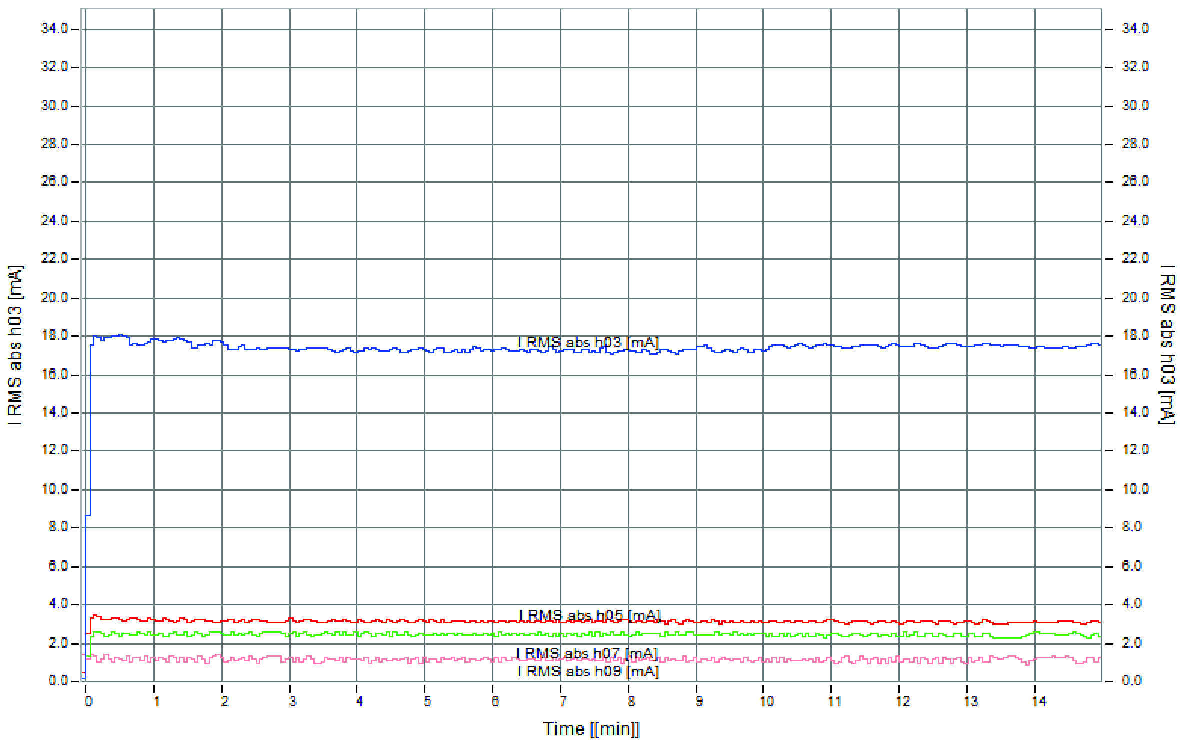


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

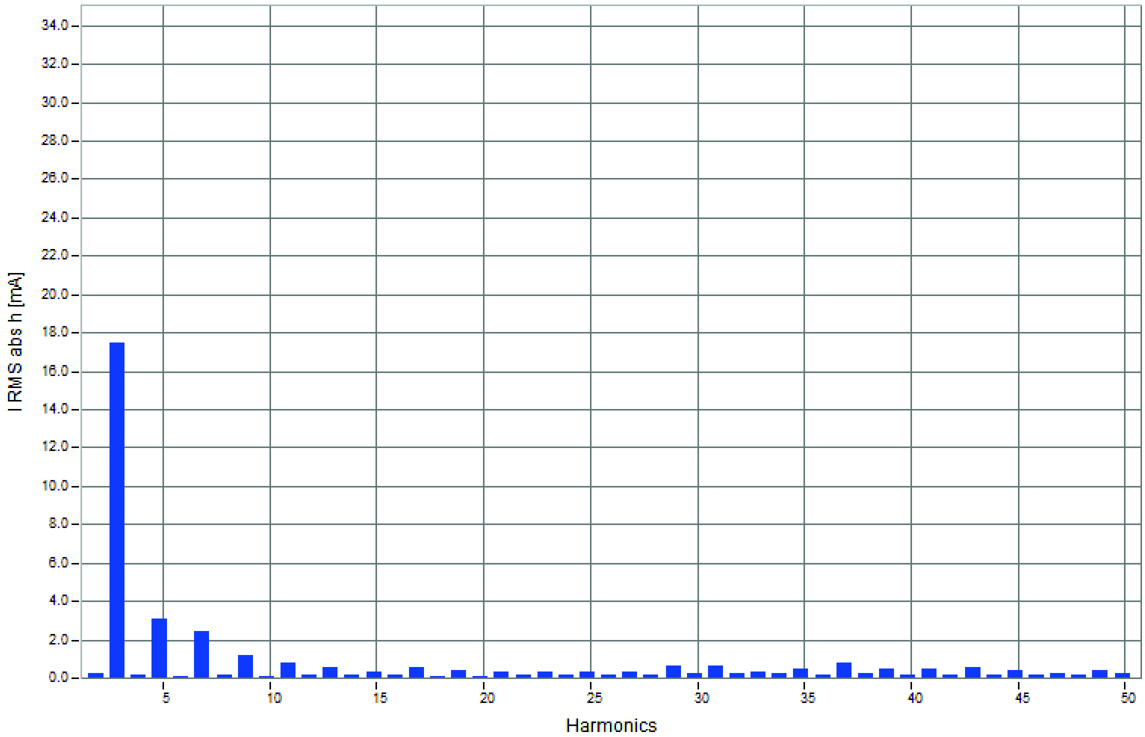


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.48\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.48\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 240.25 V
Current: I = 0.8 A
Active Power = 67.62 W
Reactive Power = 182.17 var
Apparent Power = 194.38 VA
Power Factor = 0.34

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

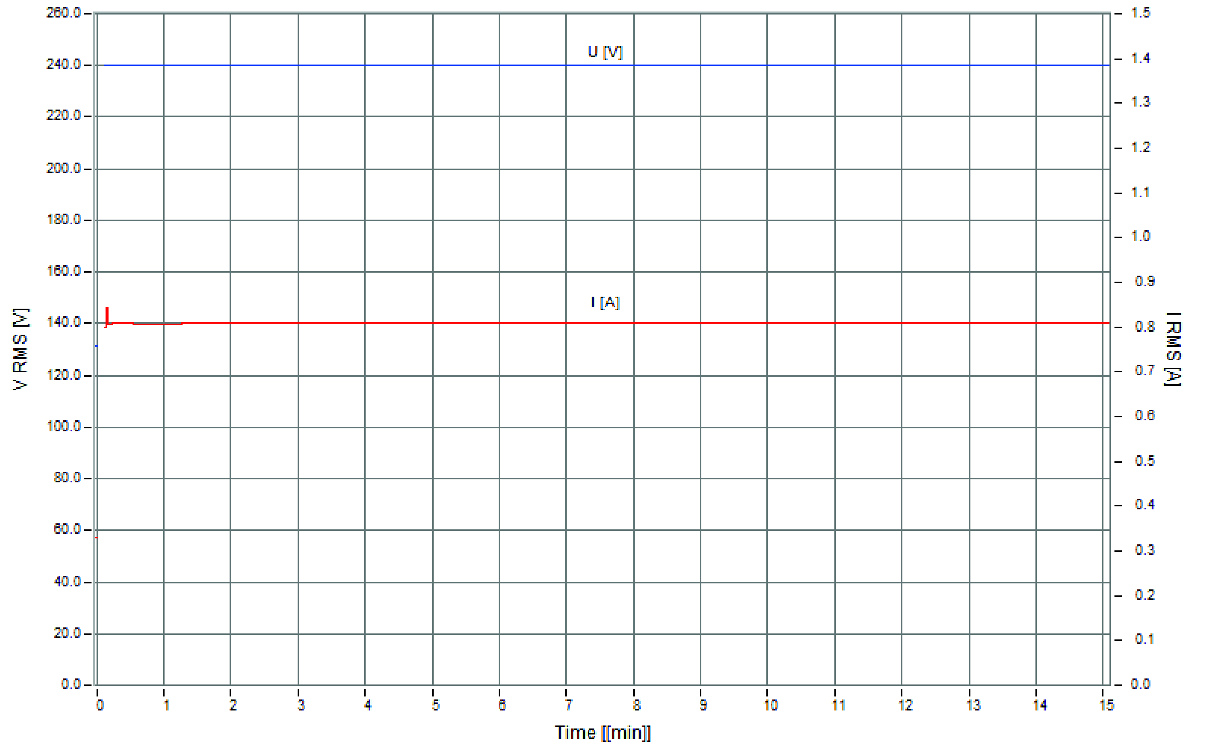


Figure 34. Root Mean Square of voltage and current - 240 V

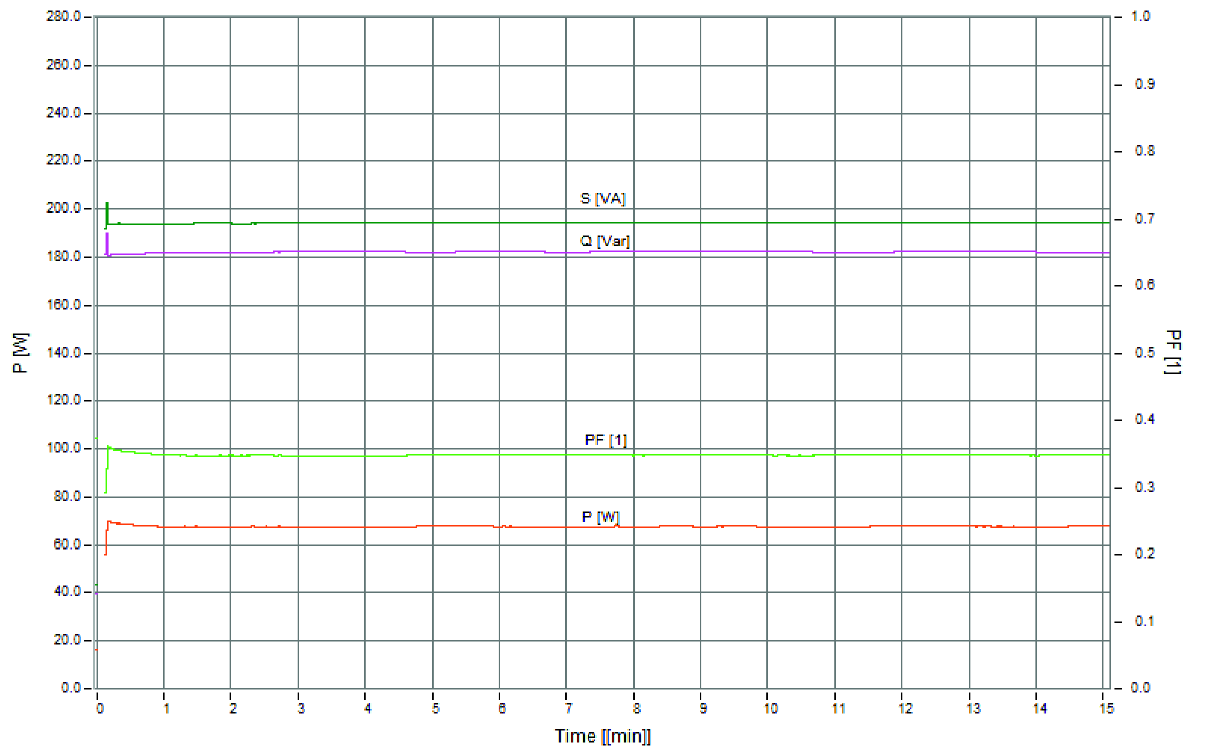


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 240.25	[V]	*****	0.00^0
I L1 = 0.80	[A]	*****	69.65^0

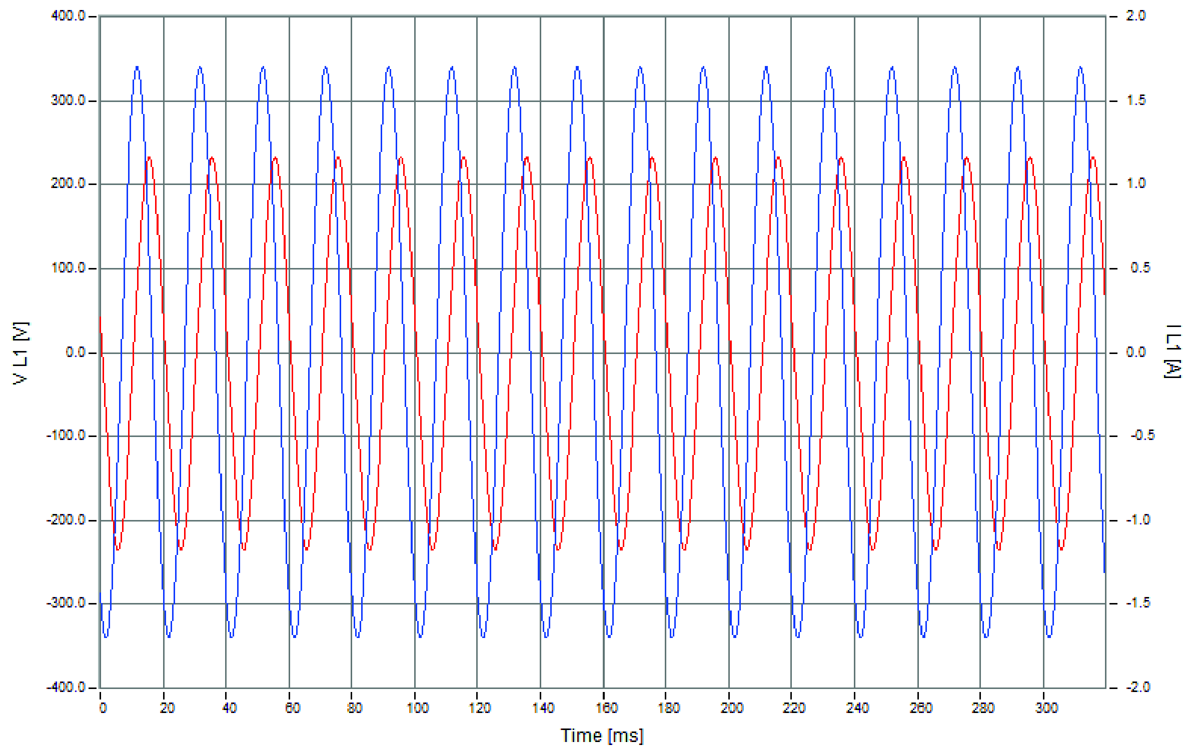


Figure 36. Current and voltage signal curve - 240 V

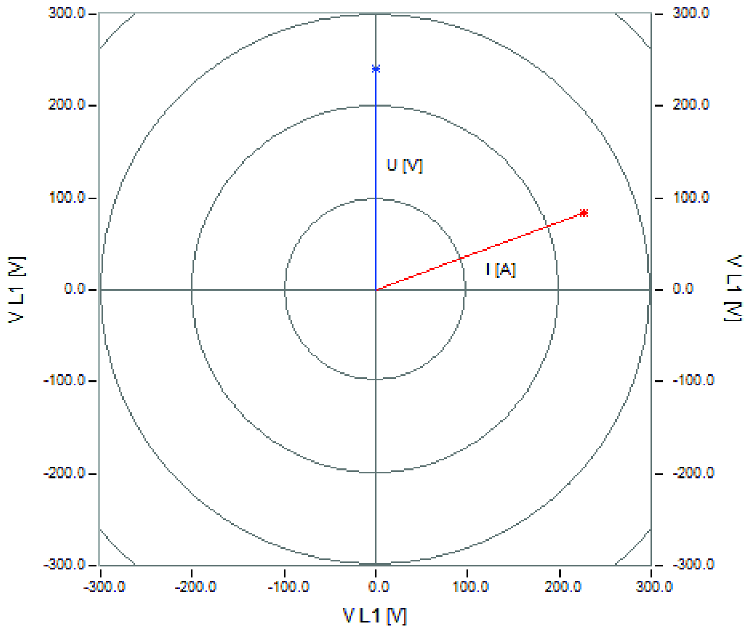


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

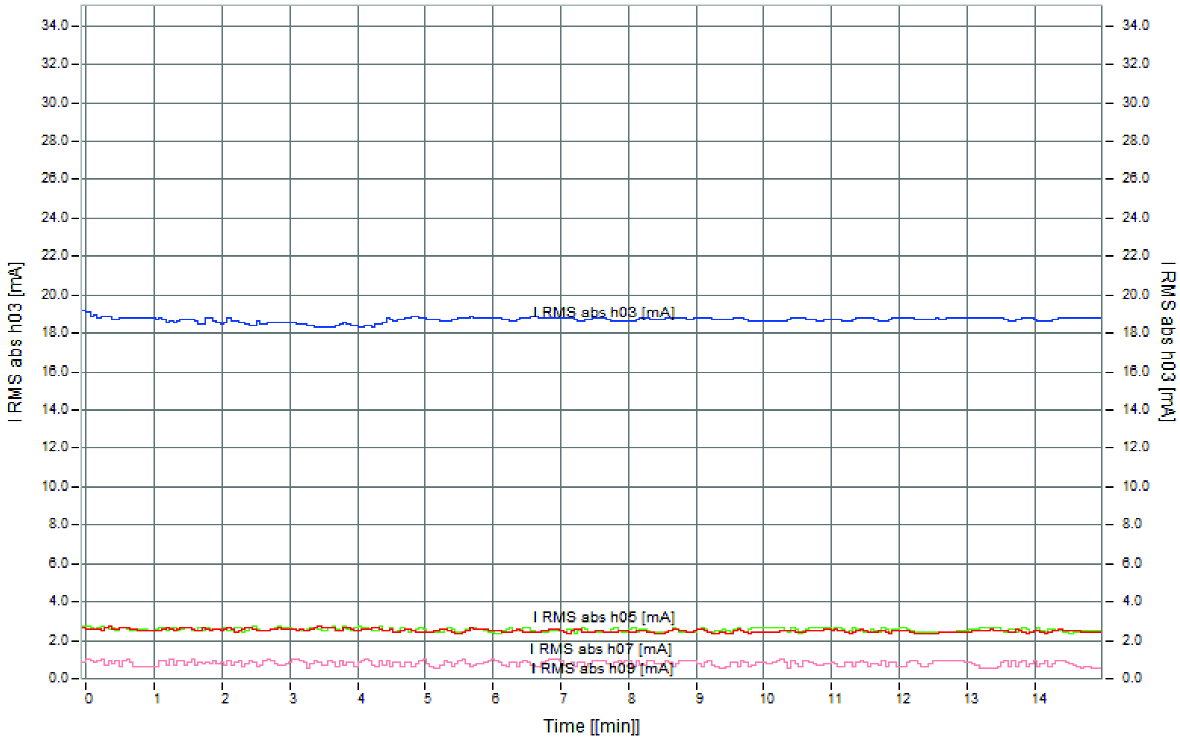


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

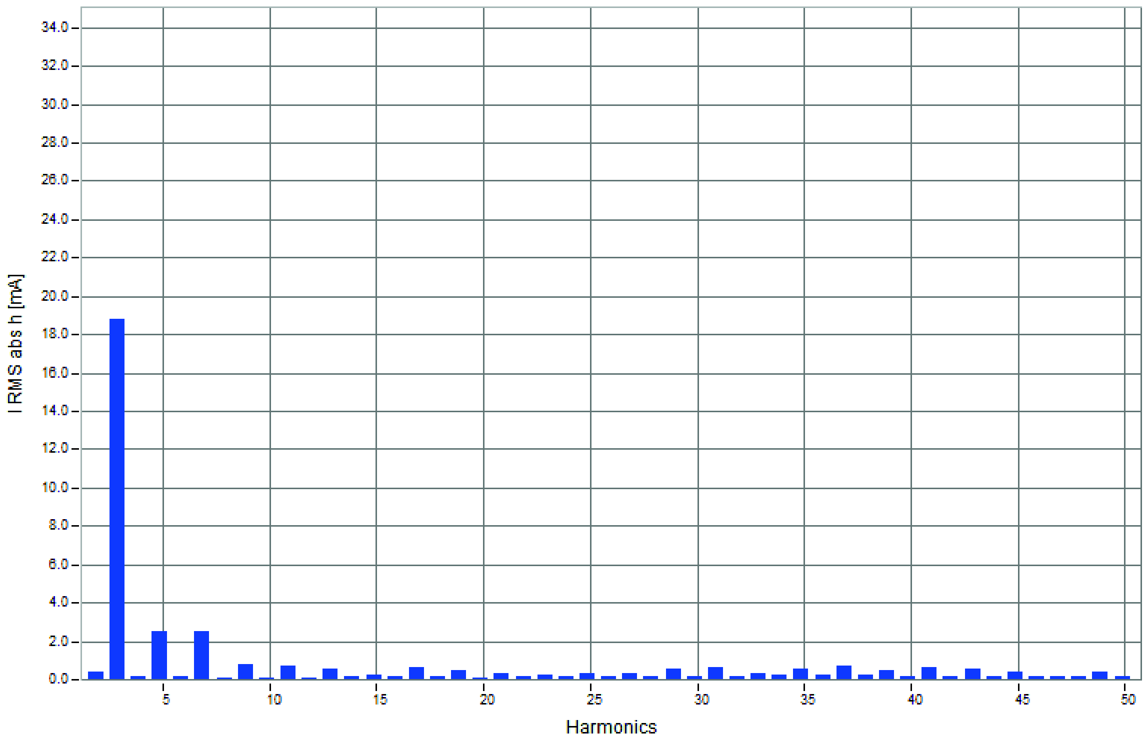


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.38\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.38\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 250.26 V
Current: I = 0.85 A
Active Power = 71.89 W
Reactive Power = 200.27 var
Apparent Power = 212.86 VA
Power Factor = 0.33

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

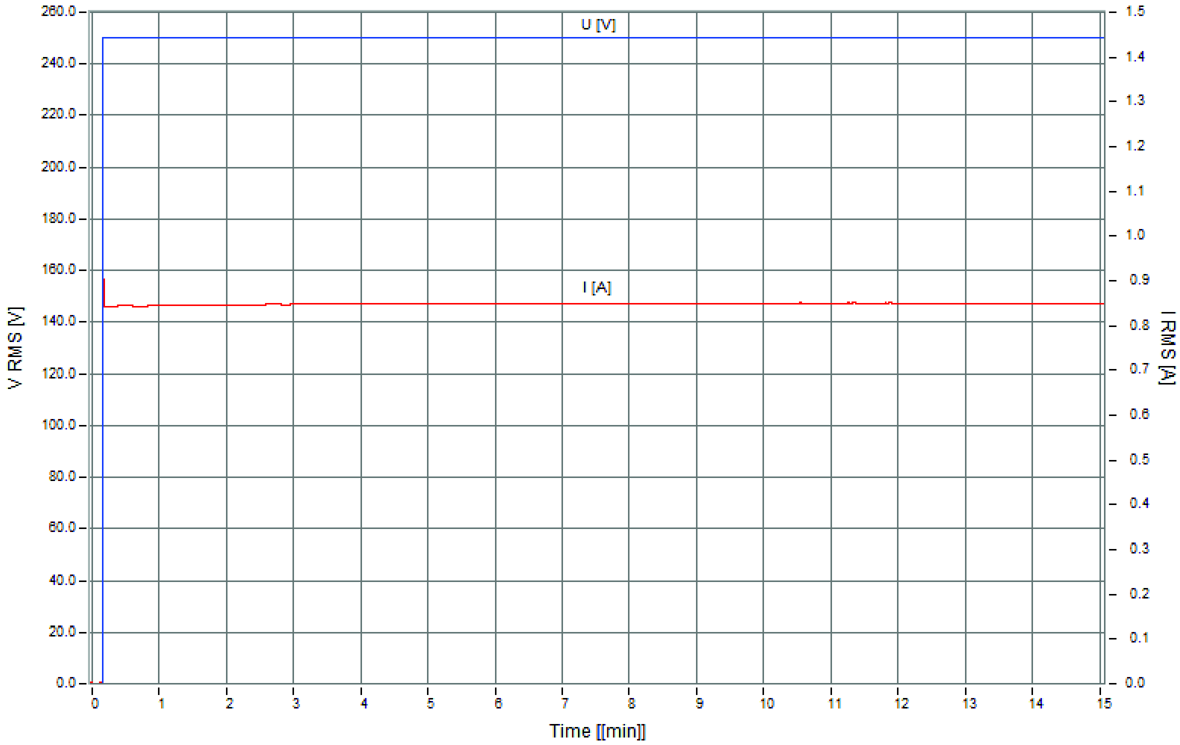


Figure 40. Root Mean Square of voltage and current - 250 V

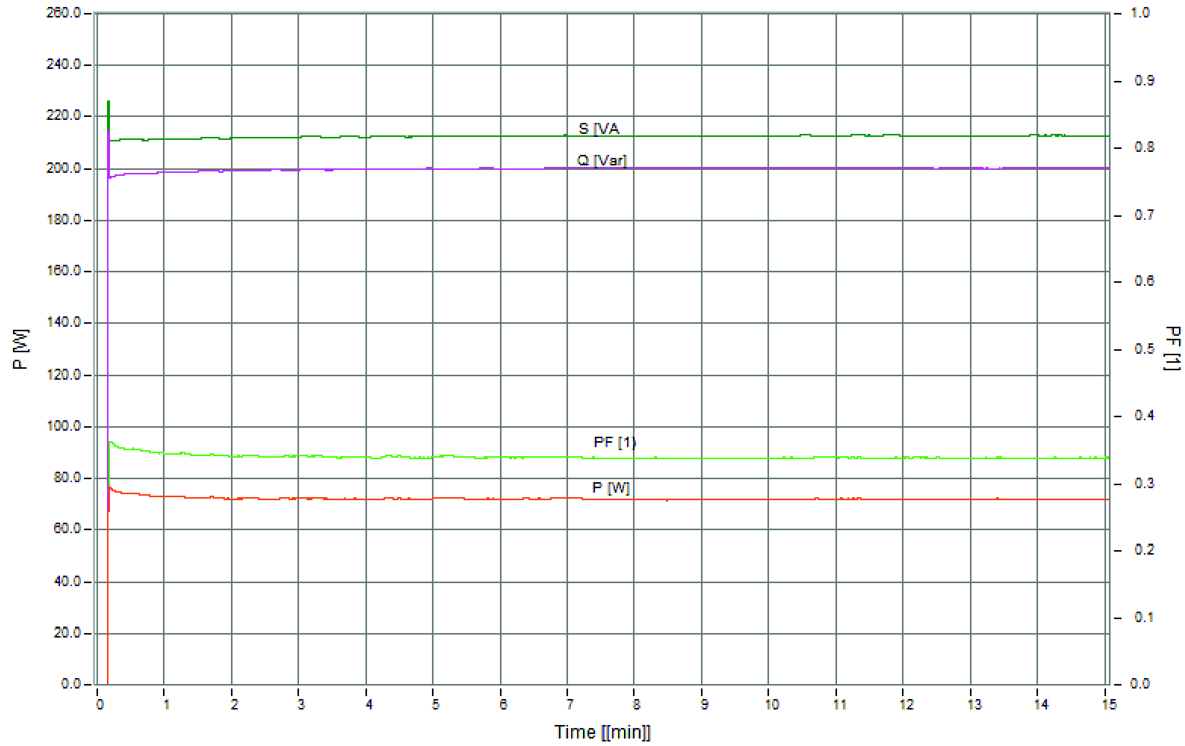


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 250.26	[V]	*****	0,00^0
I L1 = 0.84	[A]	*****	70.19^0

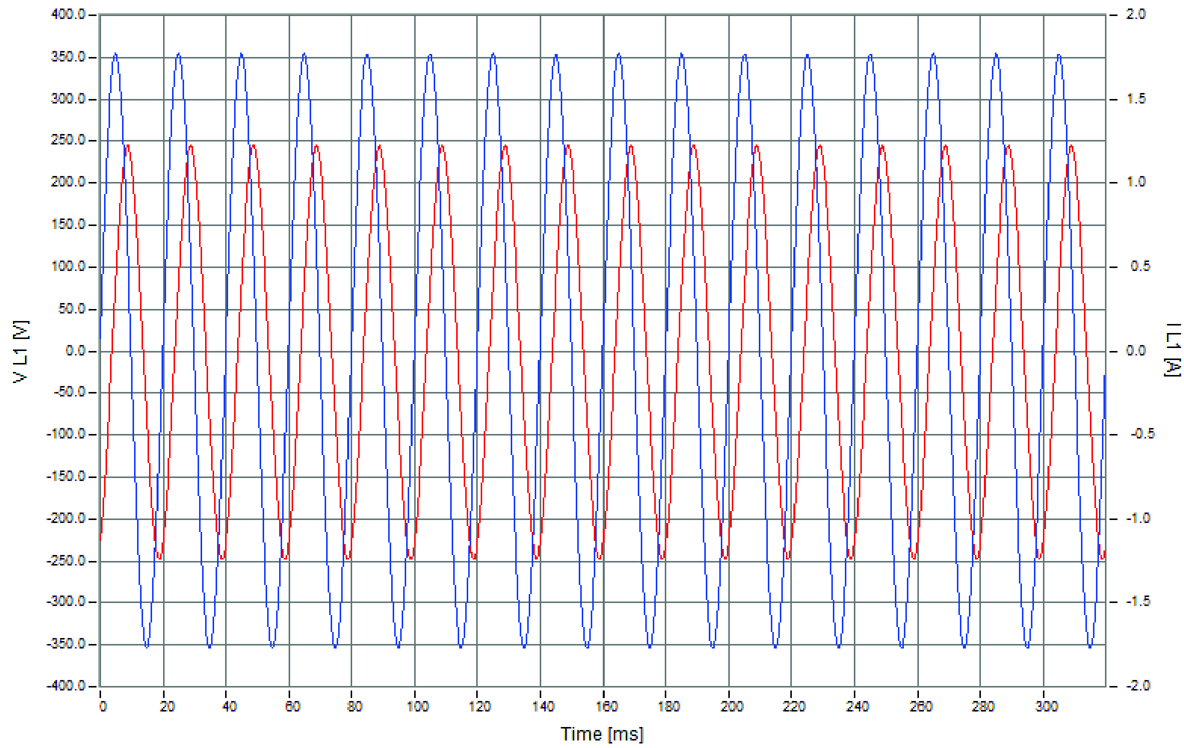


Figure 42. Current and voltage signal curve - 250 V

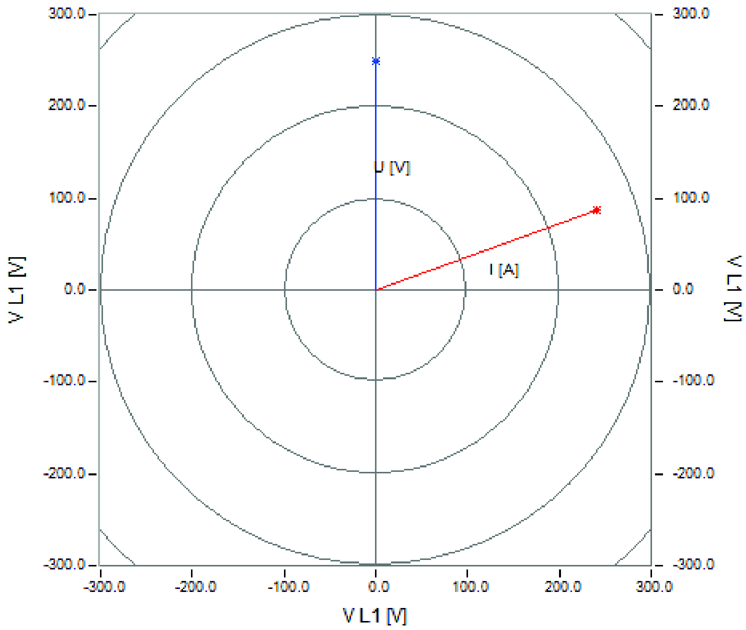


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

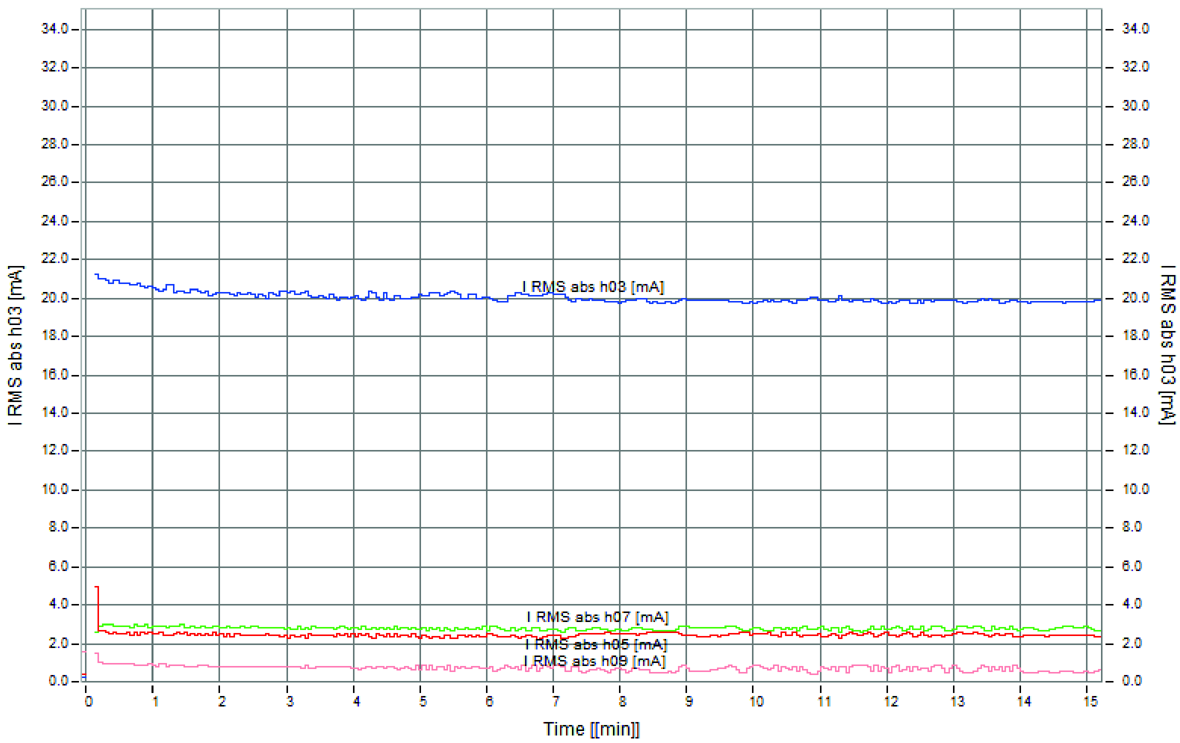


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

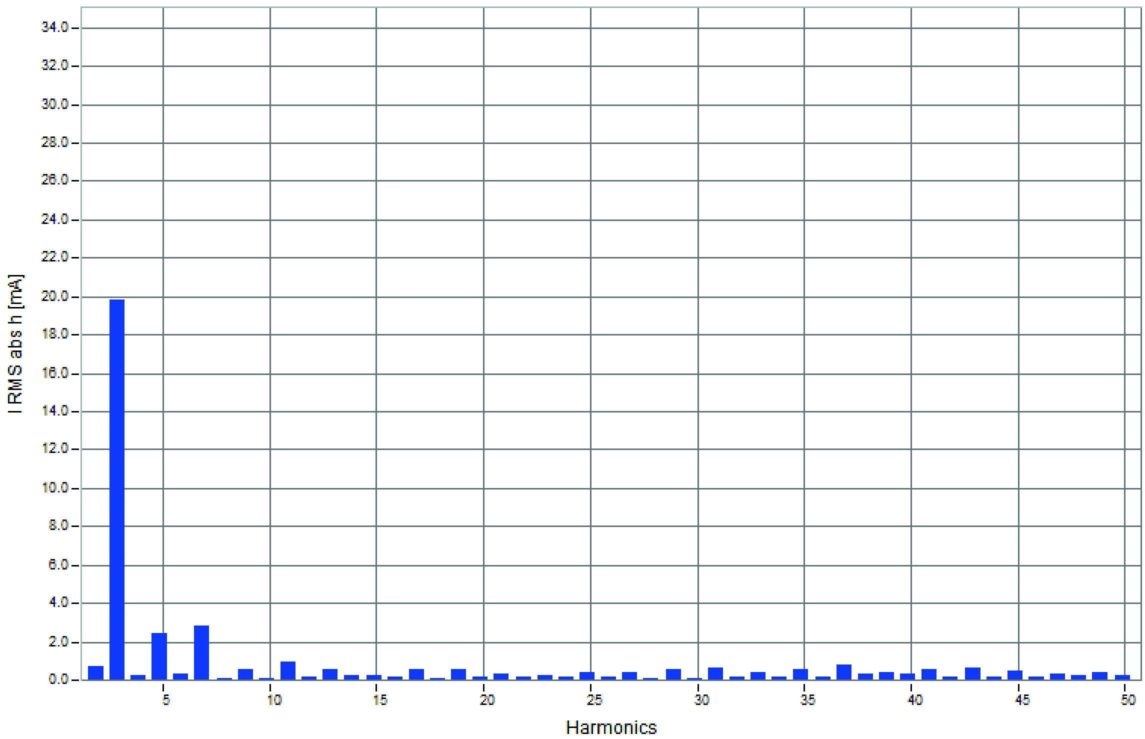


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.38\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.38\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 3.0%, for the minimum voltage, 0.82 p.u.. The minimum THD, 2.38%, is measured for the maximum voltage 0.96 p.u.. Further increase of the voltage causes a slight decrease of the THD.

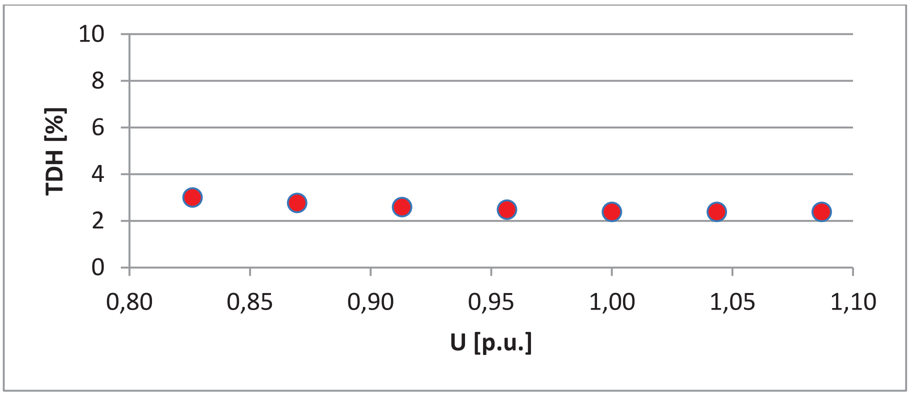
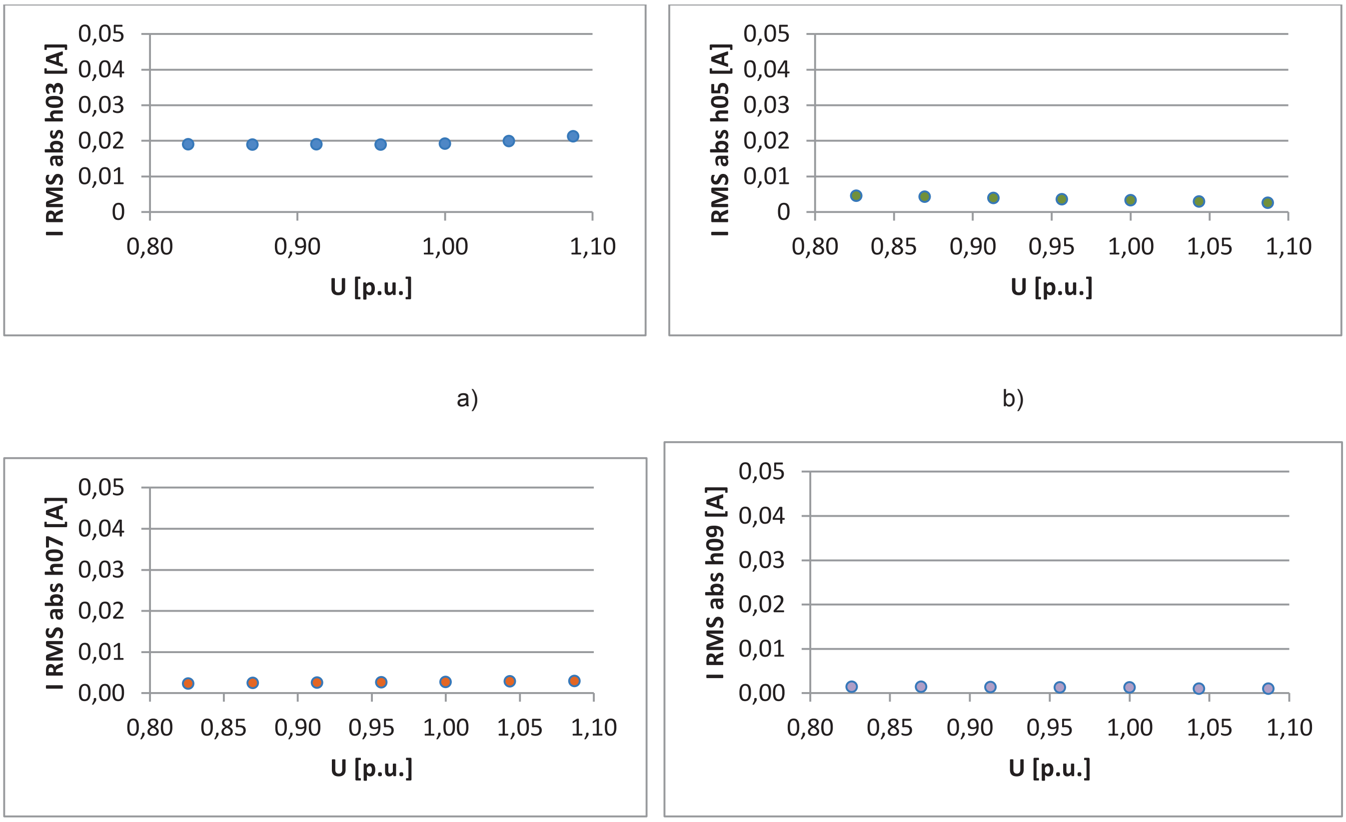


Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature



c) d)

Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which have a exponentional behaviour with a minimum of 0.018mA by voltage 0.82 p.u.. Figures 47. b) and d) show the 5th and the 9th harmonic respectively. In both cases the harmonic values are decreasing with the voltage increase. Figure 47. c) shows 7th harmonic which increases marginally with the voltage increase.

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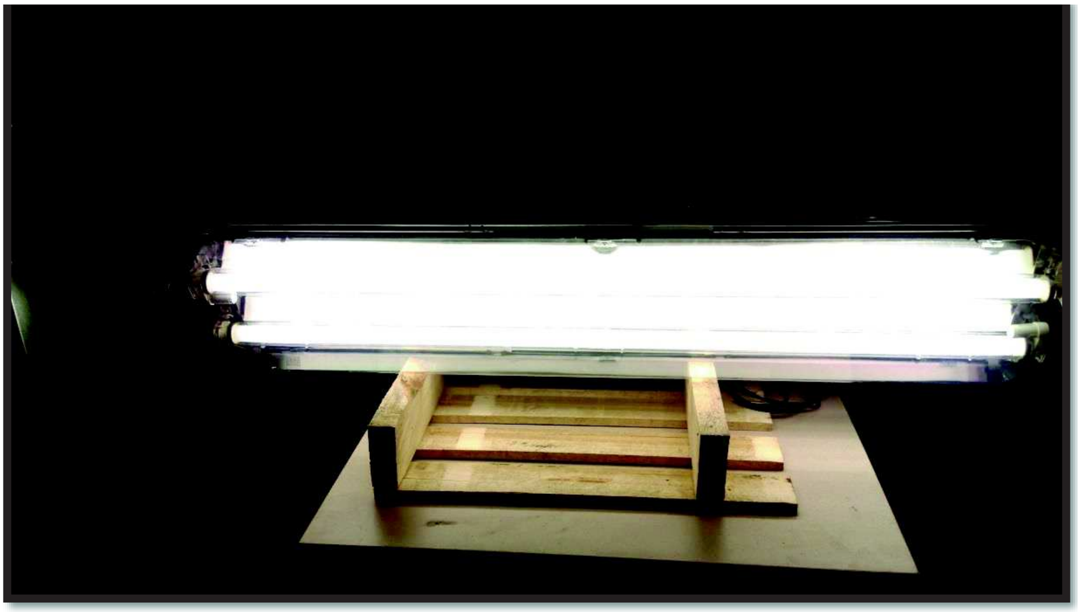
A - 1040 Wien

MEASUREMENT PROTOCOL 4

Conventional lamps-new
2XLight source: NARVA
Ballast: TRIDONIC ATCO



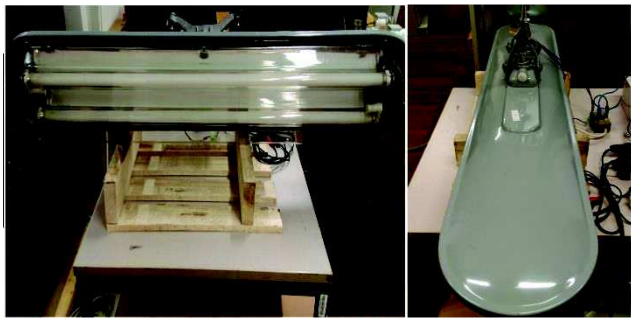
Vienna 27.January 2016

1. Content

2. List of figures

3. Light type

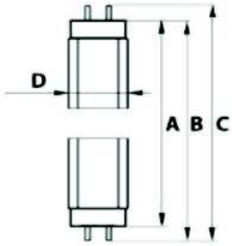
Conventional lamps
2 X NARVA fluorescent lamp
NARVA starter: BSt65
Status: new



4. Technical data

NARVA Fluorescent Lamp: LT - T8/T12 36 W COLOURLUX plus ET.XL
Voltage: 220-240 V
Real power : 36 W

Size A (max., mm)	1.199,4
Size B (min., mm)	1.204,1
Size B (max., mm)	1.206,5
Size C (max., mm)	1.213,6
Size D (max., mm)	38,0



NARVA starter: BSt65
Voltage: 220 V – 240 V
Power: 4 W – 65.80 W

TRIDONIC ATCO ballast-ETAWATT 36
Voltage: 230 V
Frequency: 50 Hz

5. Measurement

5.1. Schema

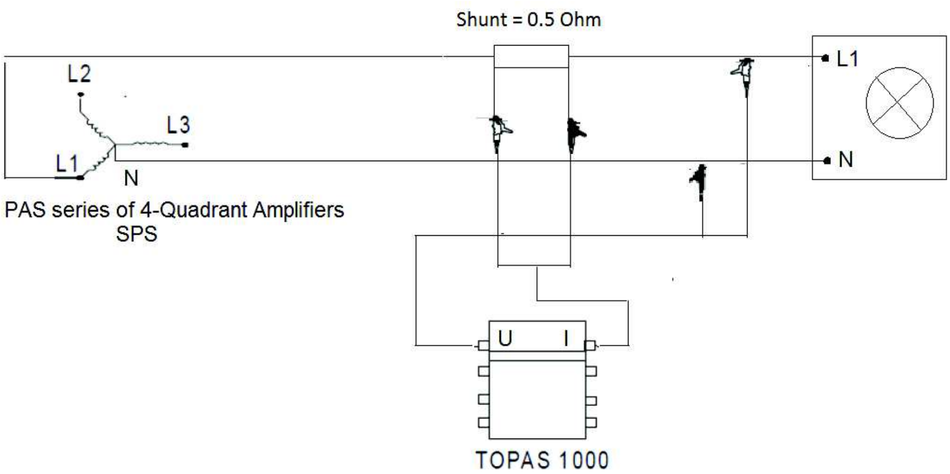


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside

Temperature: 21.9^{0}C

Voltage range: 190-250 V

Shunt: 0.5 Ω

Measurement interval: 15 min

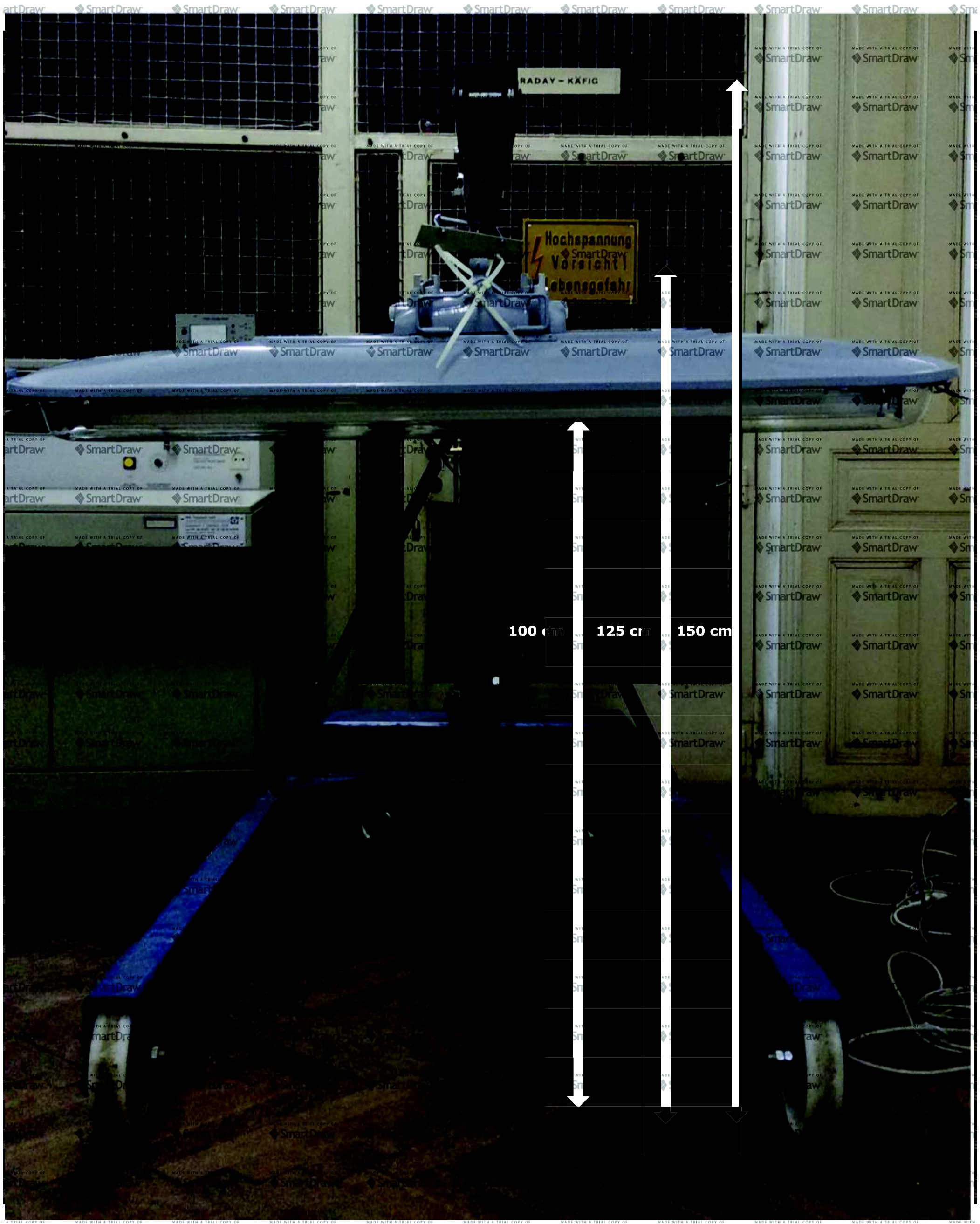


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 230.04 V
Current: I = 0.83 A
Active Power = 83.48 W
Reactive Power = 172.04 var
Apparent Power = 191.38 VA
Power Factor = 0.43

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

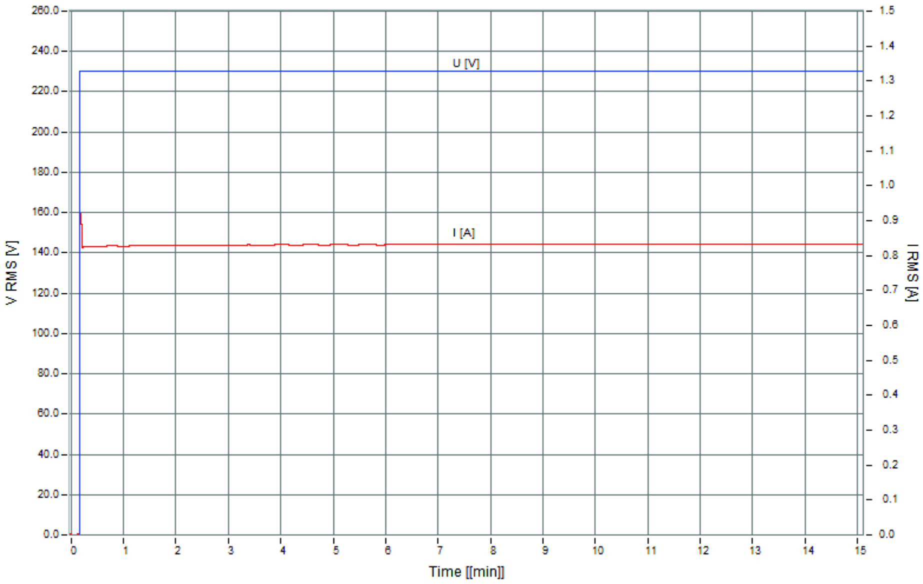


Figure 3. Root Mean Square of voltage and current - 230 V

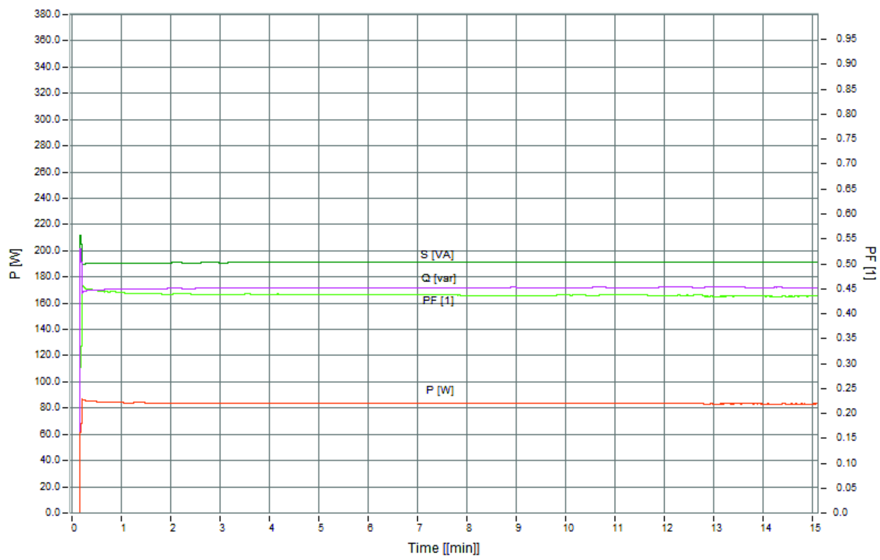


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 230.06	[V]	*****	0.00⁰
I L1 = 0.82	[A]	*****	63.99⁰

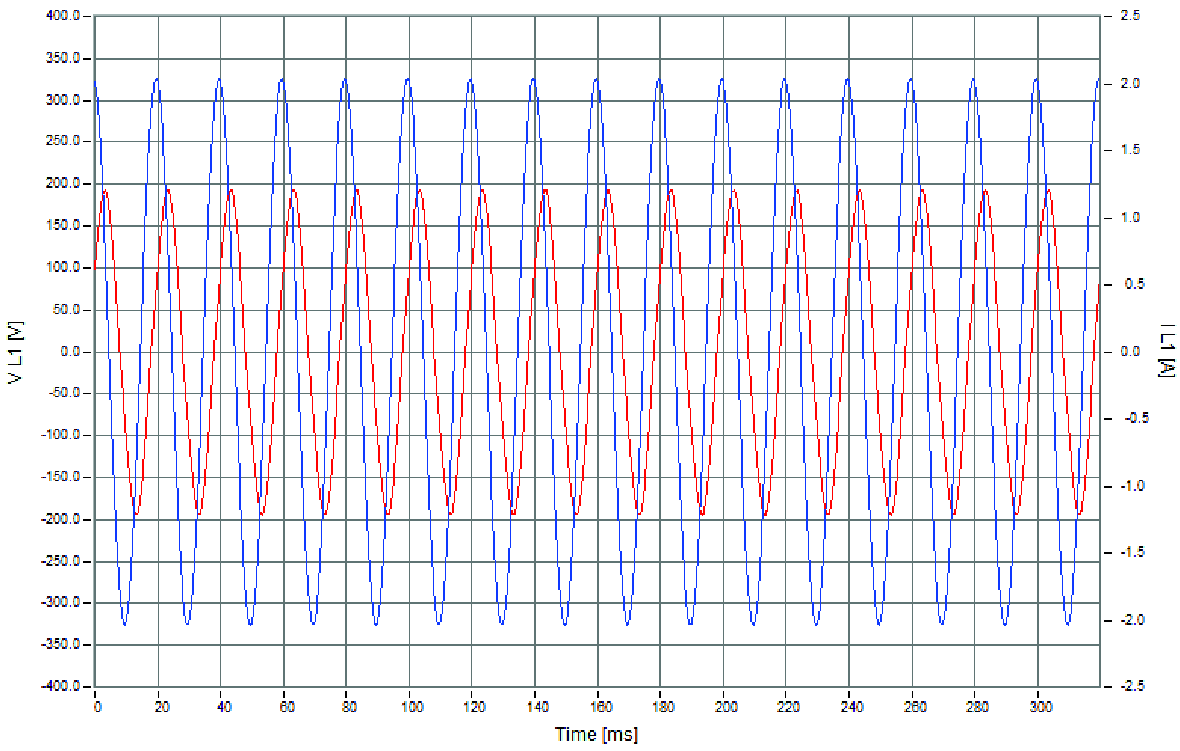


Figure 5. Current and voltage signal curve - 230 V

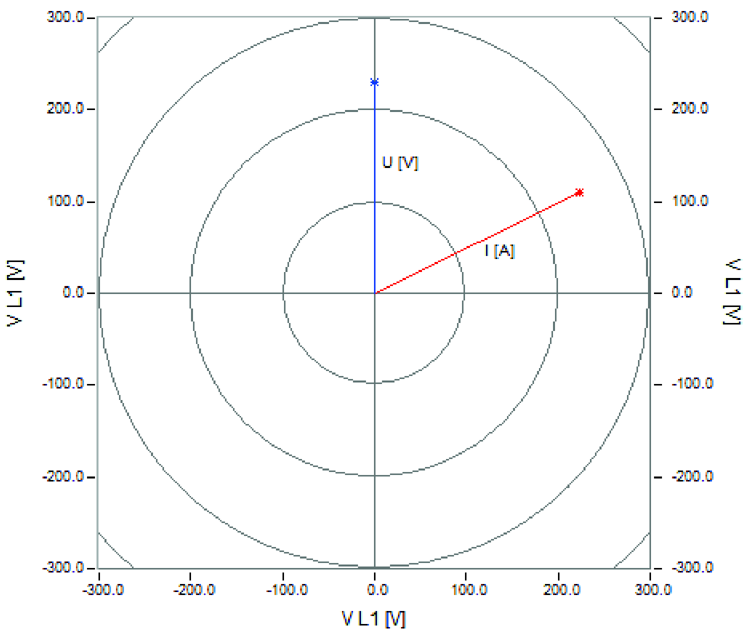


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

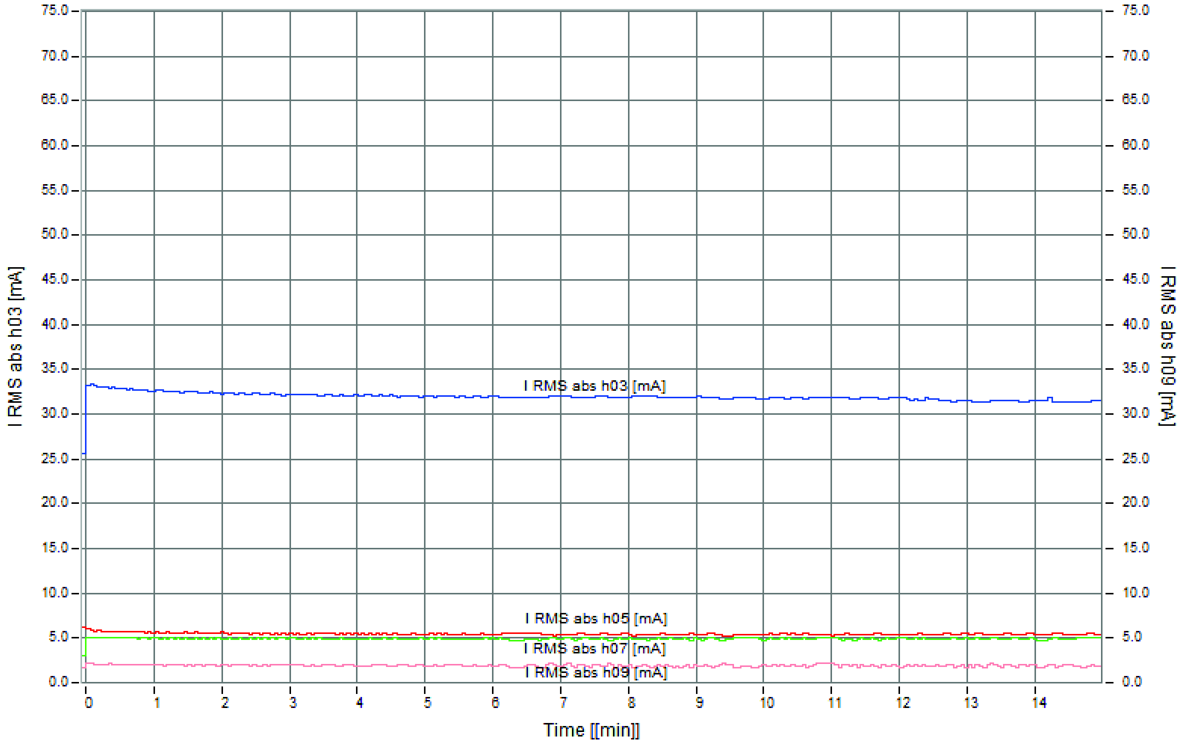


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

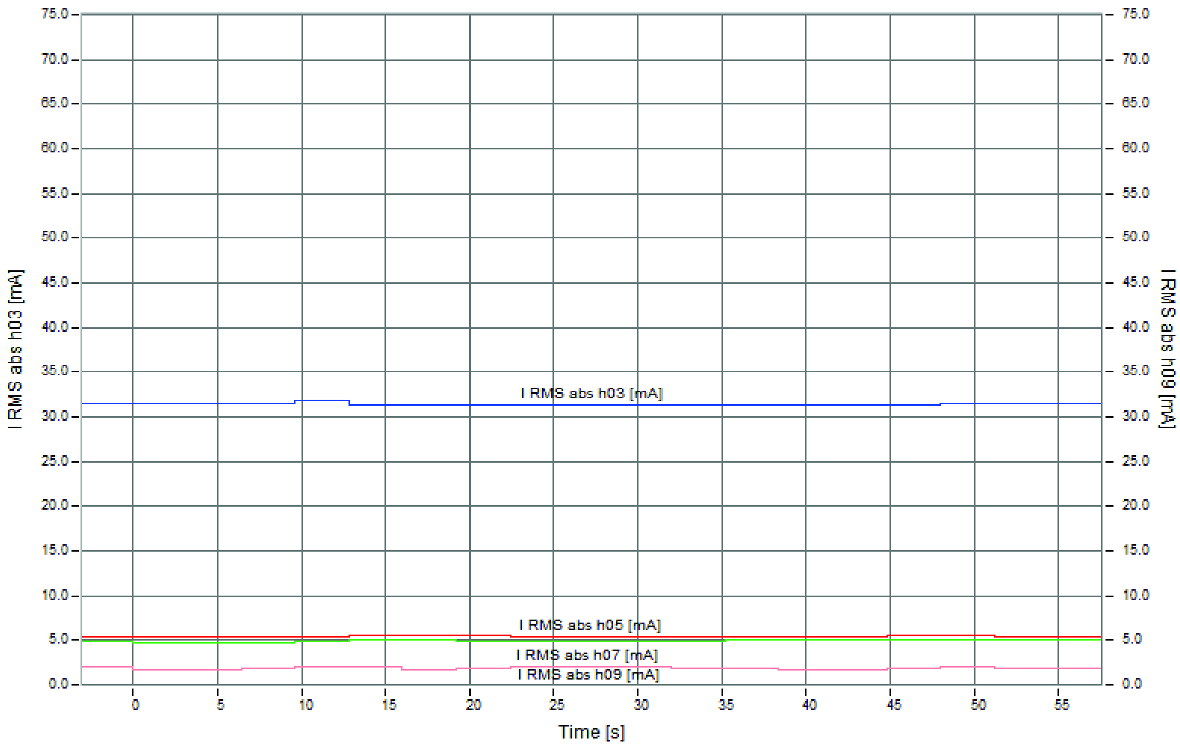


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

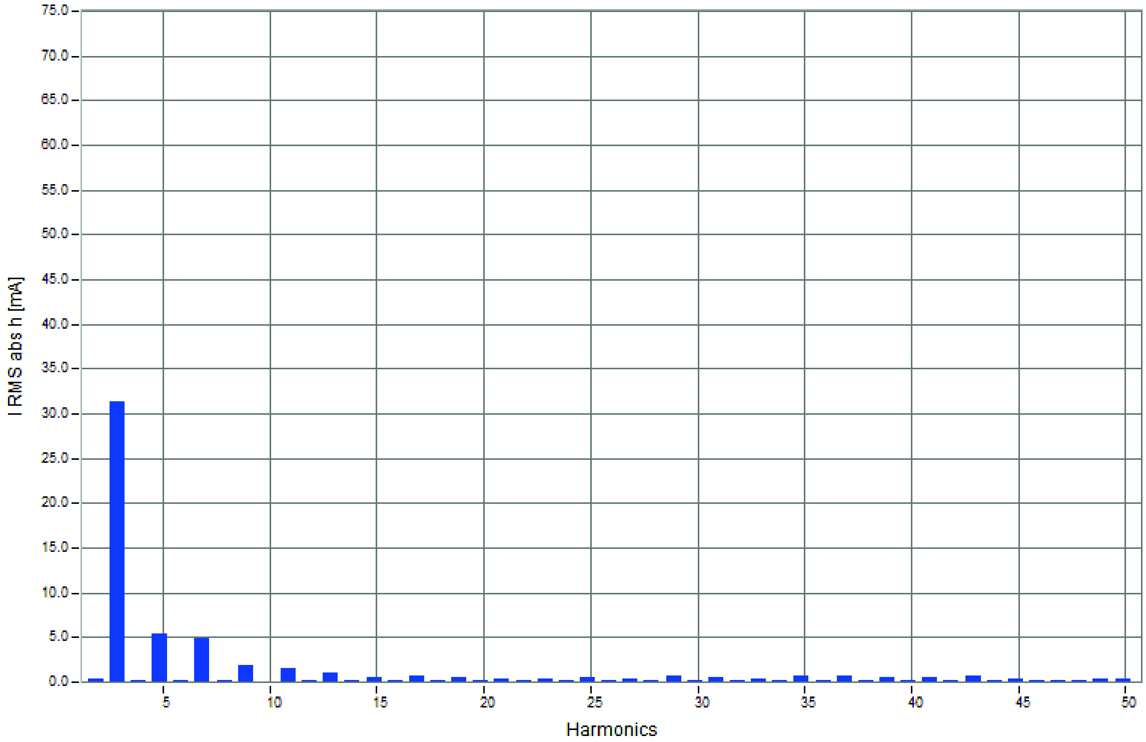


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.90\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.90\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 189.98 V
Current: I = 0.62 A
Active Power = 59.17 W
Reactive Power = 103.14 var
Apparent Power = 119.08 VA
Power Factor = 0.49

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

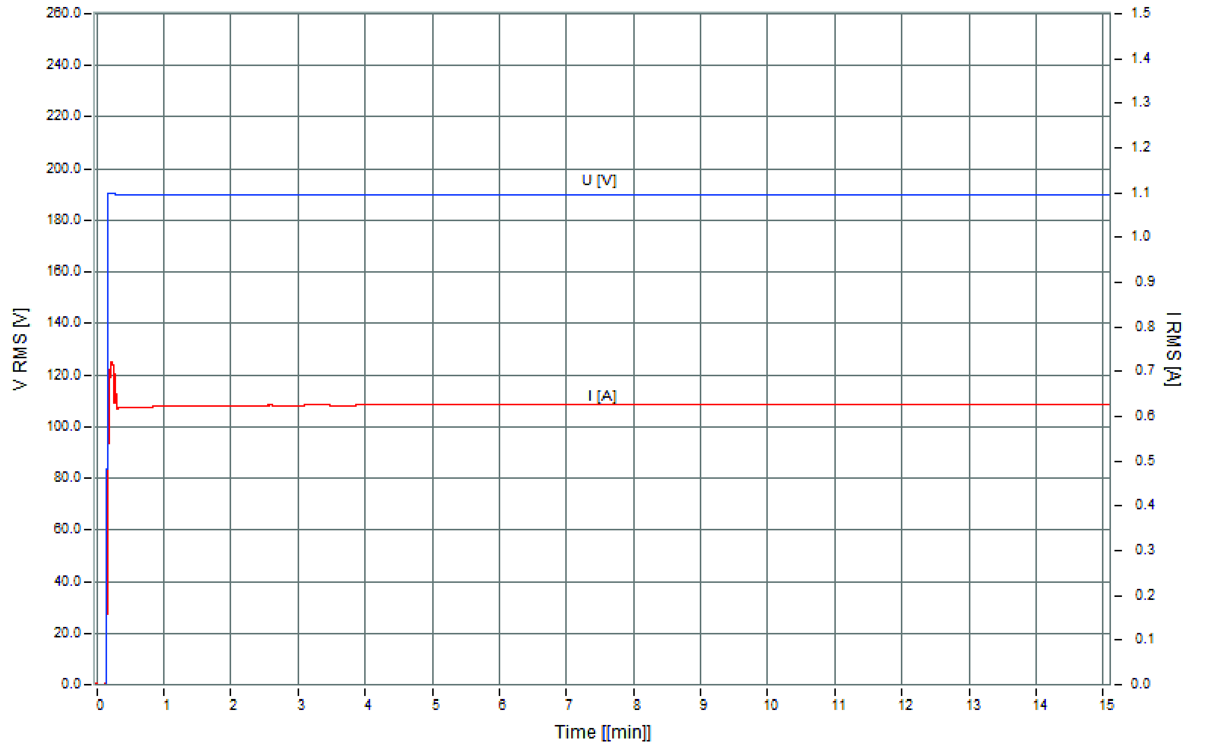


Figure 10. Root Mean Square of voltage and current - 190 V

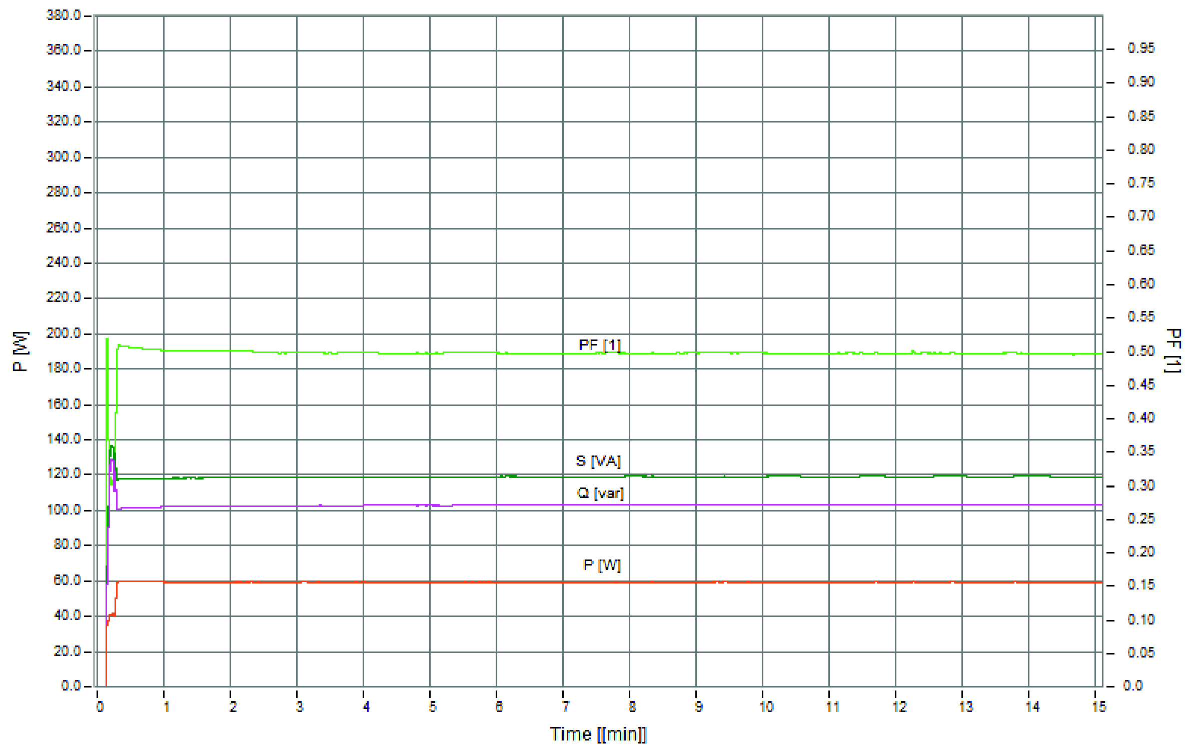


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 189.98	[V]	*****	0.00^0
I L1 = 0.62	[A]	*****	60.20^0

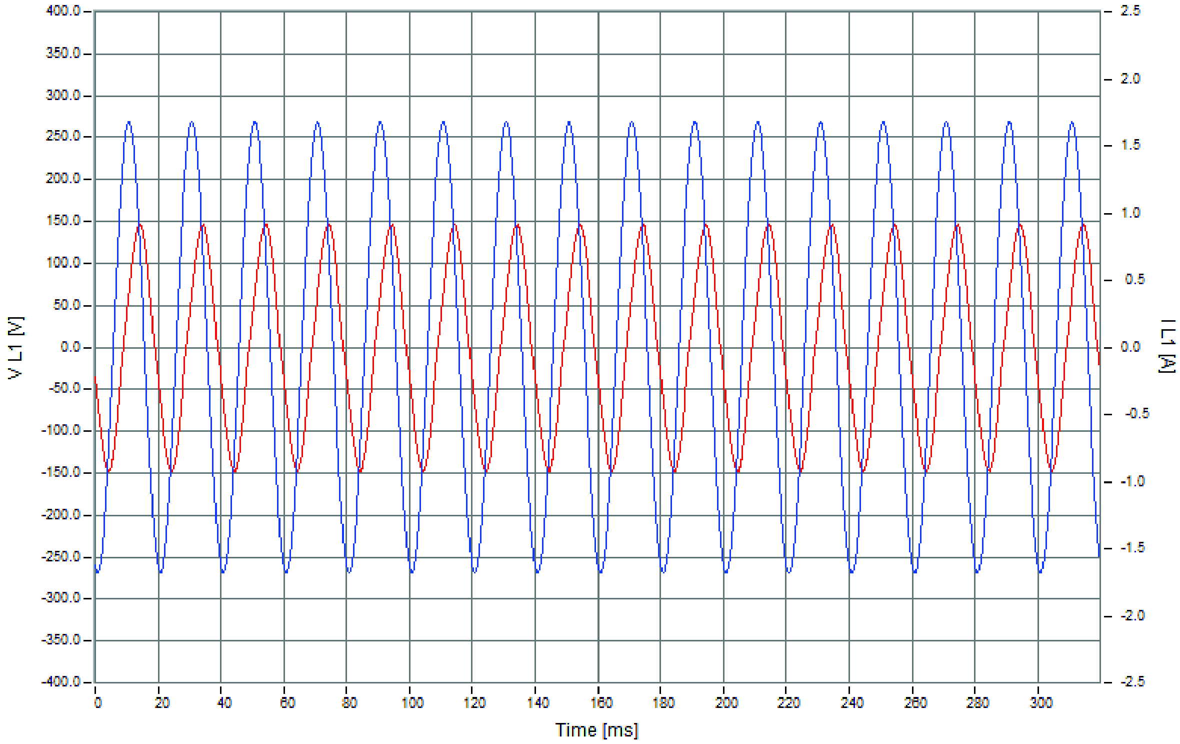


Figure 12. Current and voltage signal curve - 190 V

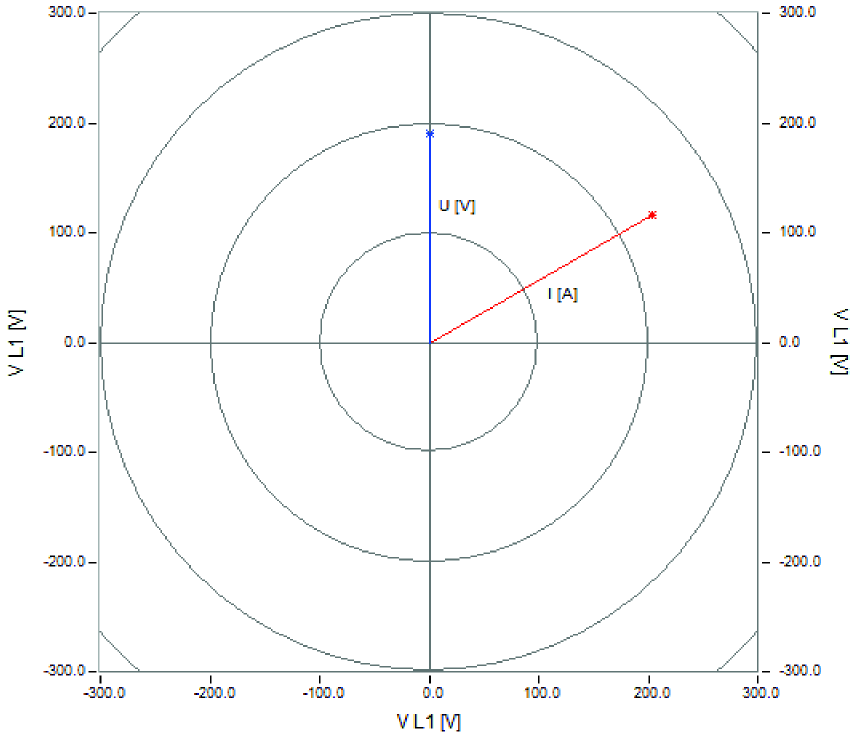


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

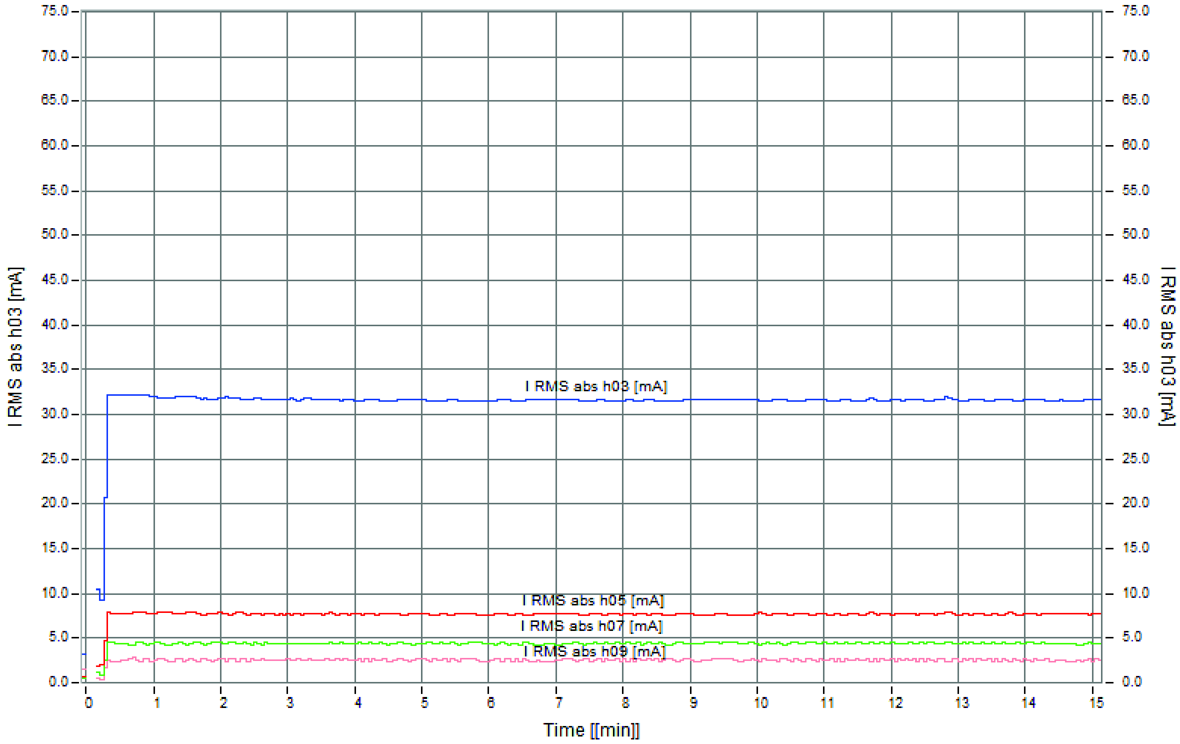


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

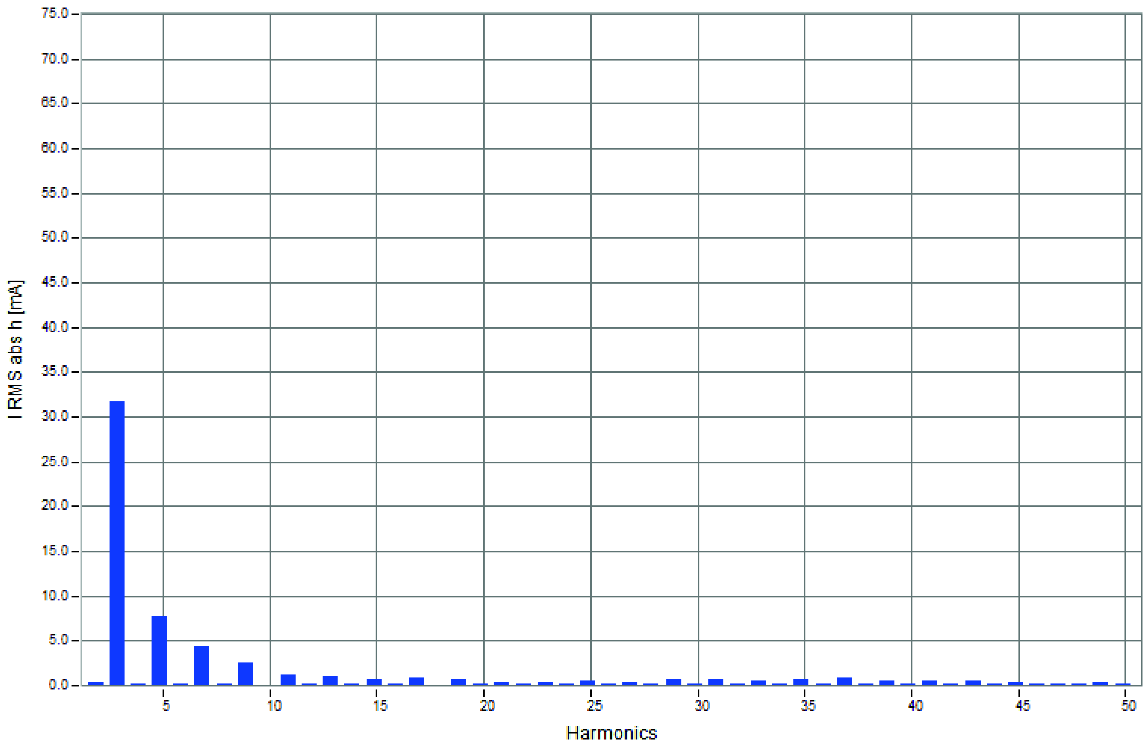


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 5.28\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 5.27\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 200 V
Current: I = 0.68 A
Active Power = 65.29 W
Reactive Power = 120.0 var
Apparent Power = 136.77 VA
Power Factor = 0.47

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

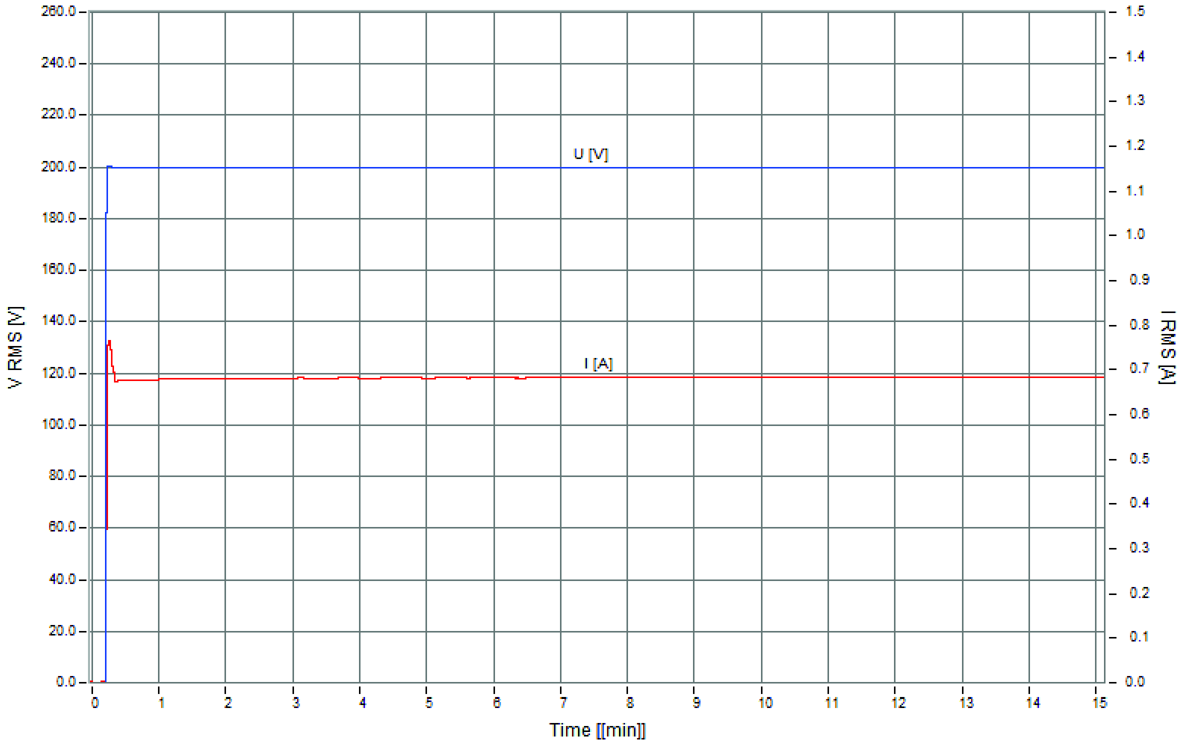


Figure 16. Root Mean Square of voltage and current - 200 V

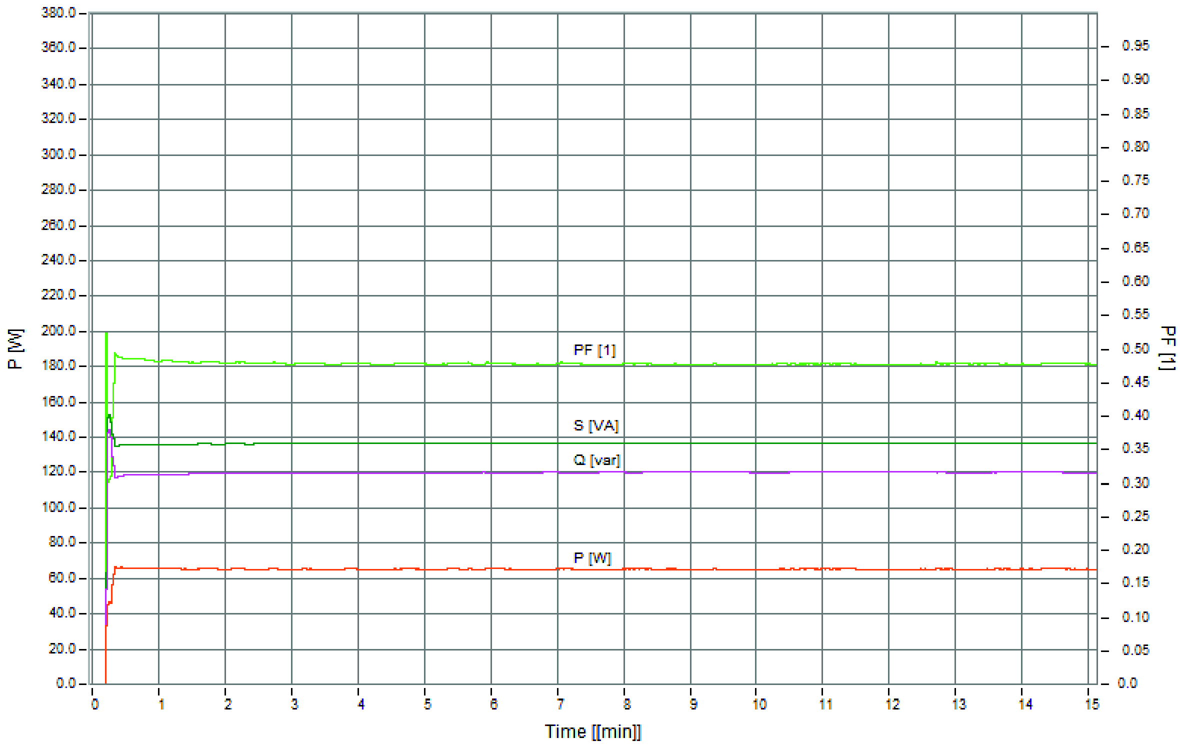


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 199.98	[V]	*****	0.00⁰
I L1 = 0.68	[A]	*****	61.44⁰

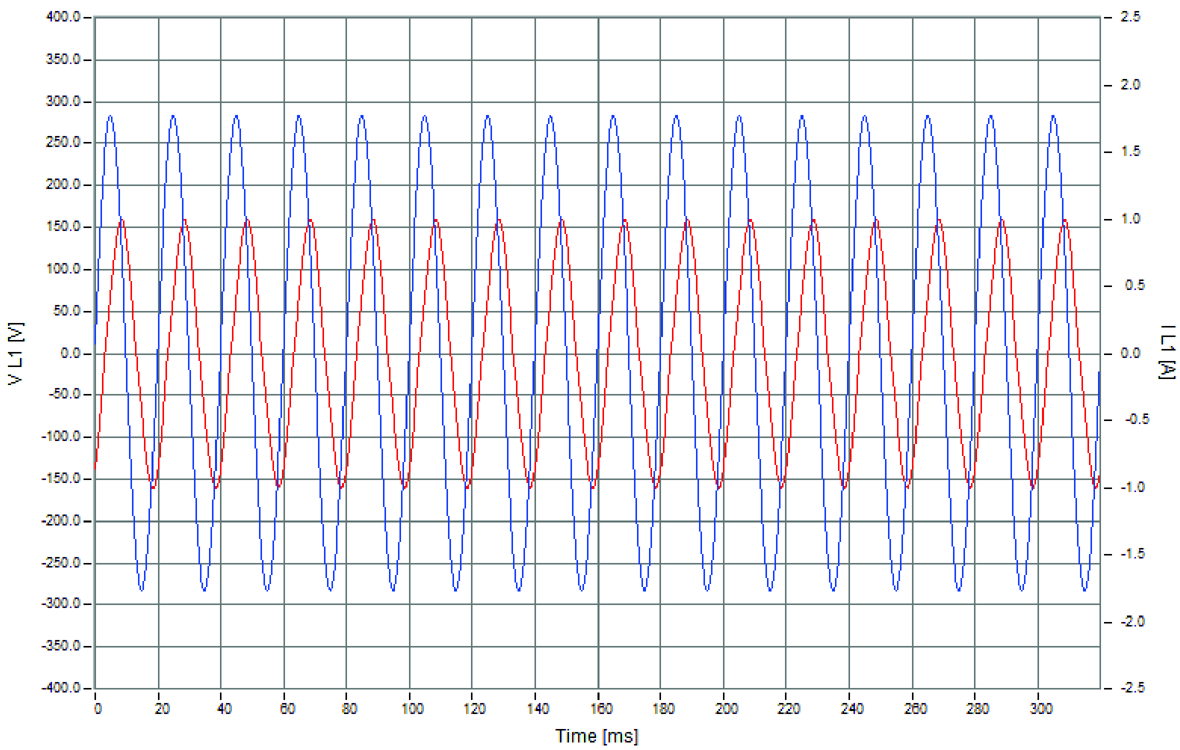


Figure 18. Current and voltage signal curve - 200 V

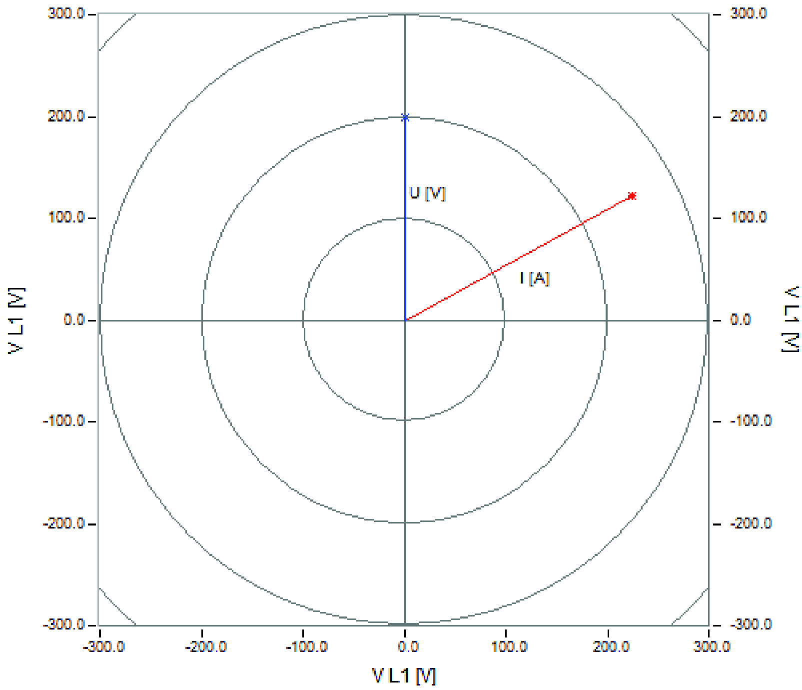


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

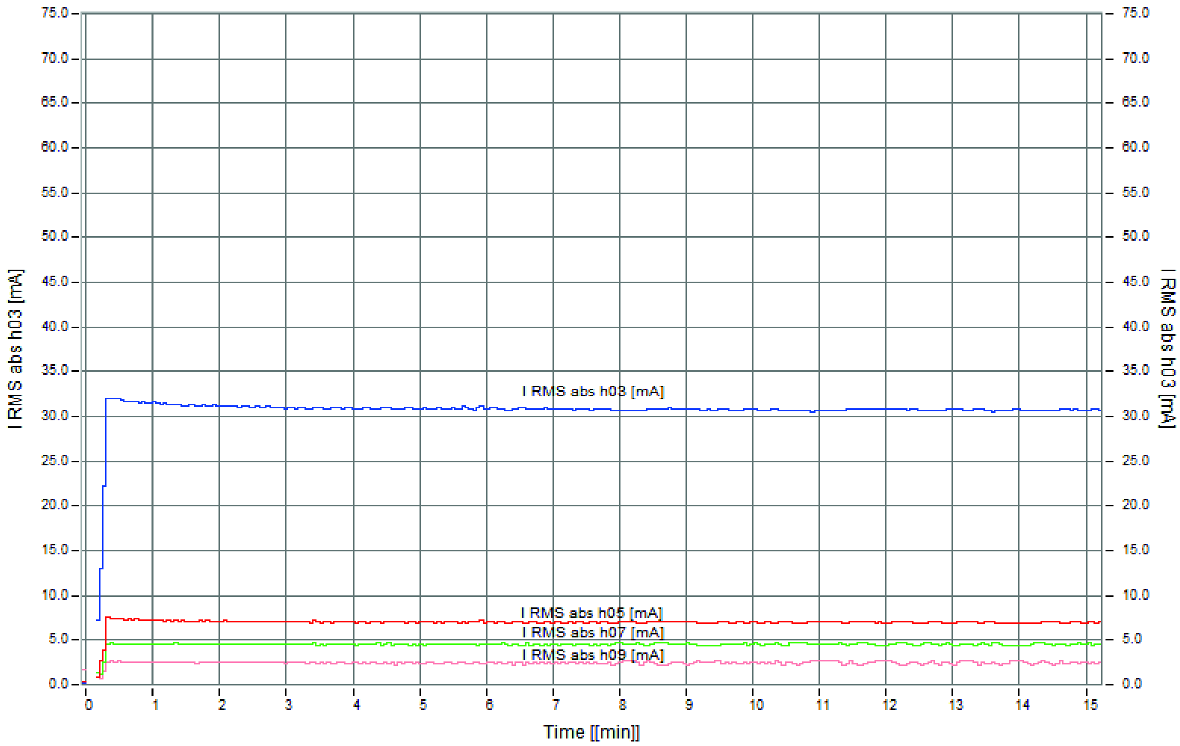


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

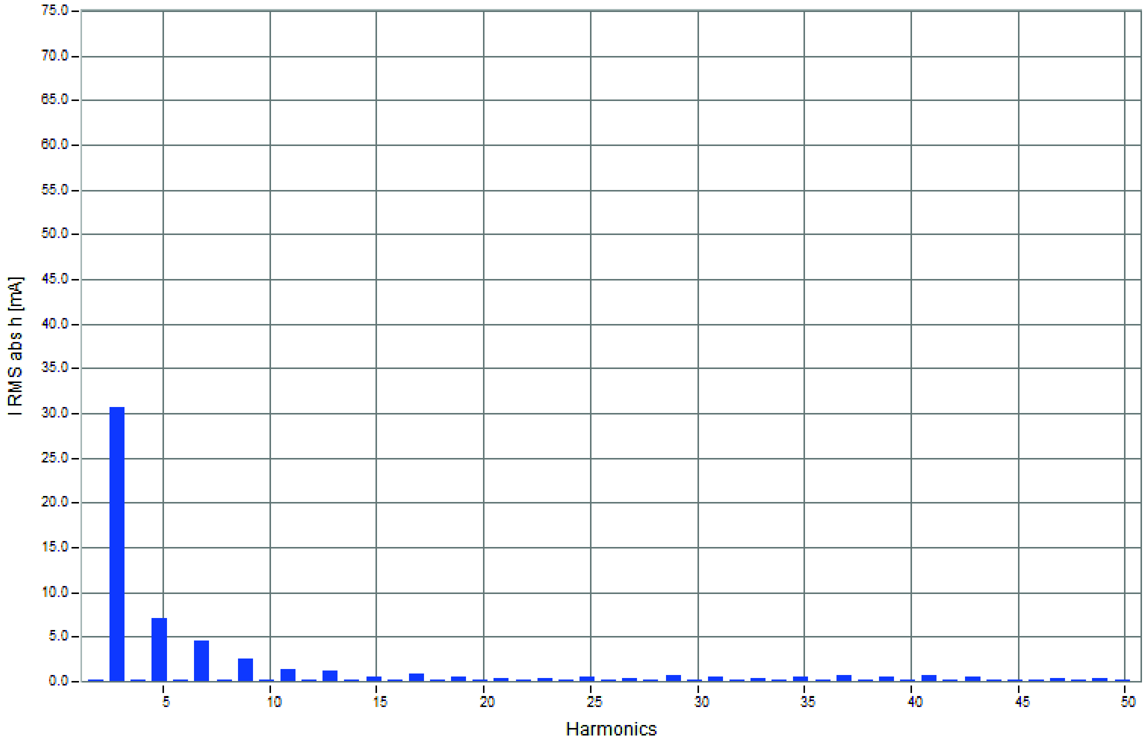


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.69\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.68\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:
Voltage: U = 209.97 V
Current: I = 0.73A
Active Power = 71.23 W
Reactive Power = 136.75 var
Apparent Power = 154.34 VA
Power Factor = 0.46

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

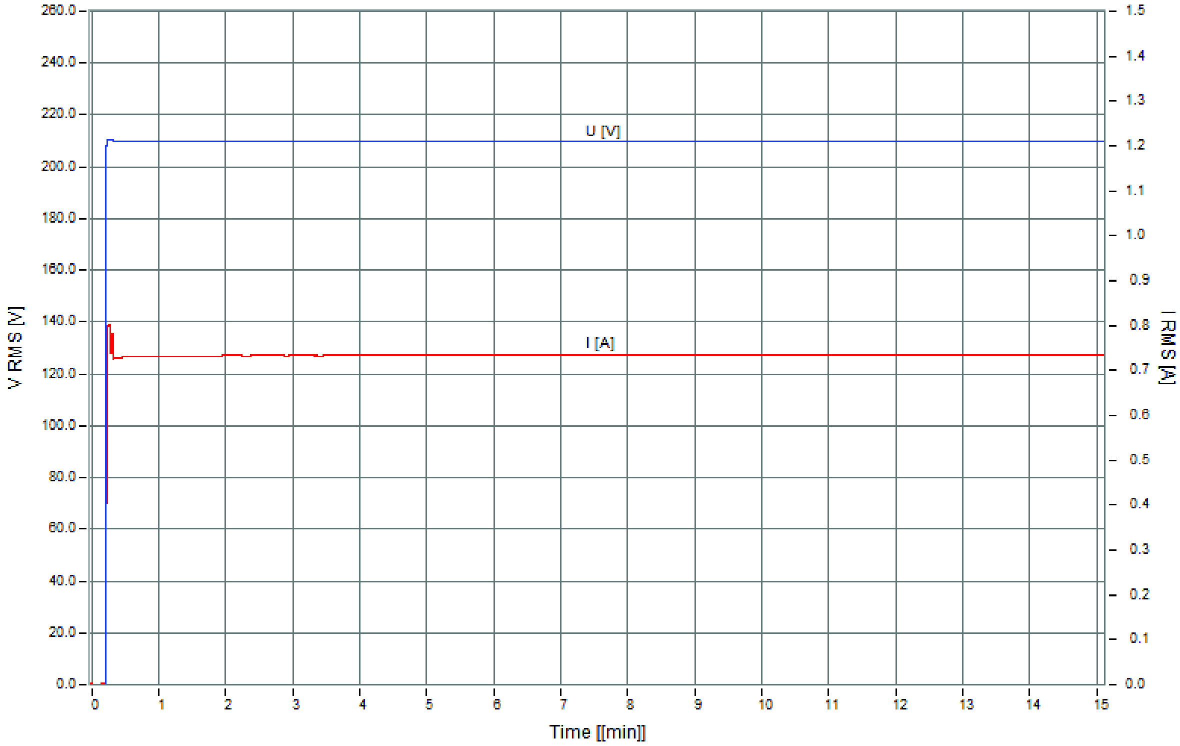


Figure 22. Root Mean Square of voltage and current - 210 V

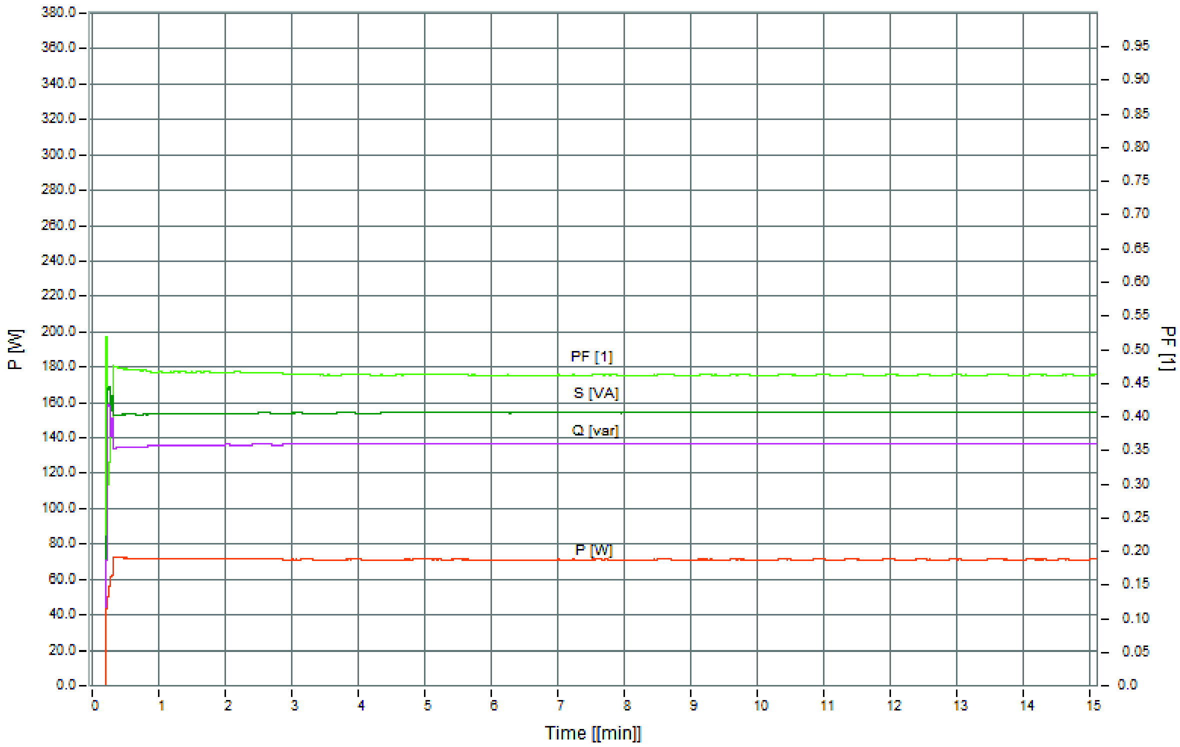


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 209.98	[V]	*****	0.00⁰
I L1 = 0.73	[A]	*****	62.45⁰

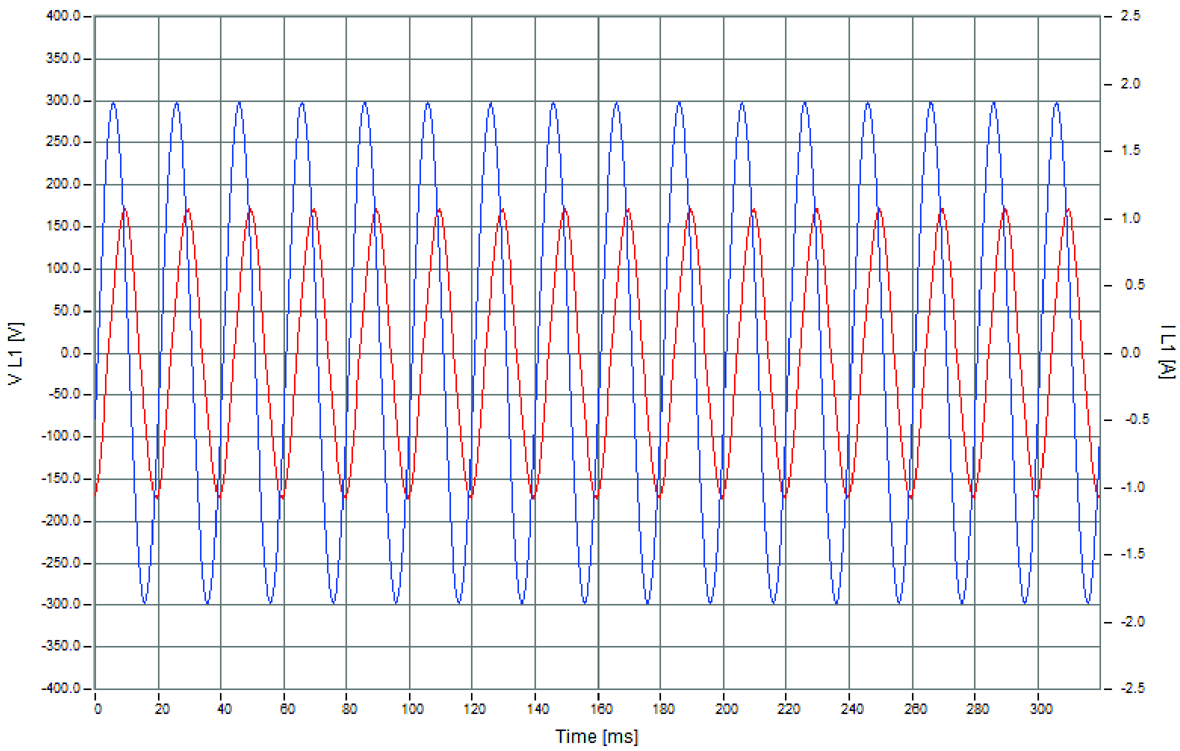


Figure 24. Current and voltage signal curve - 210 V

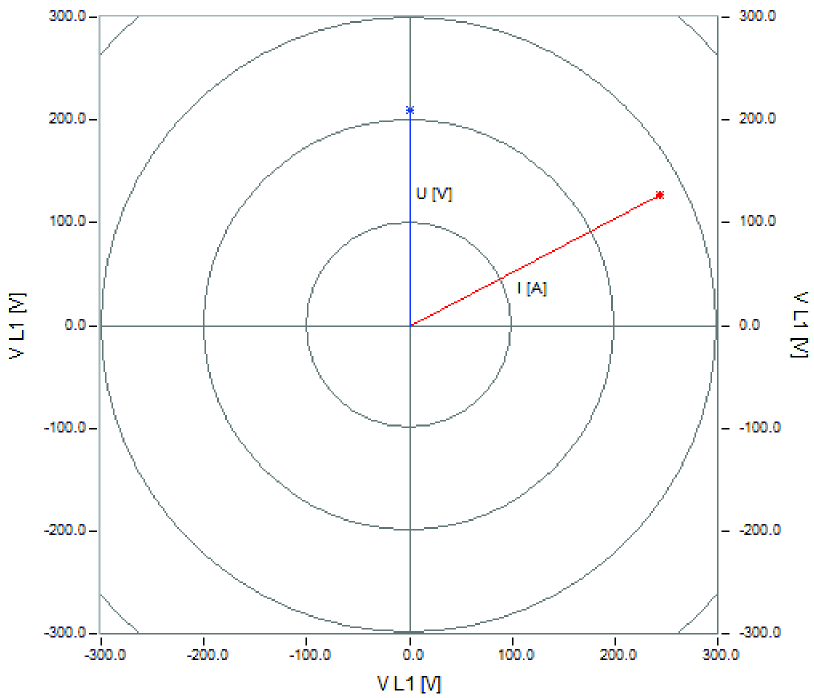


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

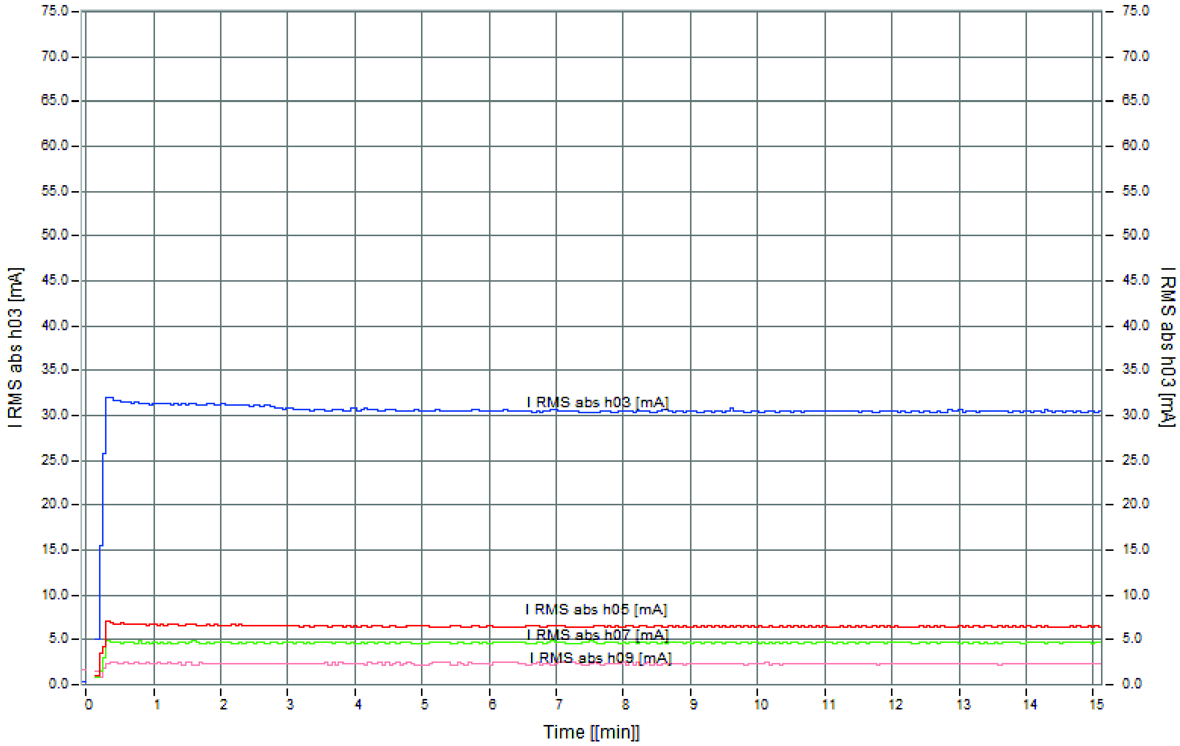


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

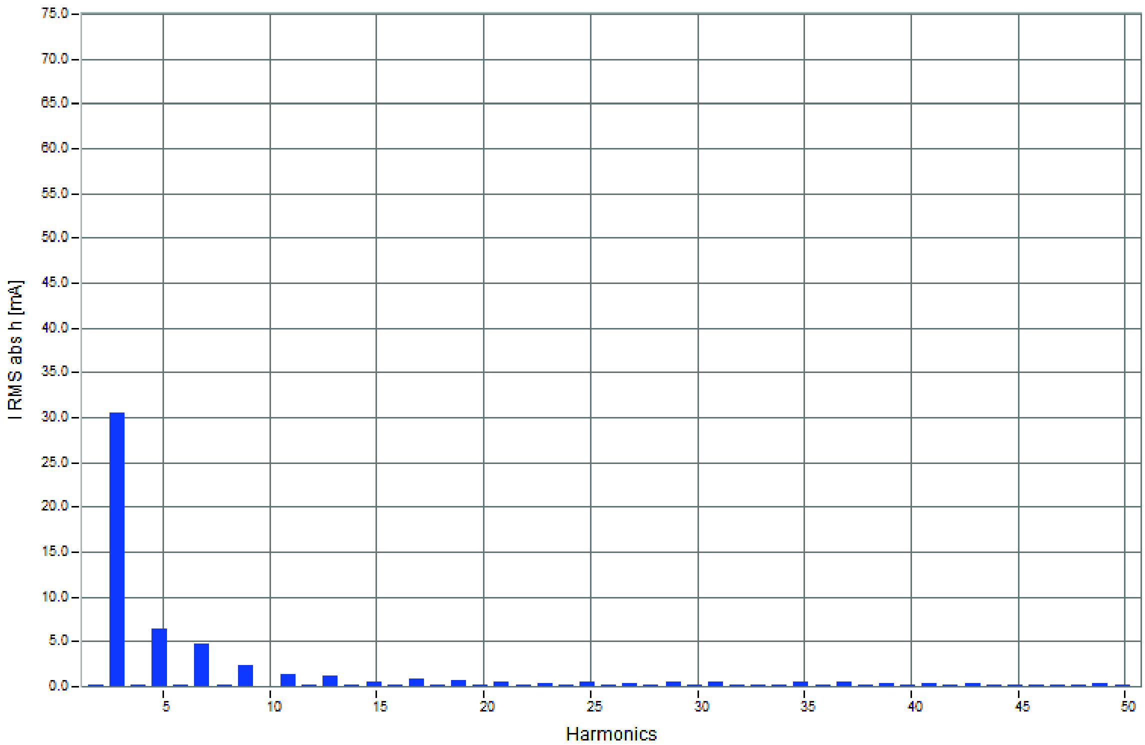


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.31\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.31\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 219.99 V

Current: I = 0.78 A

Active Power = 77.70 W

Reactive Power = 153.91 var

Apparent Power = 172.56 VA

Power Factor = 0.45

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

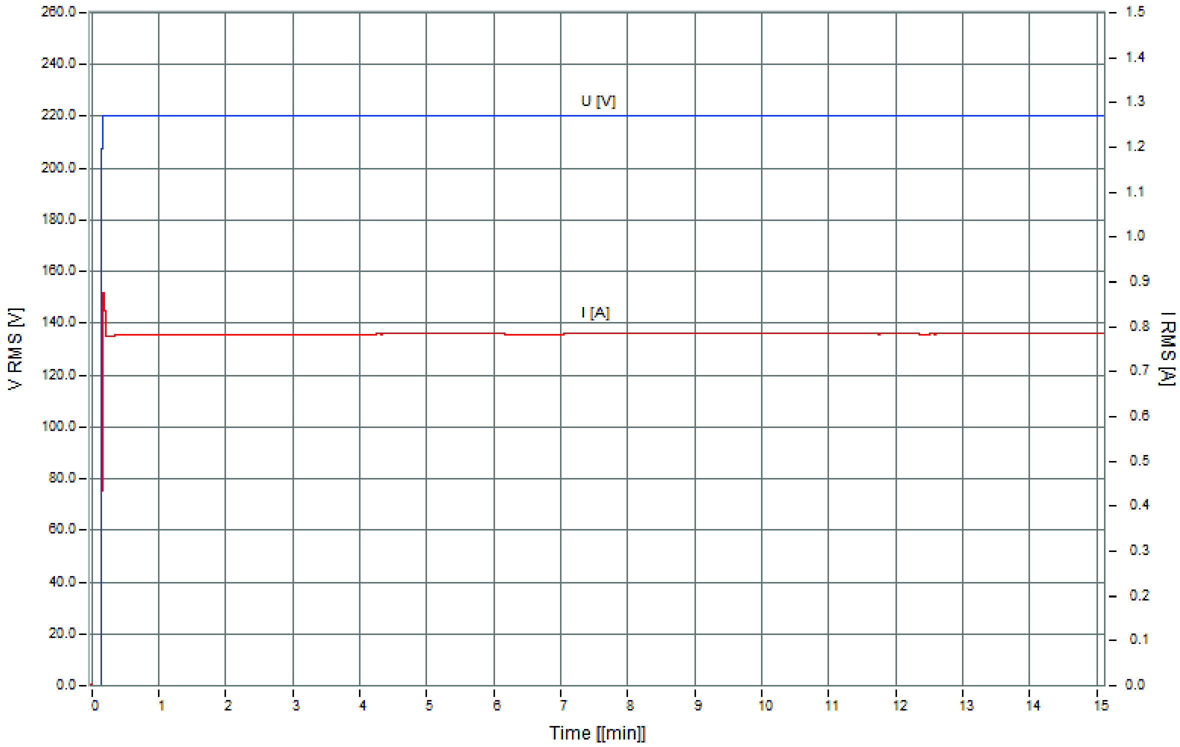


Figure 28. Root Mean Square of voltage and current - 220 V

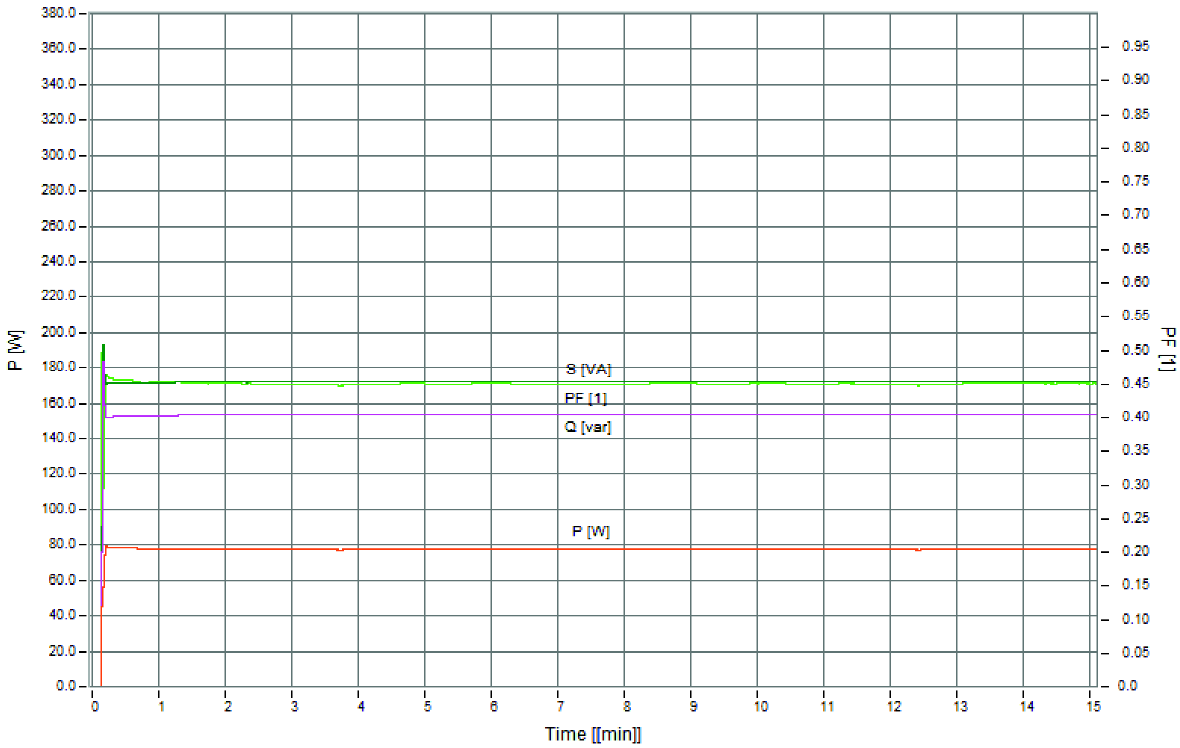


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 219.99	[V]	*****	0.00⁰
I L1 = 0.78	[A]	*****	63.31⁰

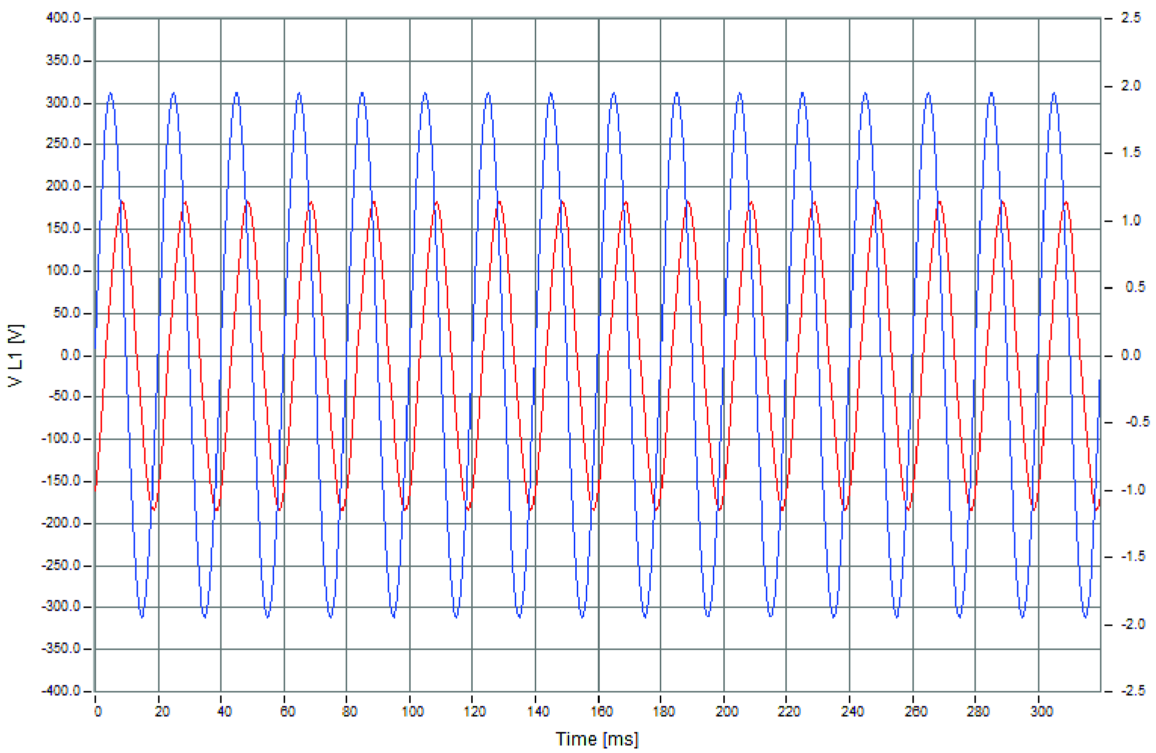


Figure 30. Current and voltage signal curve - 220 V

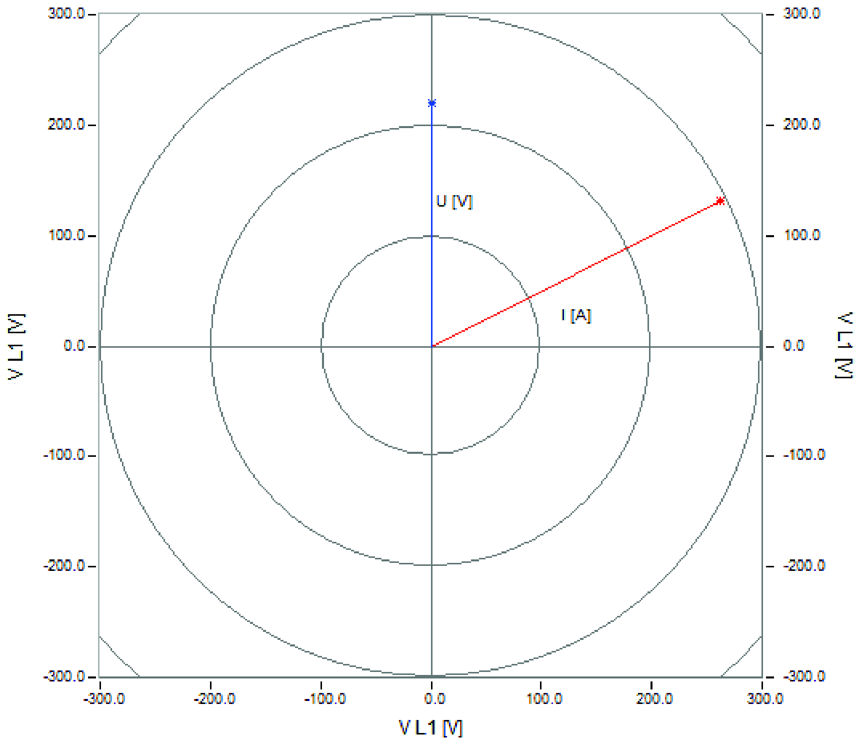


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

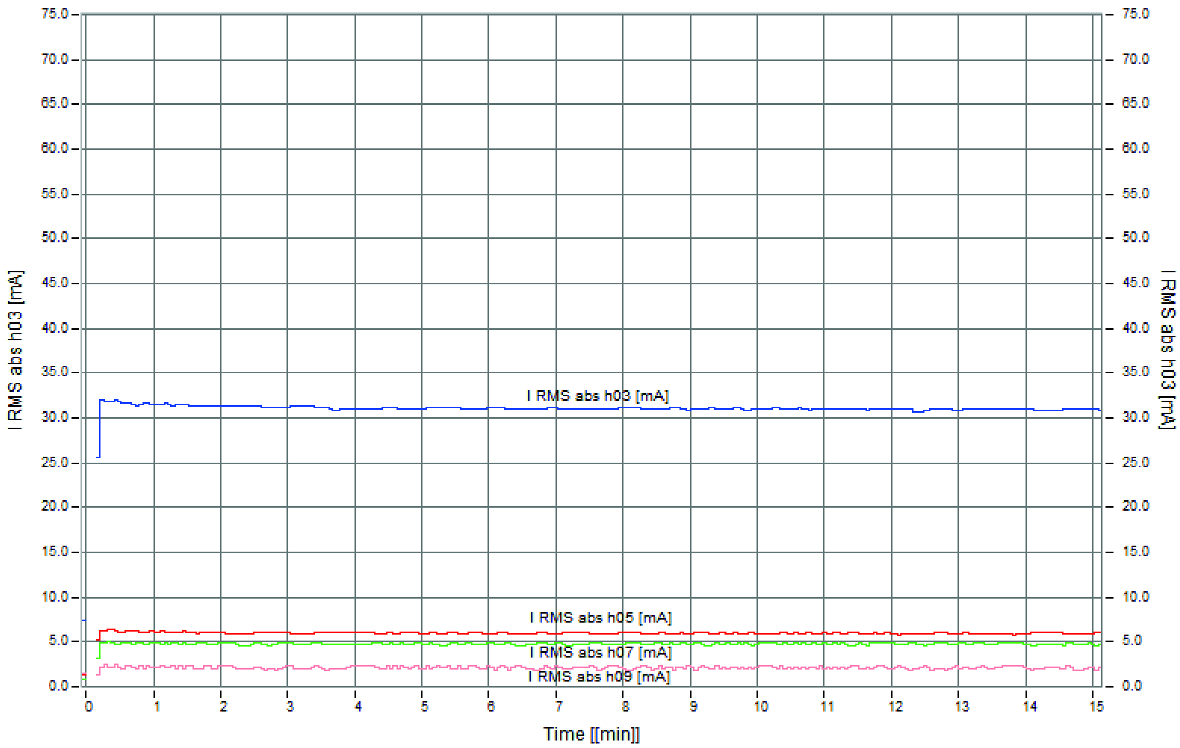


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

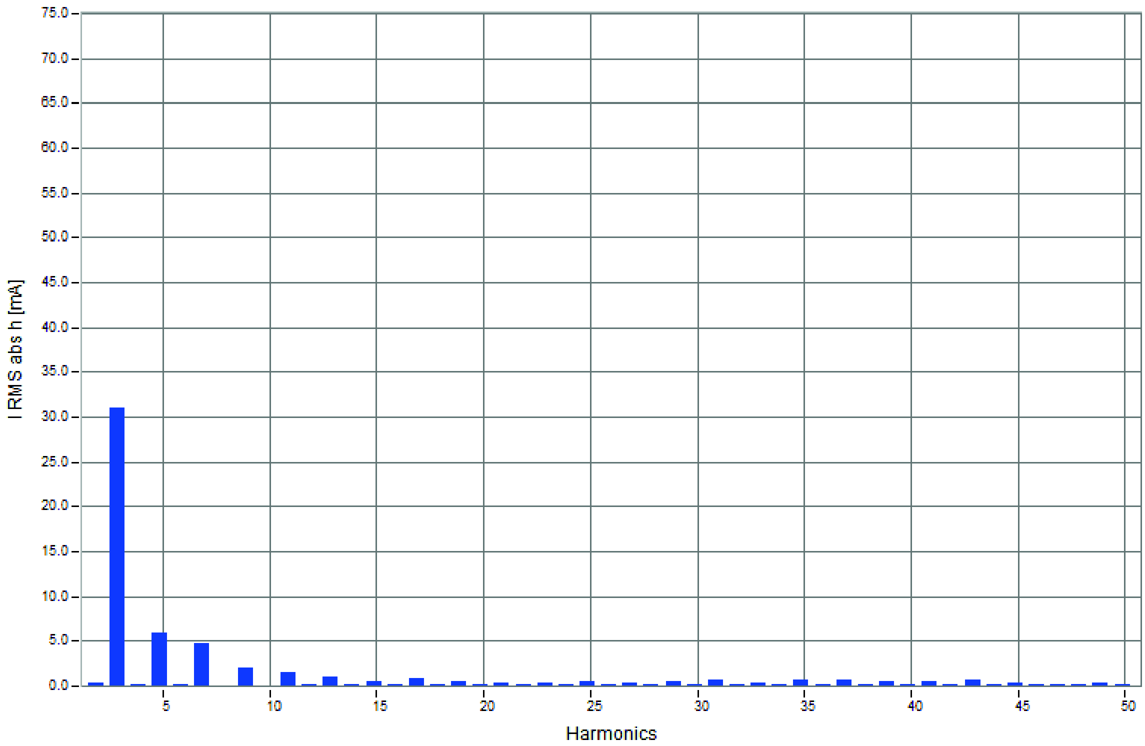


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.09\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.08\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 240.06 V
Current: I = 0.87 A
Active Power = 89.70 W
Reactive Power = 190.63 var
Apparent Power = 210.85 VA
Power Factor = 0.42

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

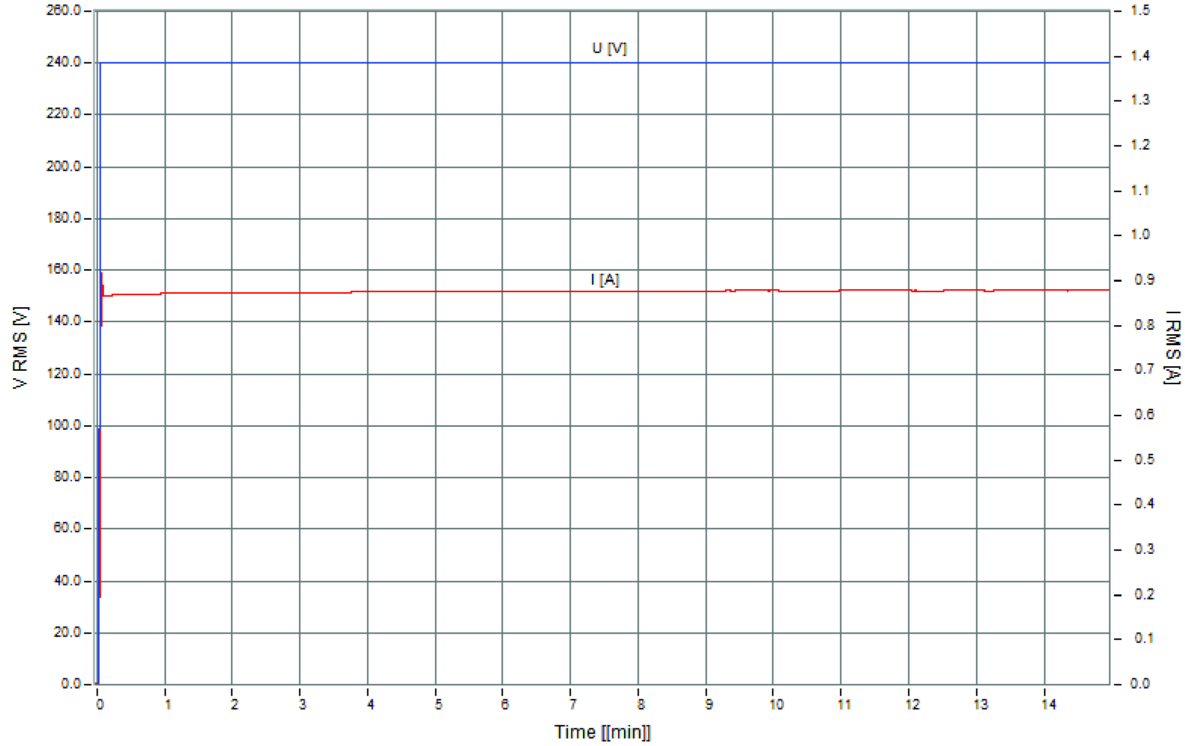


Figure 34. Root Mean Square of voltage and current - 240 V

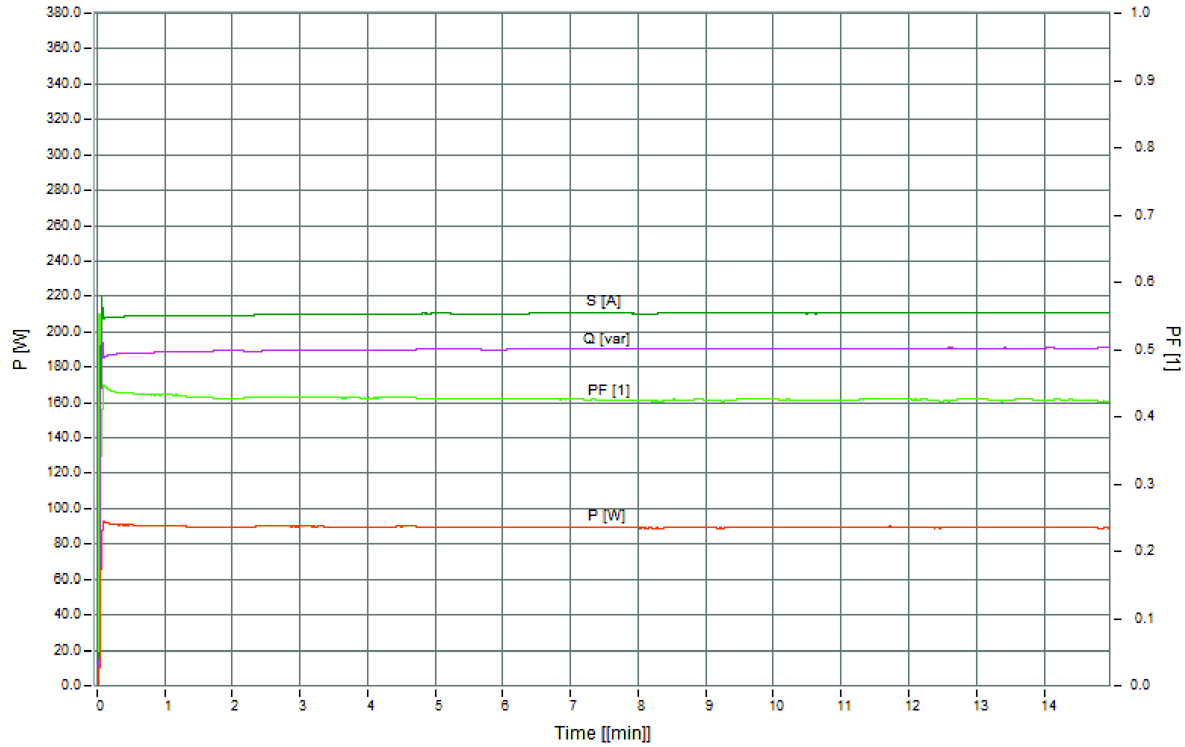


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 240.05	[V]	*****	0.00^0
I L1 = 0.87	[A]	*****	64.76^0

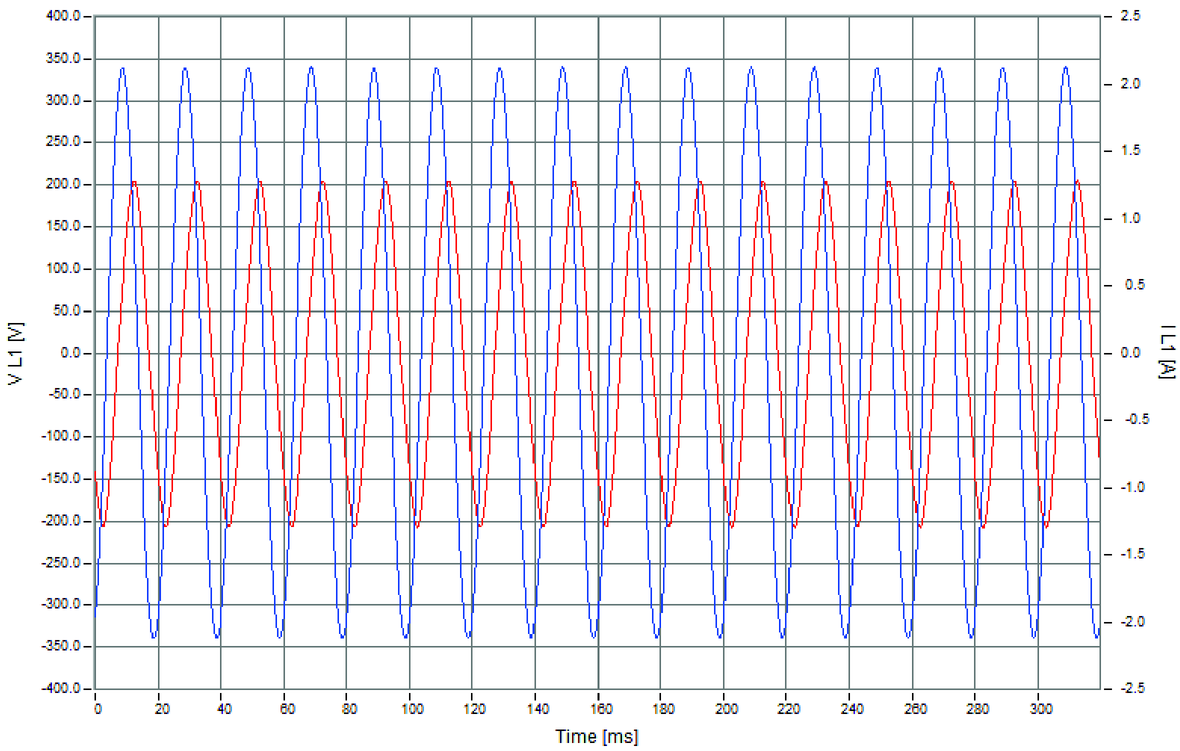


Figure 36. Current and voltage signal curve - 240 V

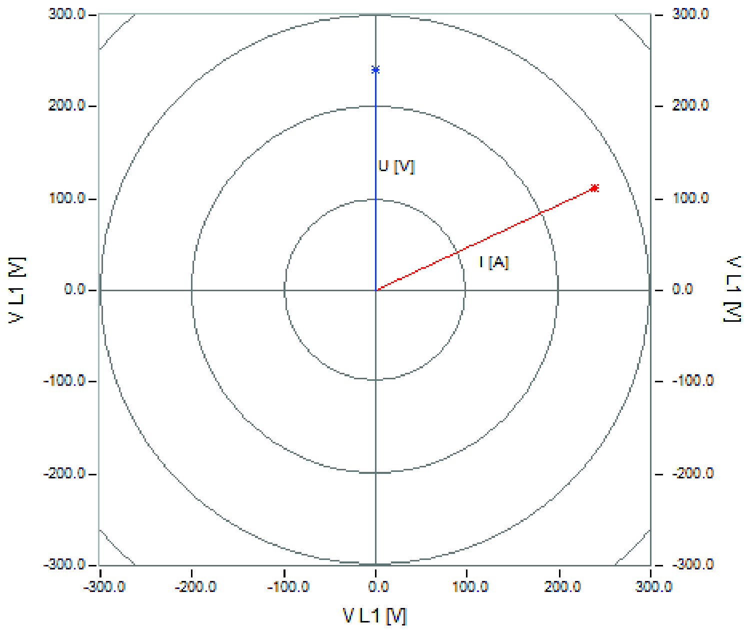


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

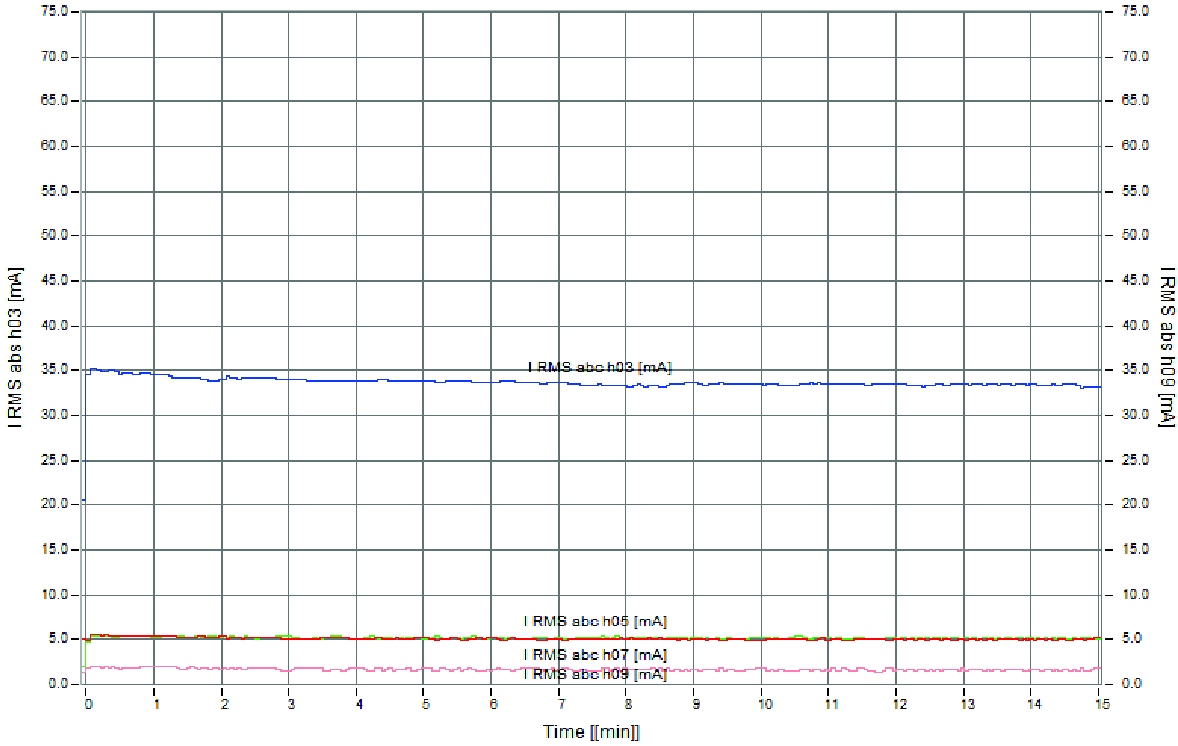


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

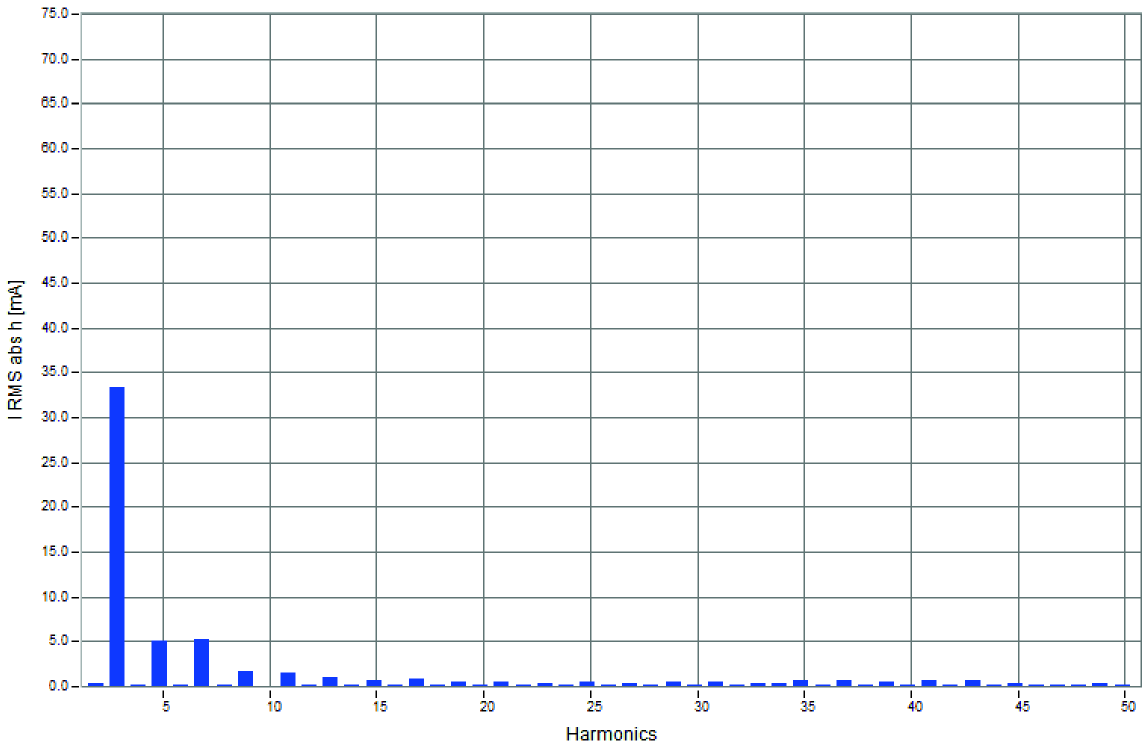


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.90\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.90\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 250.12 V
Current: I = 0.91 A
Active Power = 96.15 W
Reactive Power = 208.21 var
Apparent Power = 229.55 VA
Power Factor = 0.41

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

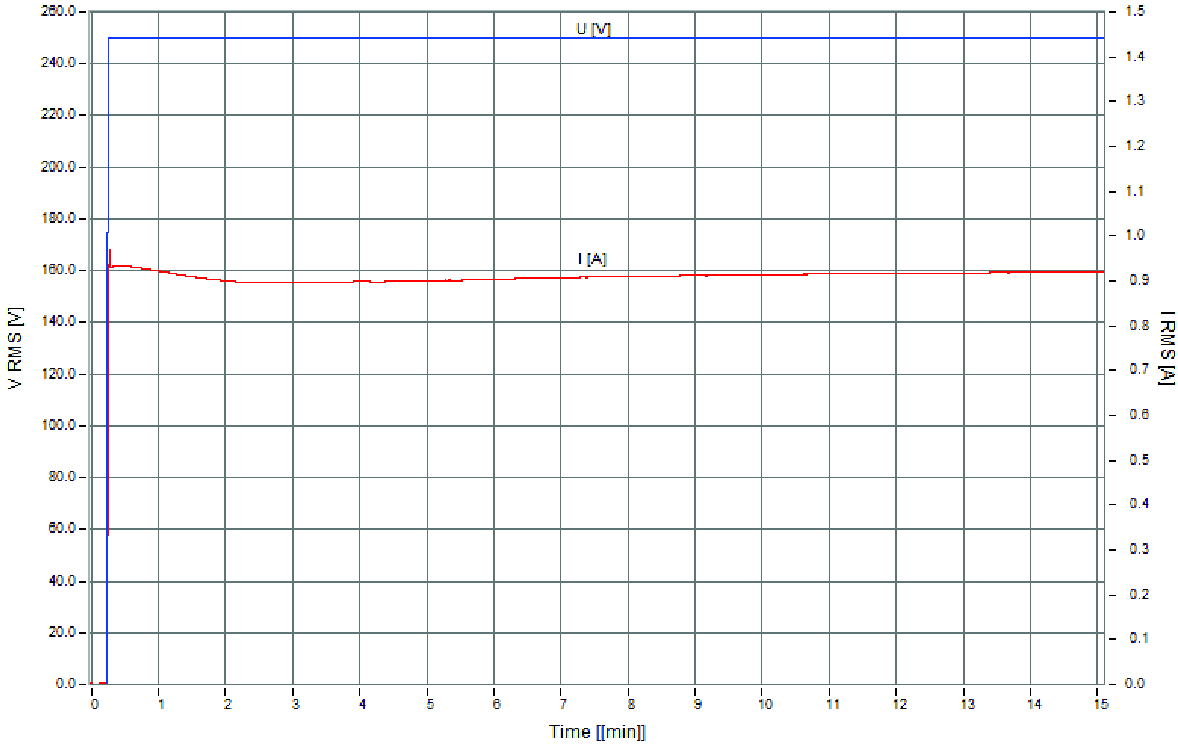


Figure 40. Root Mean Square of voltage and current - 250 V

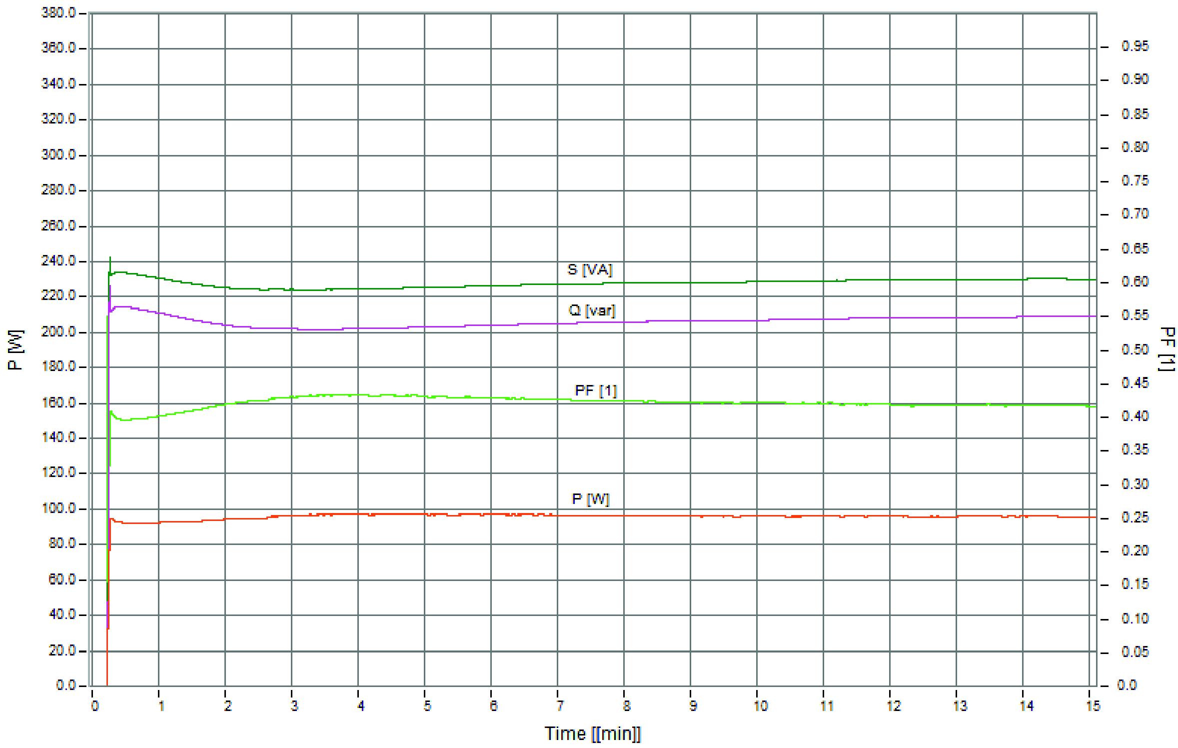


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 250.19	[V]	*****	0,00^{0}
I L1 = 0.92	[A]	*****	66.44^{0}

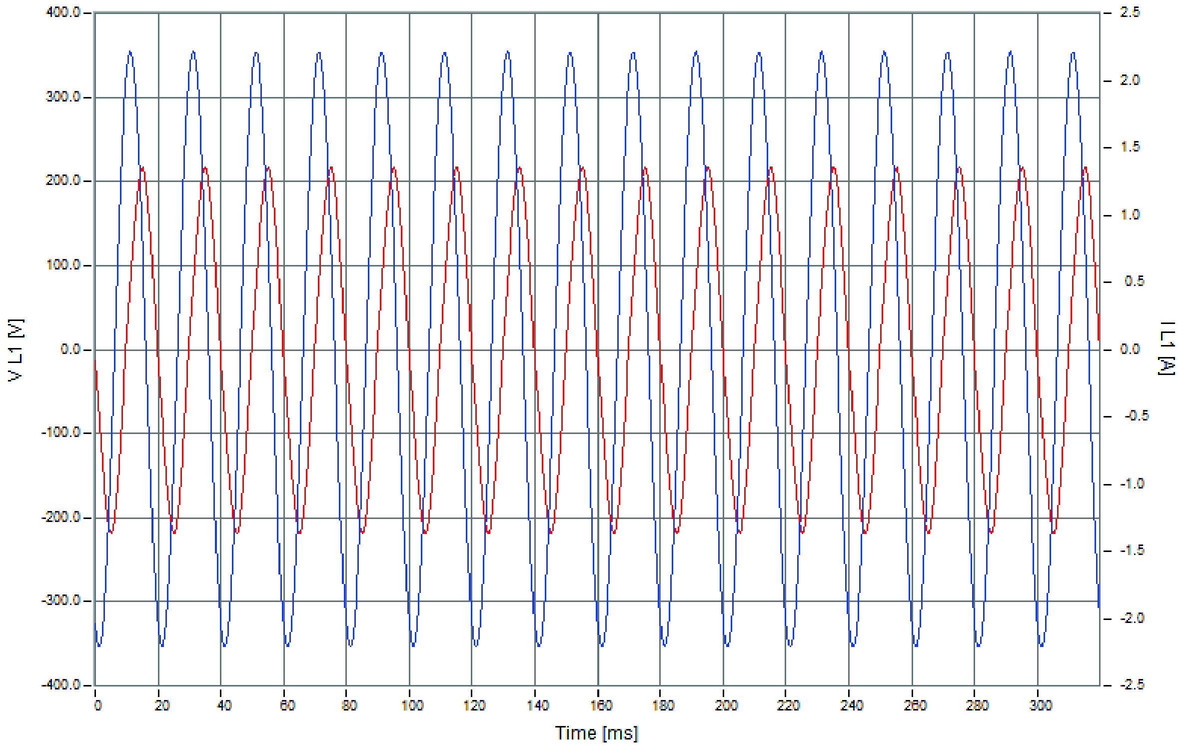


Figure 42. Current and voltage signal curve - 250 V

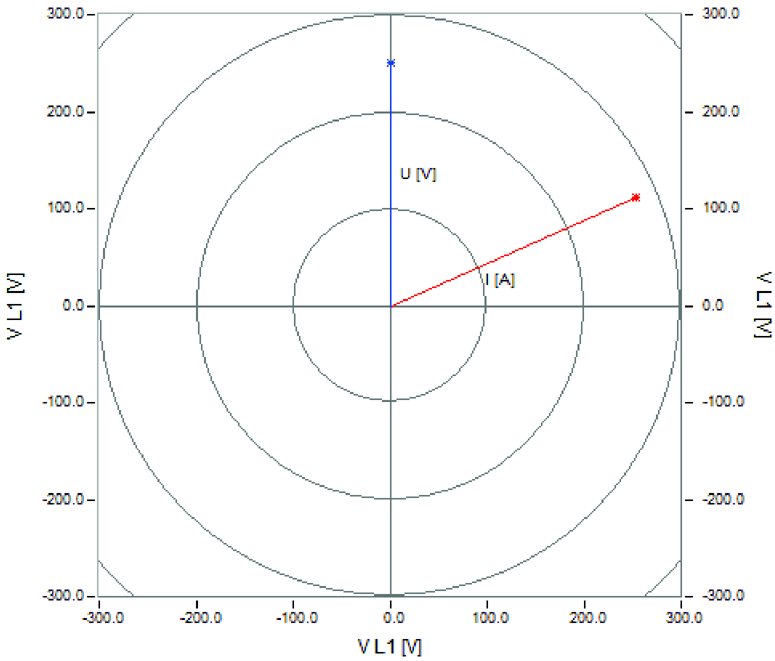


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

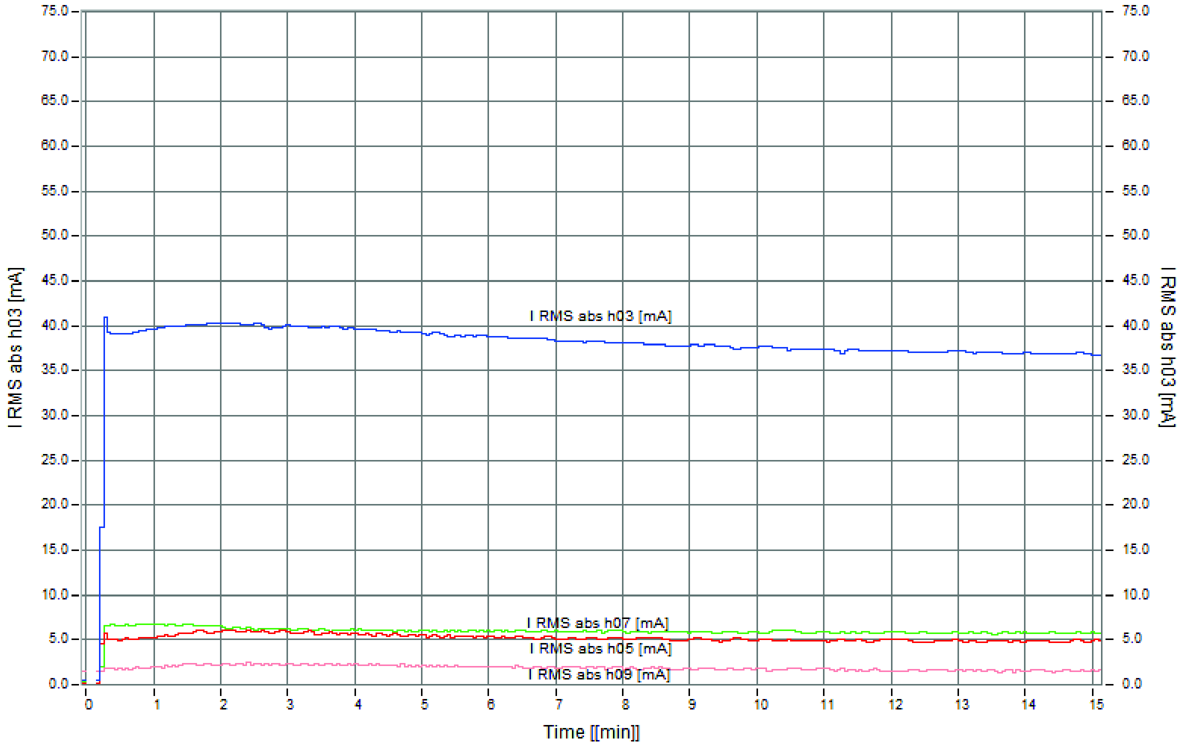


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

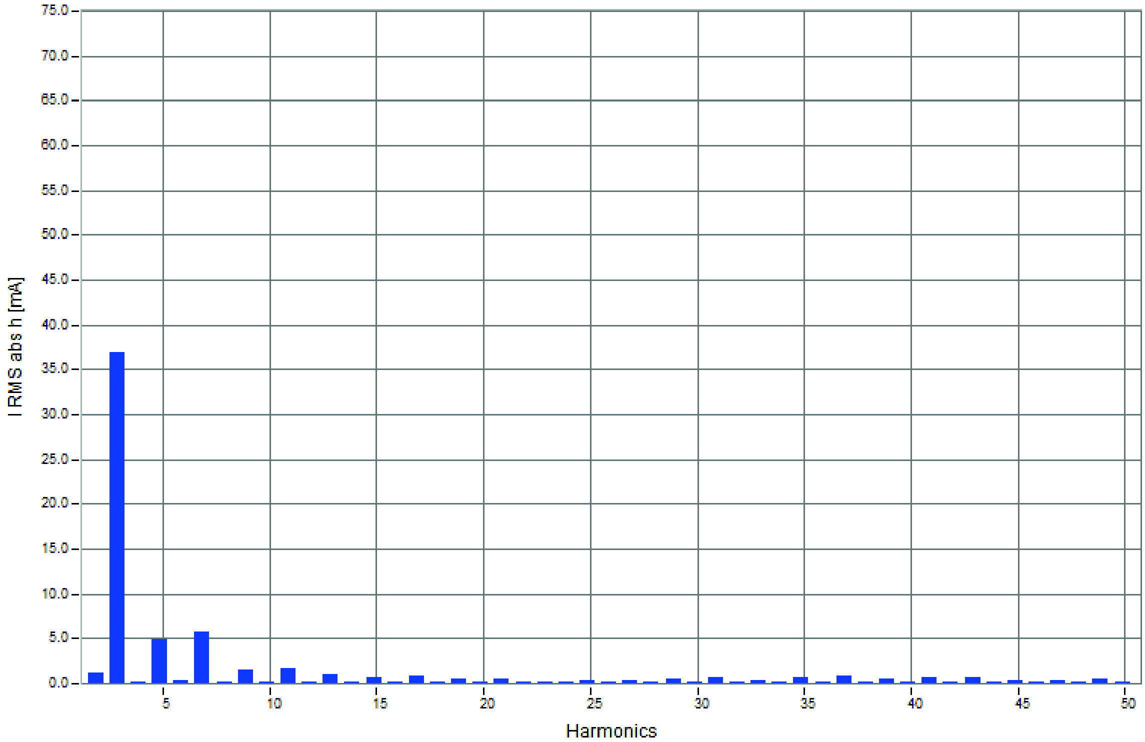


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.11\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.47\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 5.28%, for the minimum voltage, 0.82 p.u.. The minimum THD, 3.9%, is measured for the nominal voltage 1 p.u.. Further increase of the voltage causes a slight increase of the THD.

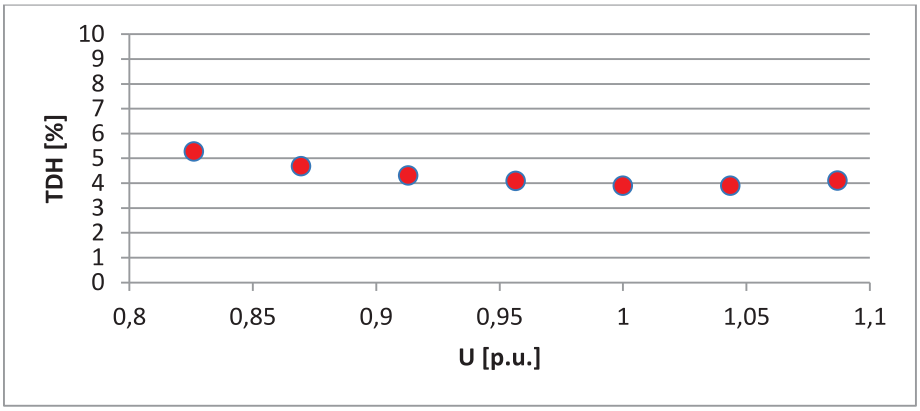


Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature

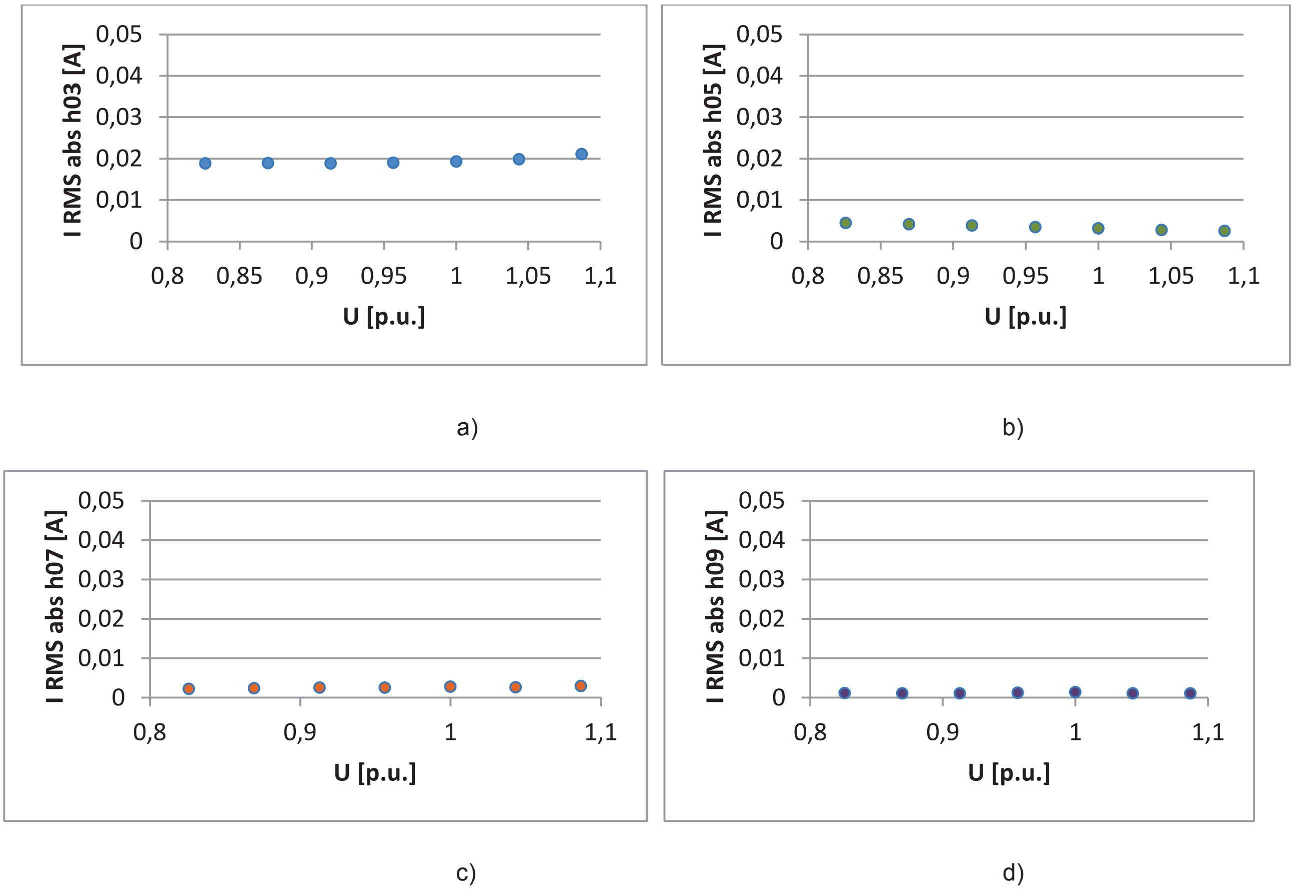


Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which have a exponentional behaviour with a minimum of 0.018mA by voltage 0.82 p.u.. Figures 47. b) and d) shows the 5th and the 9th harmonic respectively. In both cases the harmonic values are decreasing with the voltage increase. Figure 47. c) shows 7th harmonic which increases marginally with the voltage increase.

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Institut für Energiesysteme und Elektrische Antriebe
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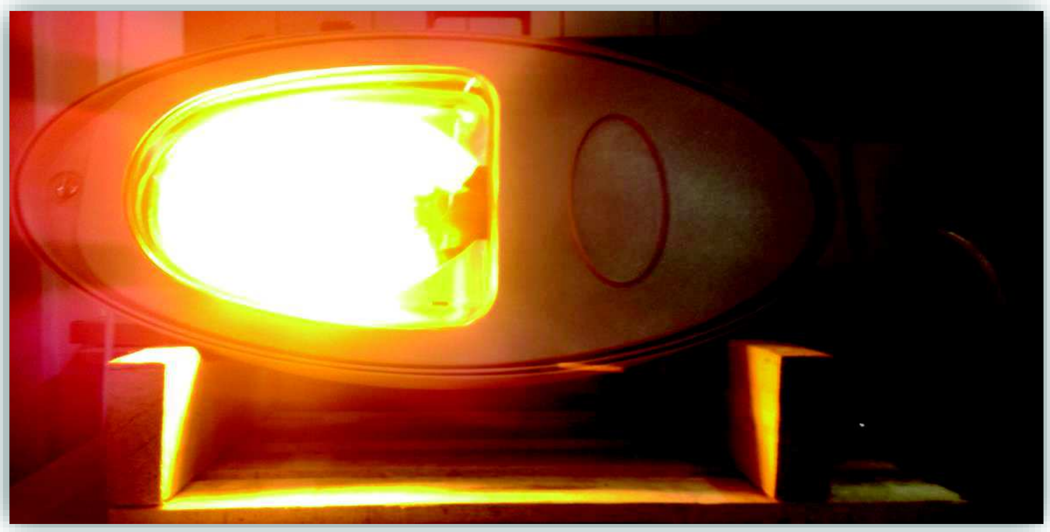
A - 1040 Wien

MEASUREMENT PROTOCOL 5

High pressure Sodium lamp-new
Lamp: NARVA
Ballast: TRIDONIC



Vienna 29.January 2016

1. Content

2. List of figures

3. Light type

High pressure sodium lamp
1X light source
Status: new

4. Technical data

NARVA NAT-S 150 W
Voltage: 230 V
Real power: 150 W
Lamp operating current: 1.8 A
Lamp starting current: 2.2 A
Run-up time: 5 min
Reignition time: 2 min

Maximum overall length L: 211 mm
Diameter d: 46 mm

Ballast: TRIDONIC
OMBS150/100 A603W
Voltage: 230/240 V
Real Power: 150 W
Current: 1.8 A

5. Measurement

5.1. Schema

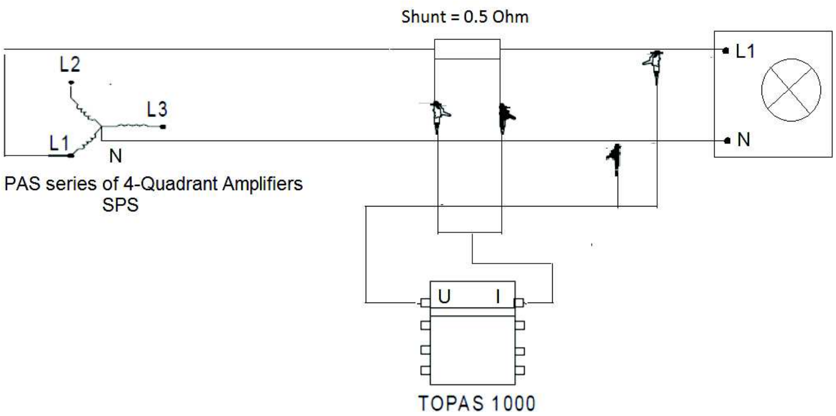


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside **Temperature**: 22.4^{0}C
Voltage range: 190-250 V **Shunt:** 0.5 Ω
easurement interval: 30 min

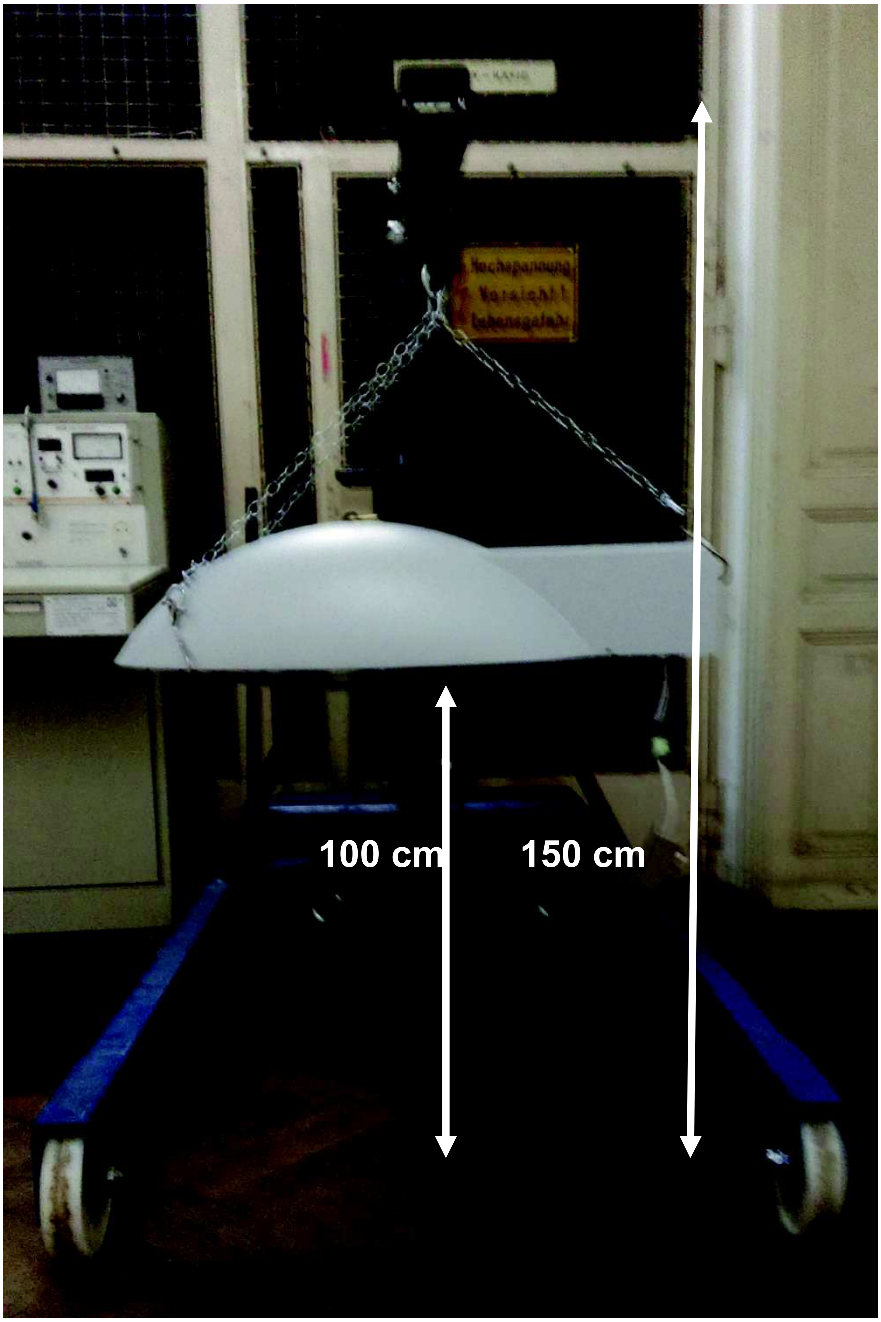


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 229.37 V
Current: I = 0.93 A
Active Power = 136.67 W
Reactive Power = 164.60 var
Apparent Power = 214.75 VA
Power Factor = 0.63

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

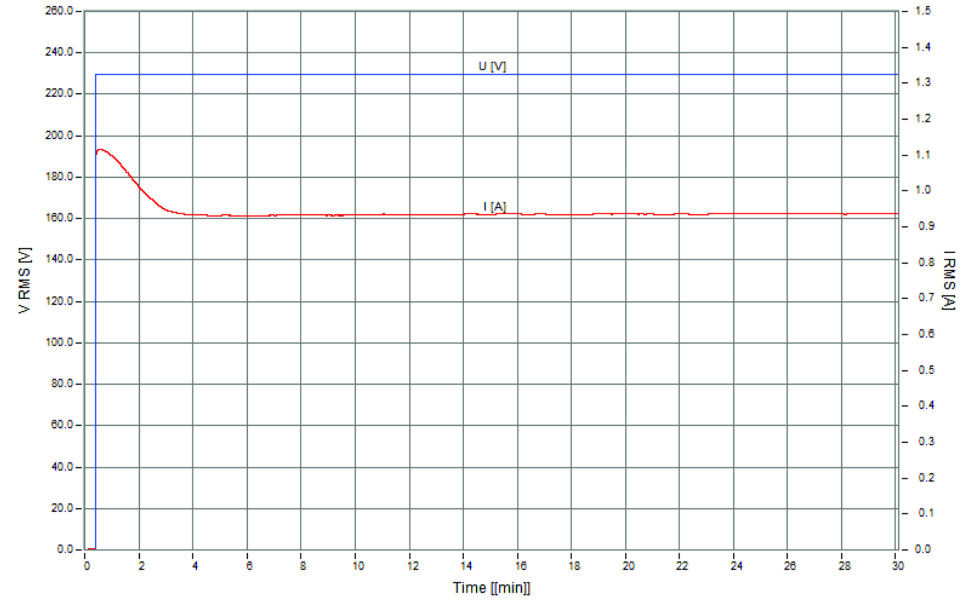


Figure 3. Root Mean Square of voltage and current - 230 V

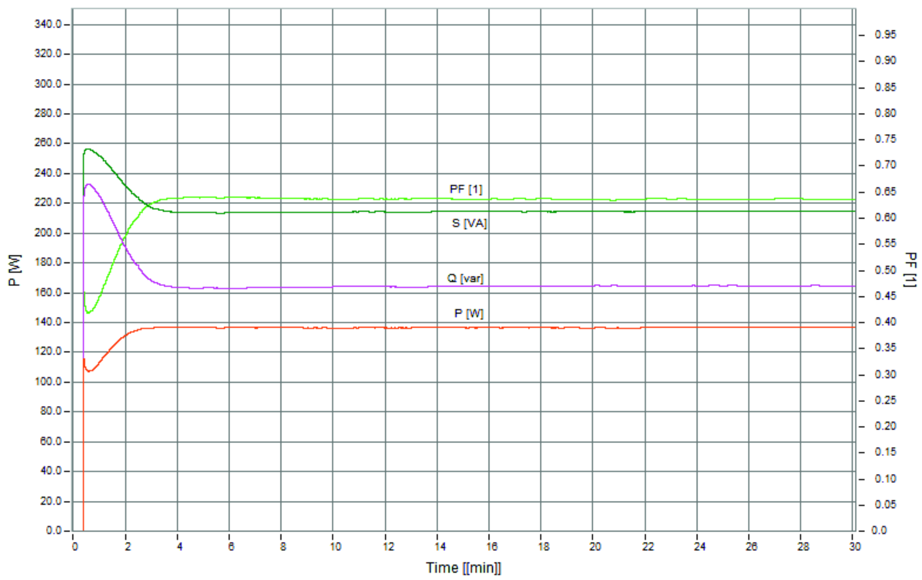


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 229.72	[V]	*****	0.00⁰
I L1 = 0.93	[A]	*****	50.39⁰

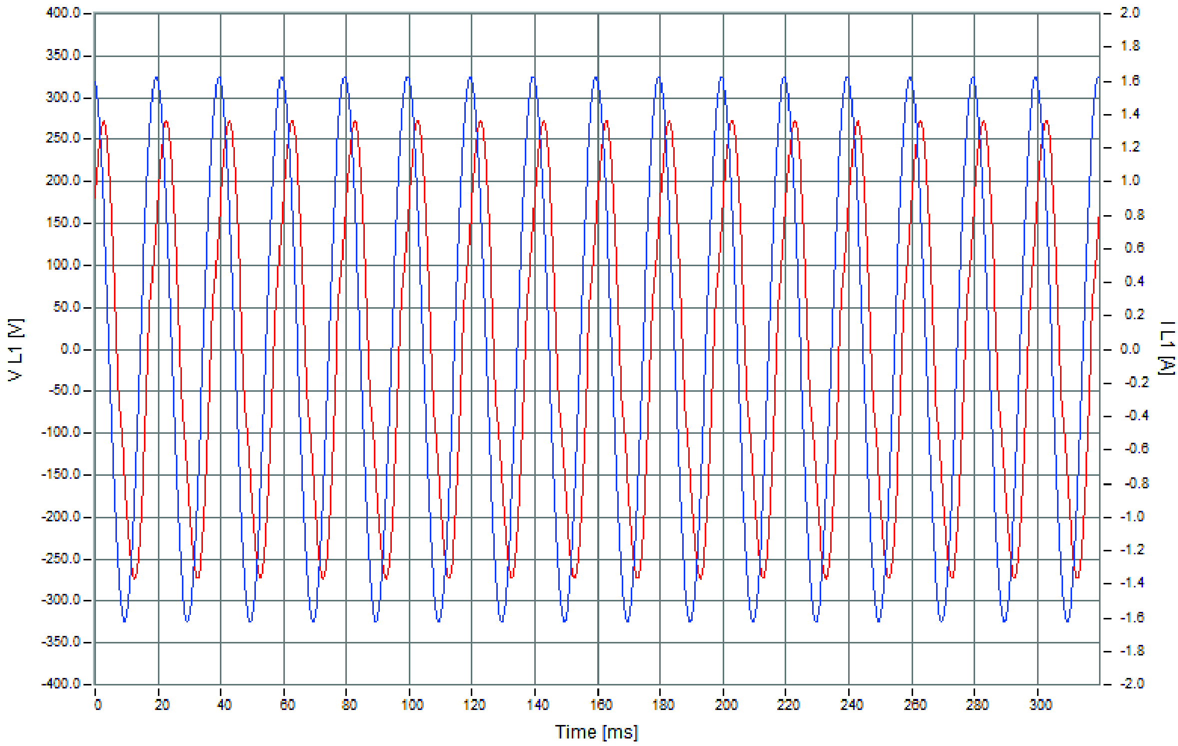


Figure 5. Current and voltage signal curve - 230 V

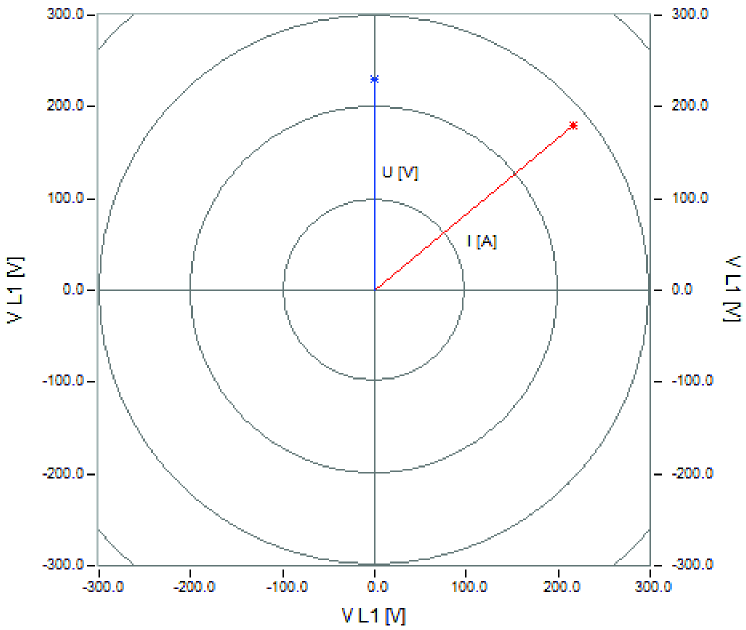


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

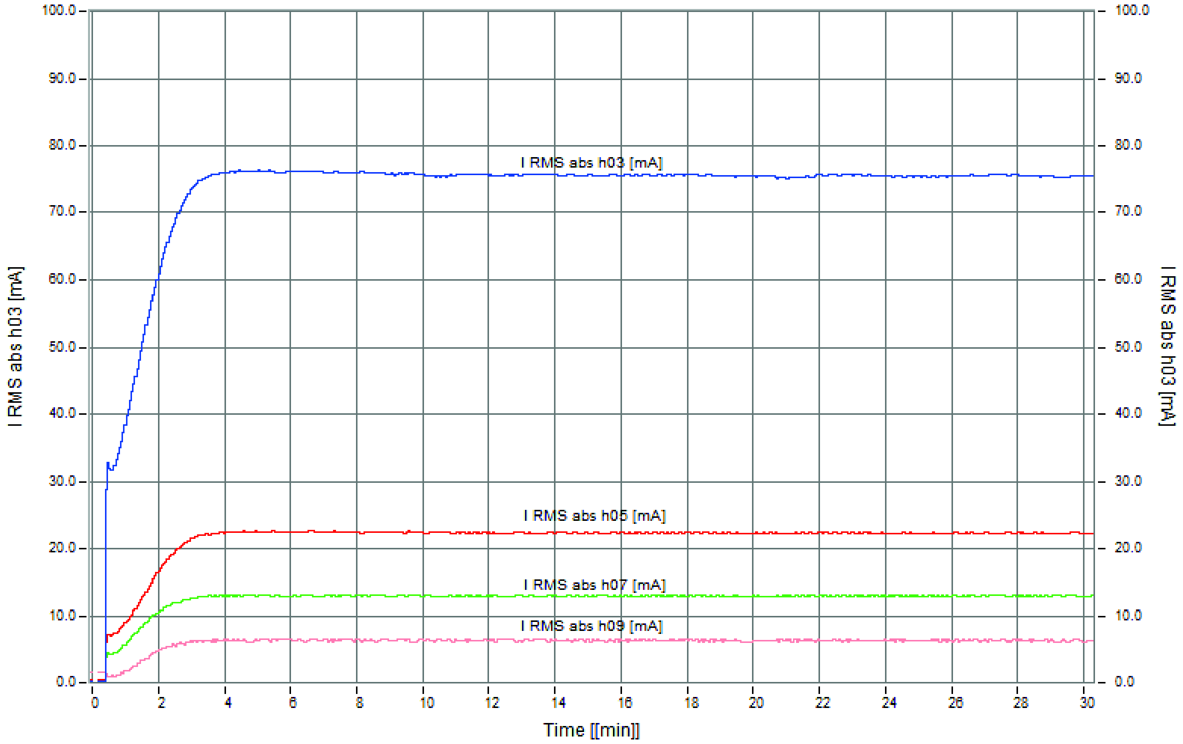


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

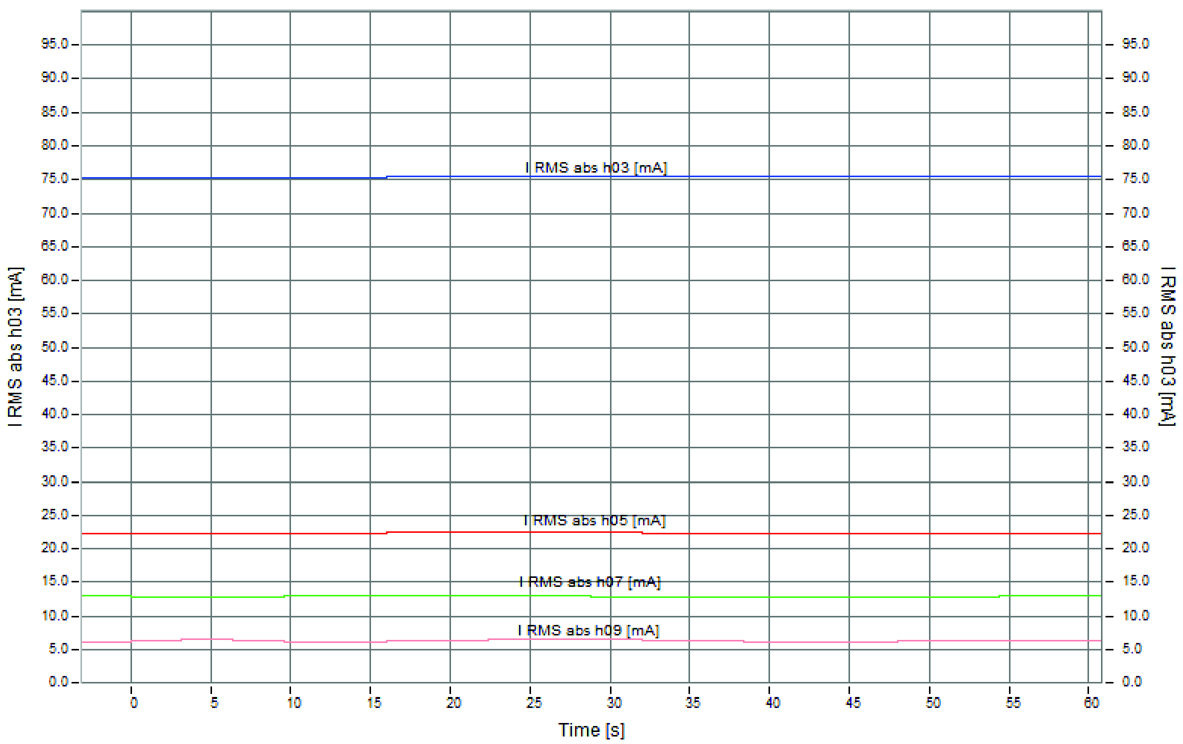


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

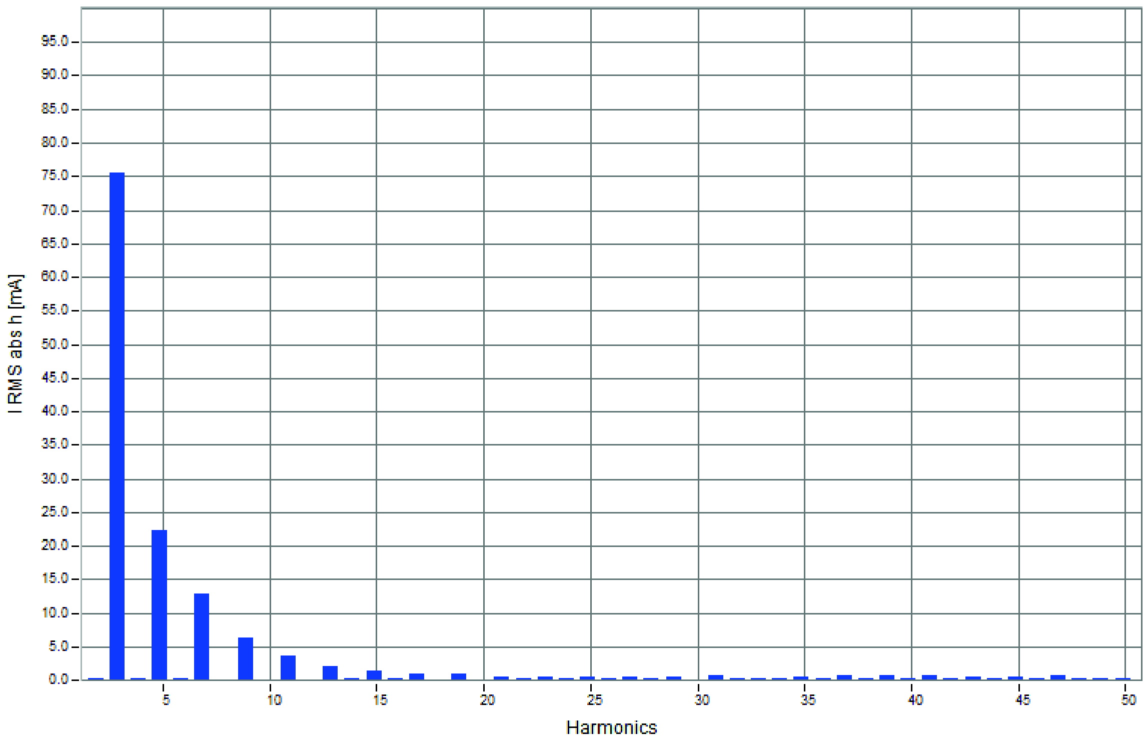


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 8.58\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 8.55\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 189.46 V
Current: I = 0.77 A
Active Power = 92.79 W
Reactive Power = 114.09 var
Apparent Power = 147.53 VA
Power Factor = 0.62

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

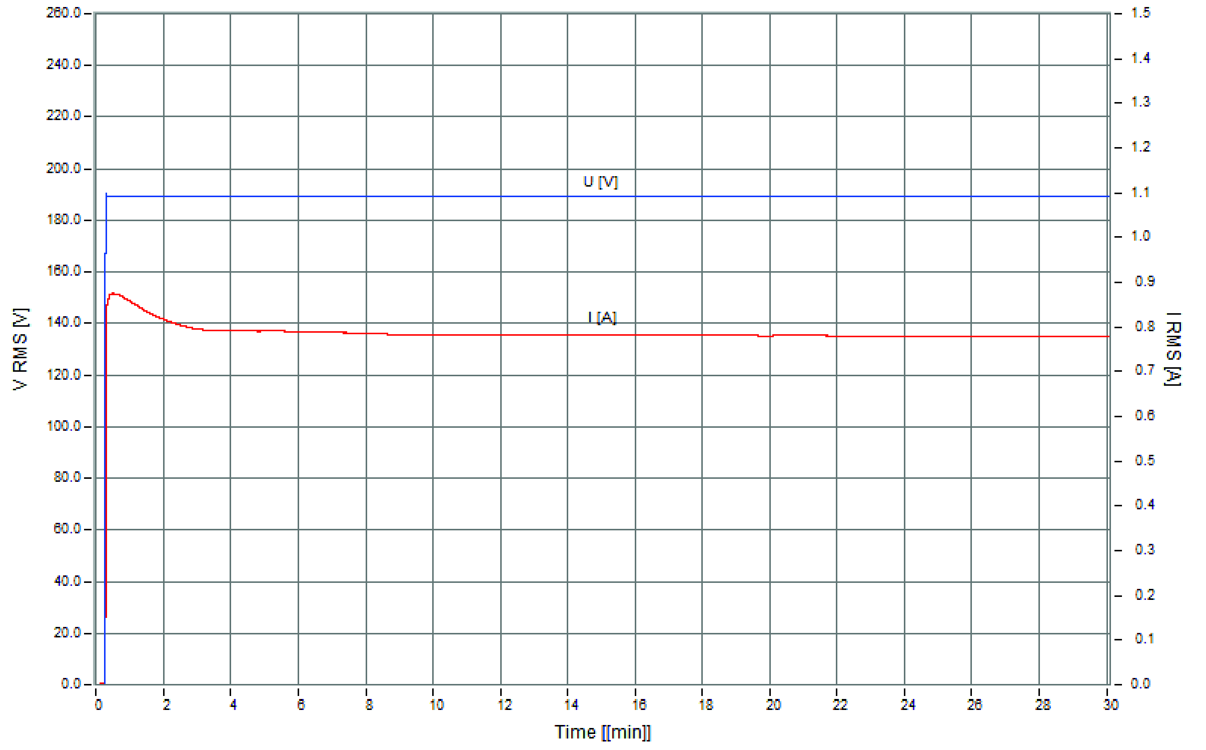


Figure 10. Root Mean Square of voltage and current - 190 V

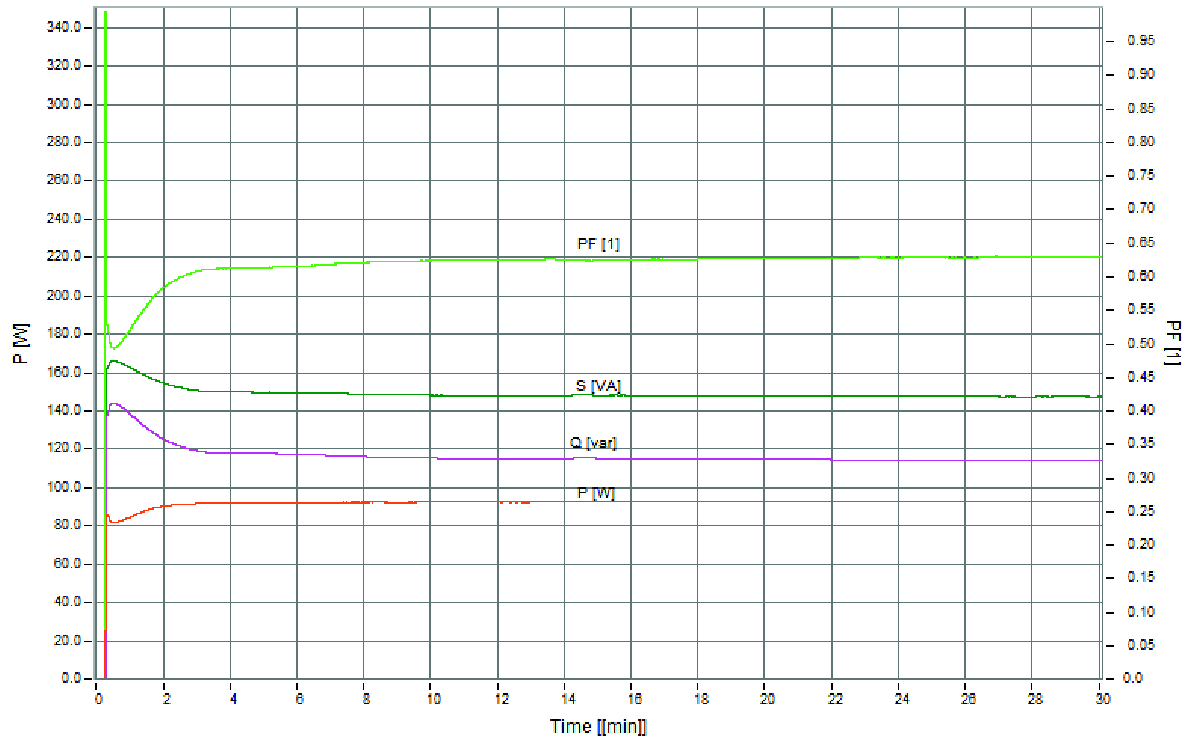


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 189.46	[V]	*****	0.00^0
I L1 = 0.78	[A]	*****	51.47^0

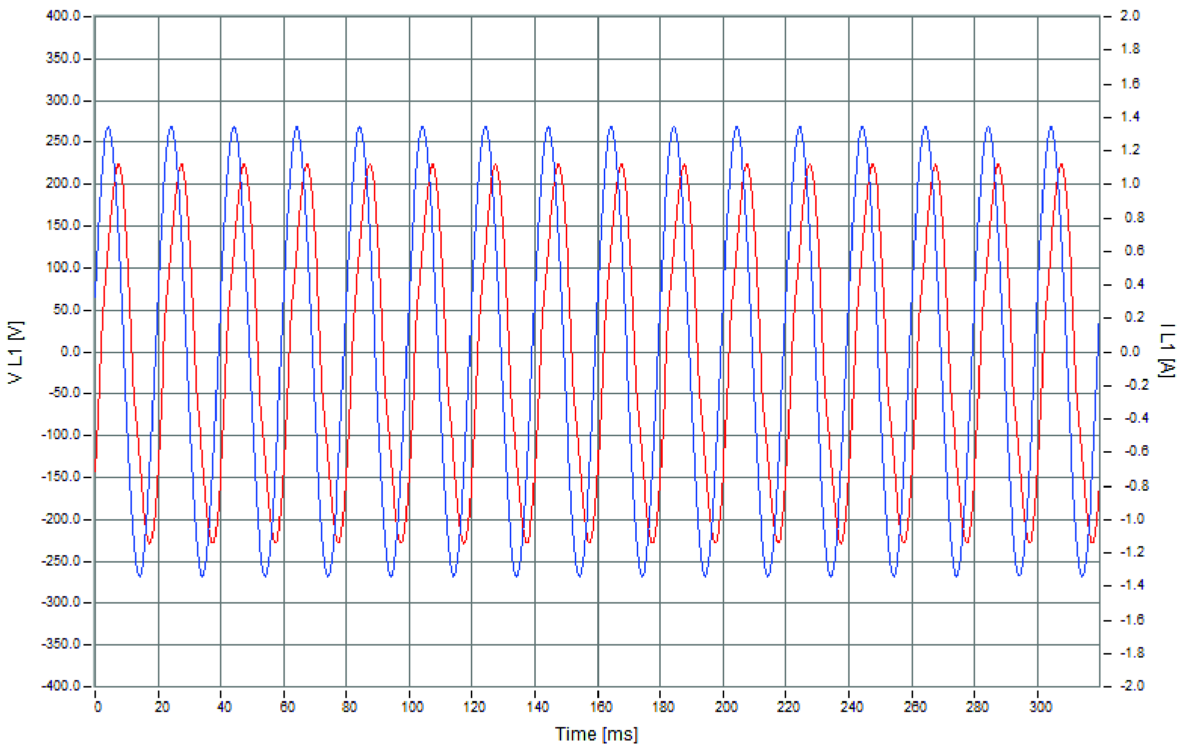


Figure 12. Current and voltage signal curve - 190 V

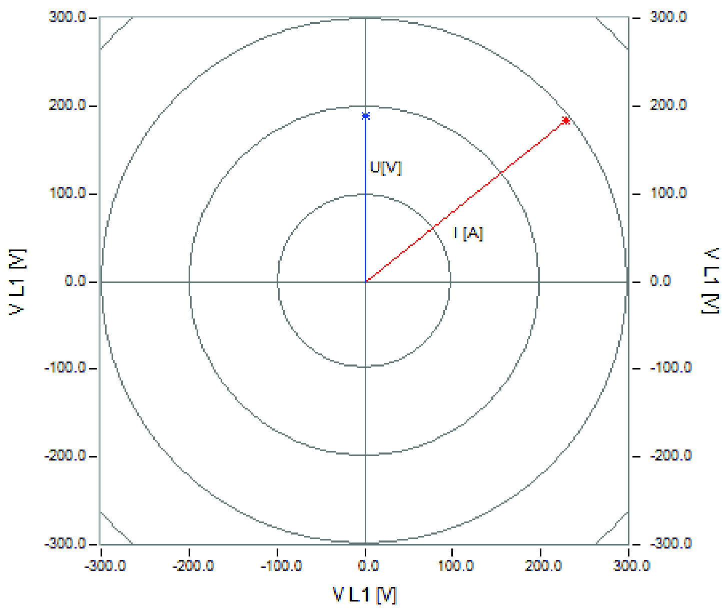


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

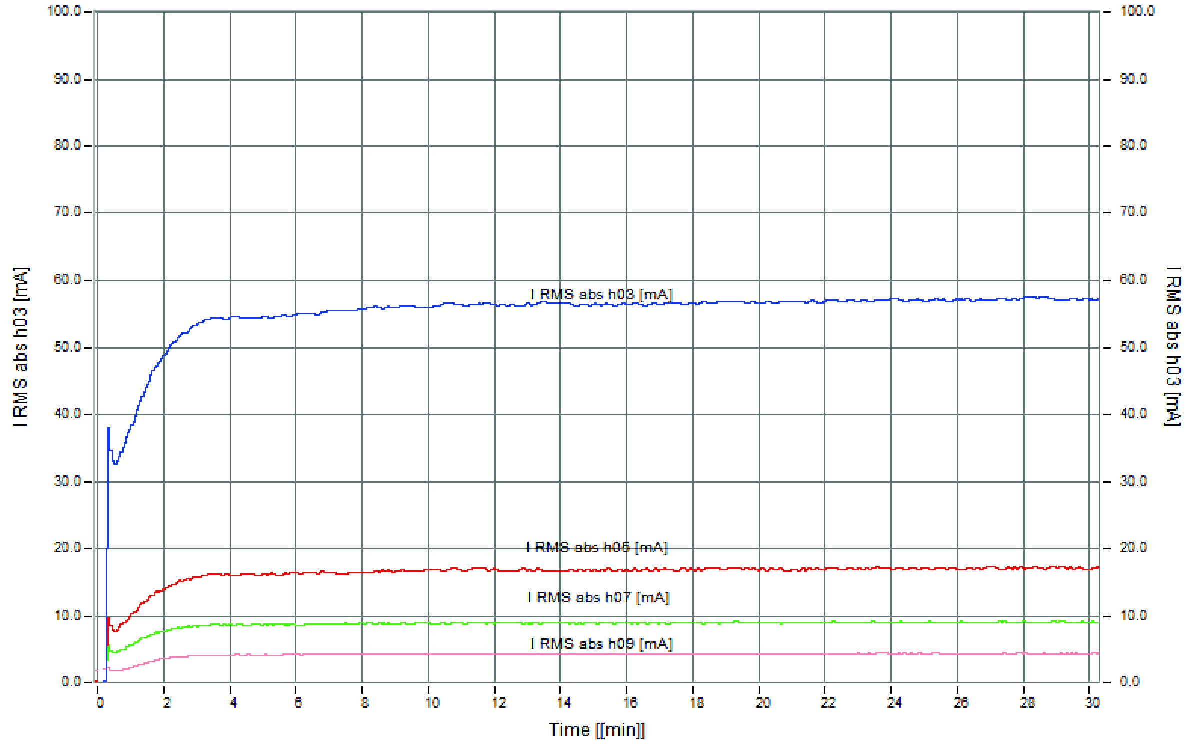


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

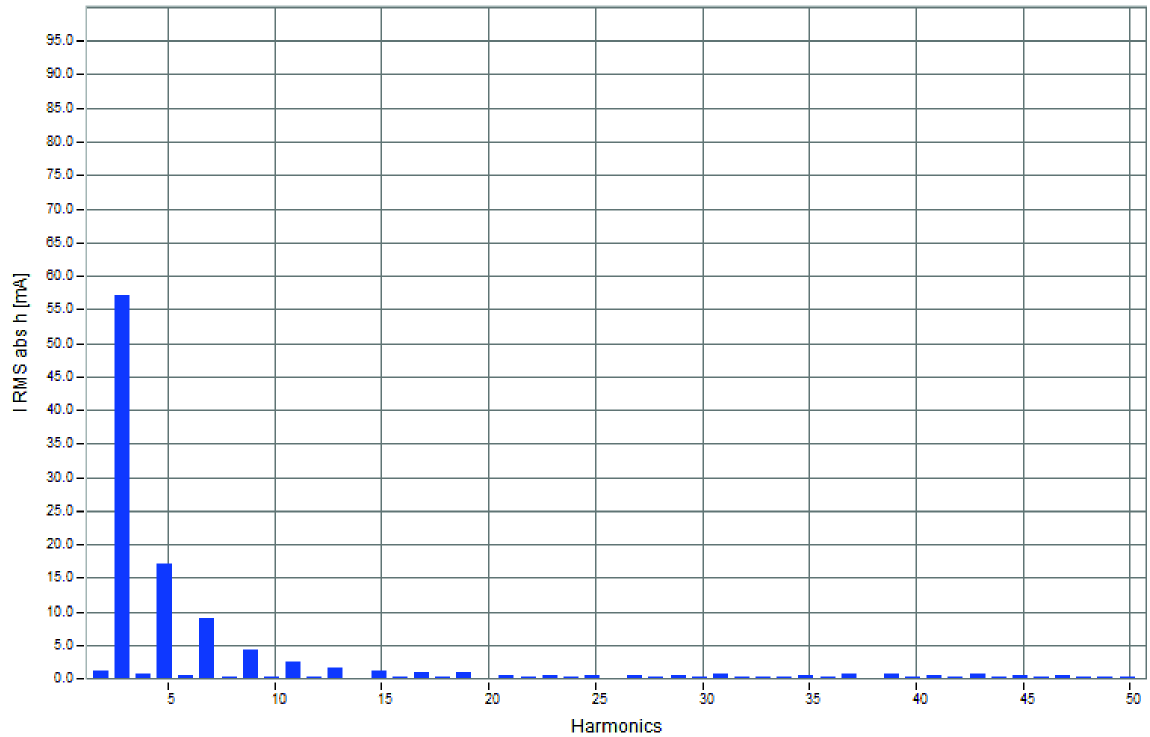


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 7.81\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 7.78\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 199.56 V
Current: I = 0.82 A
Active Power = 102.04 W
Reactive Power = 128.59 var
Apparent Power = 164.67 VA
Power Factor = 0.61

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

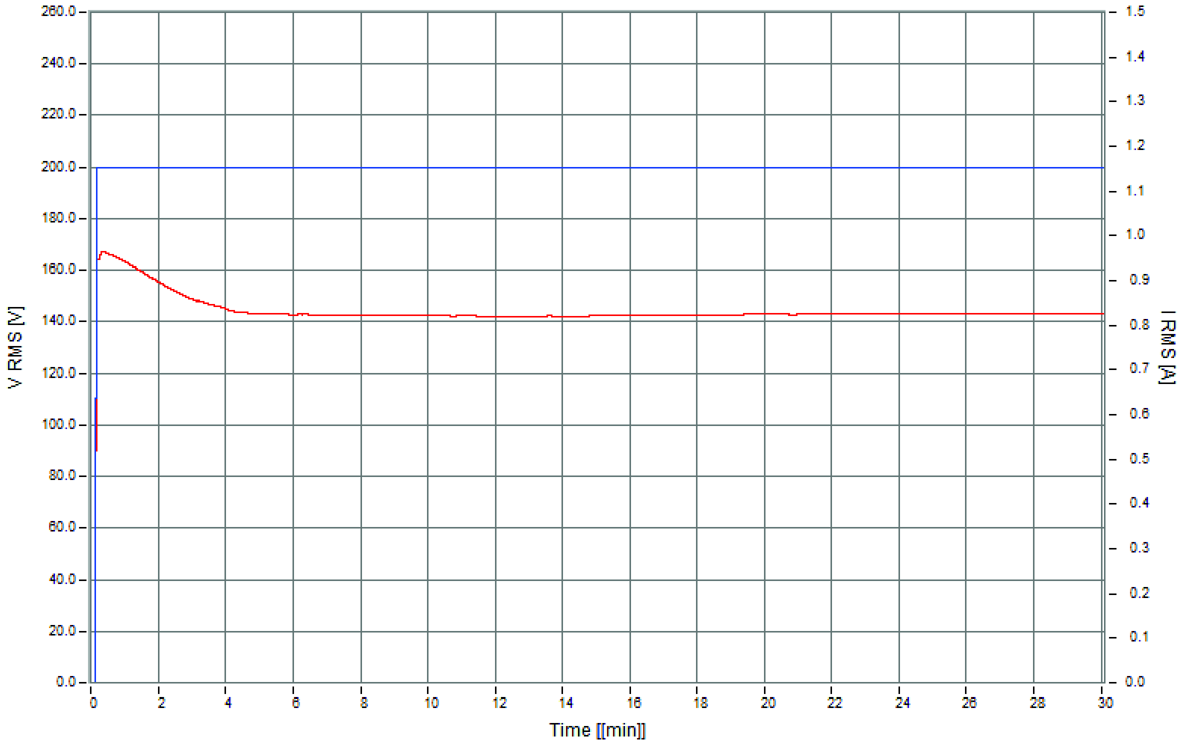


Figure 16. Root Mean Square of voltage and current - 200 V

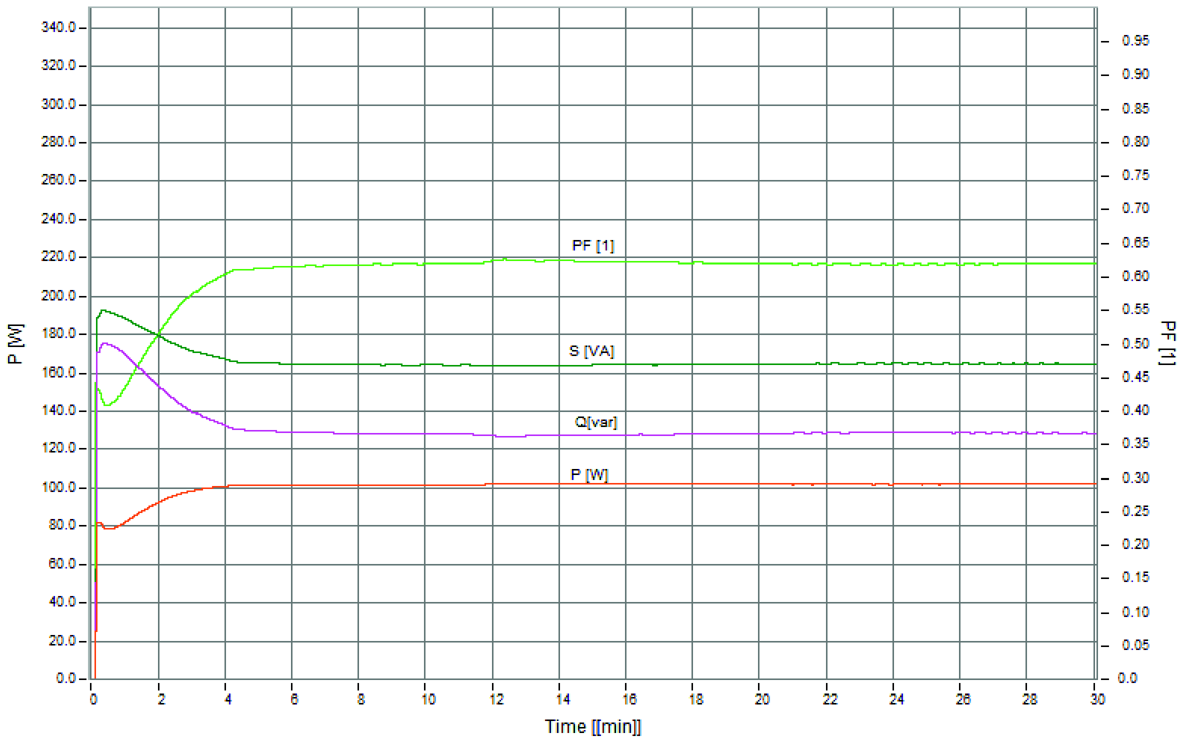


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 199.61	[V]	*****	0.00^0
I L1 = 0.82	[A]	*****	59.51^0

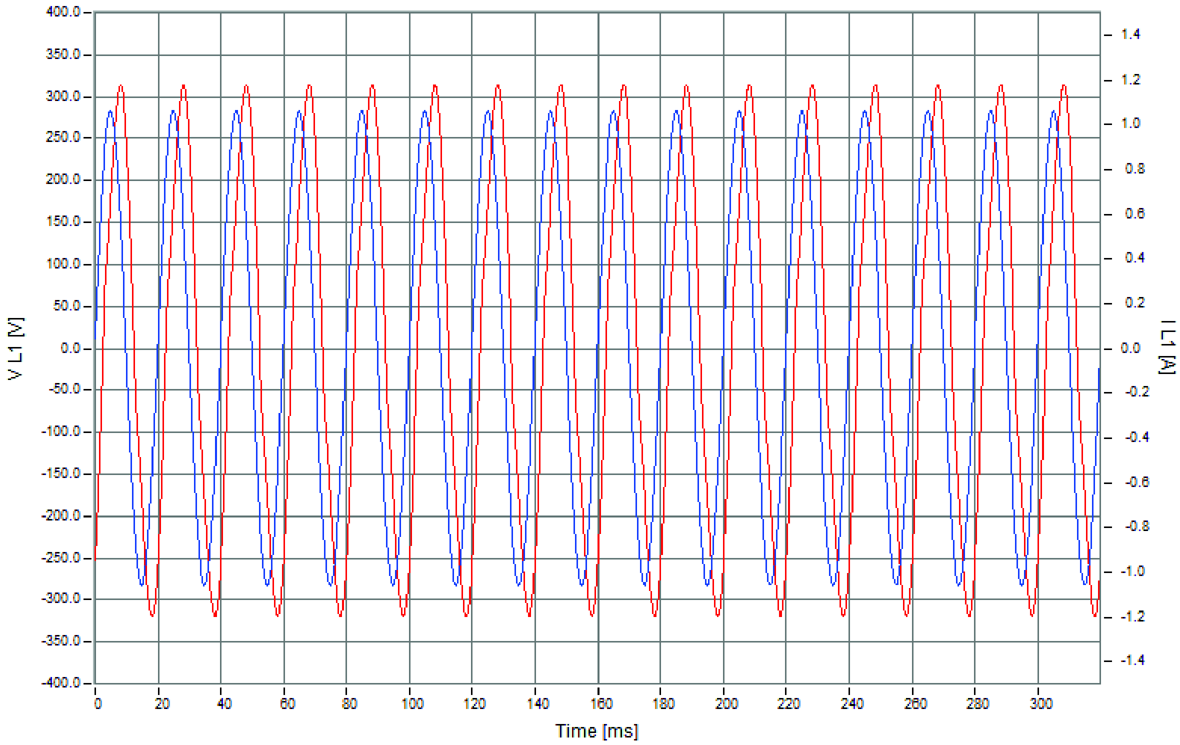


Figure 18. Current and voltage signal curve - 200 V

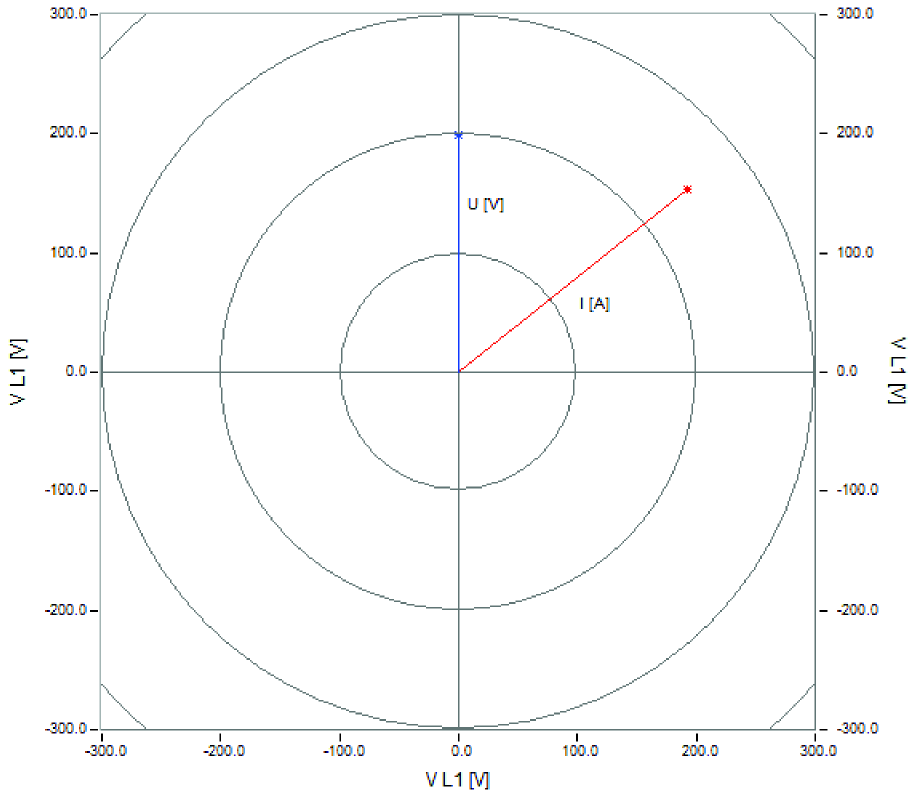


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

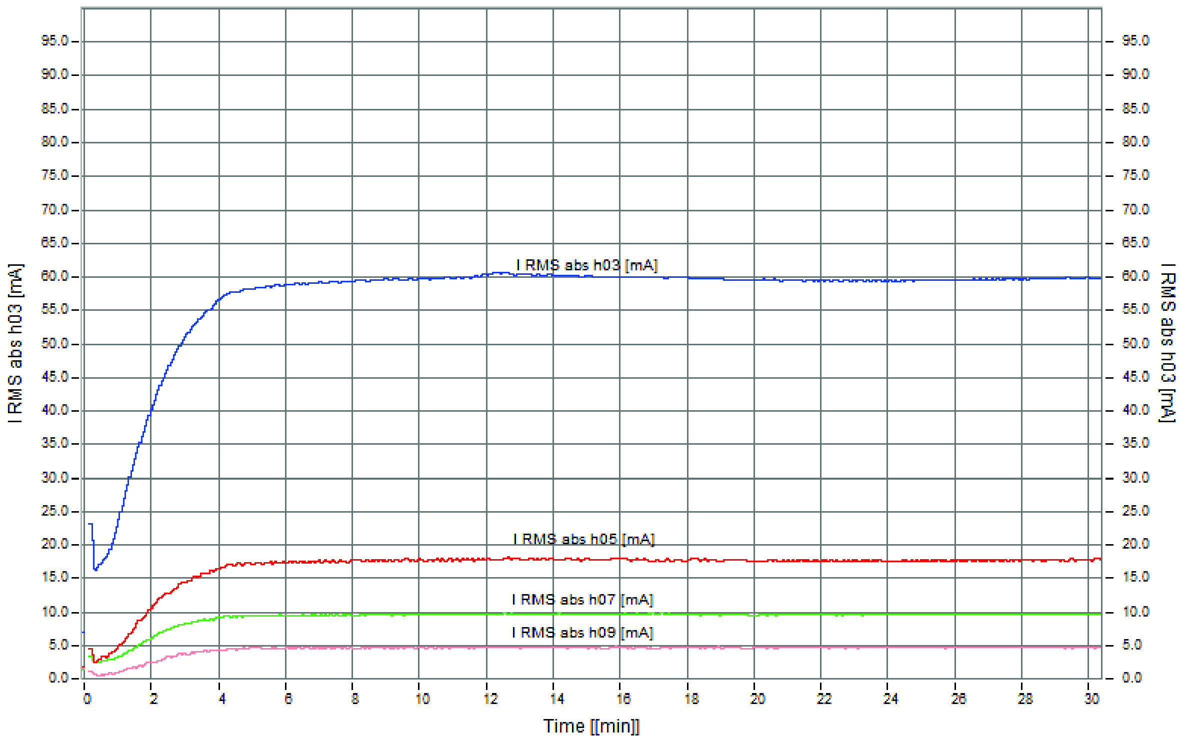


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

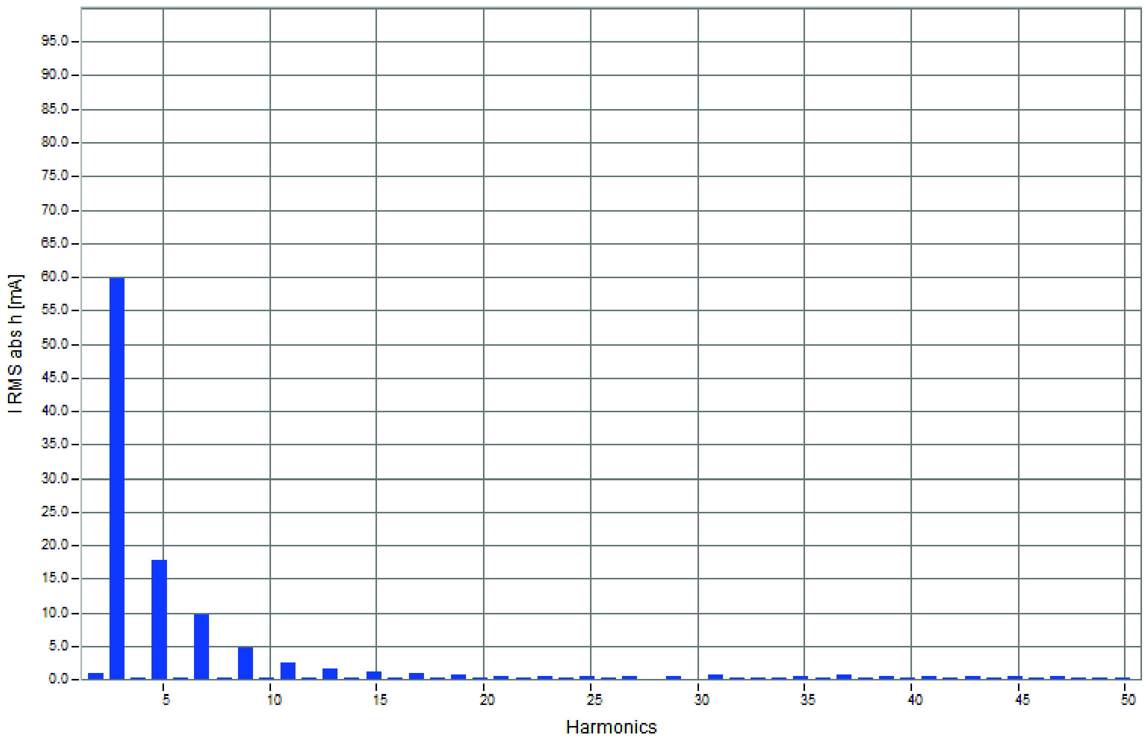


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 7.71\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 7.69\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:

Voltage: U = 209.46 V

Current: I = 0.86A

Active Power = 113.13 W

Reactive Power = 139.46 var

Apparent Power = 180.16 VA

Power Factor = 0.62

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

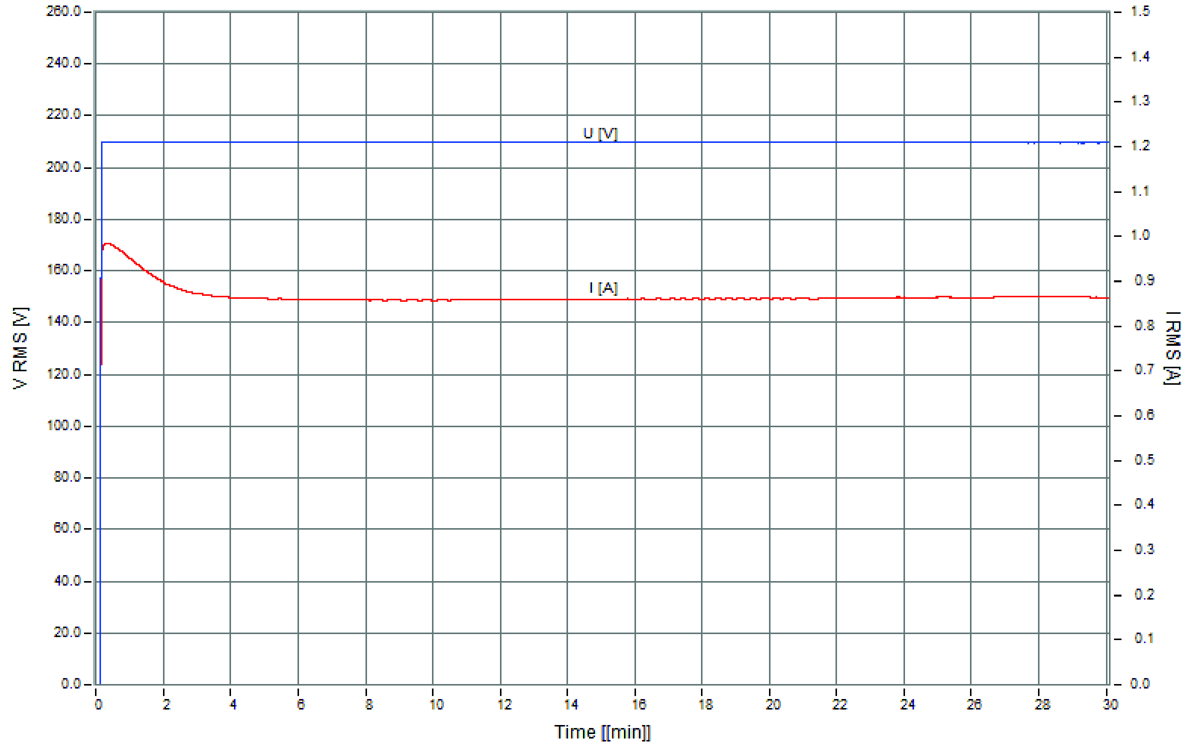


Figure 22. Root Mean Square of voltage and current - 210 V

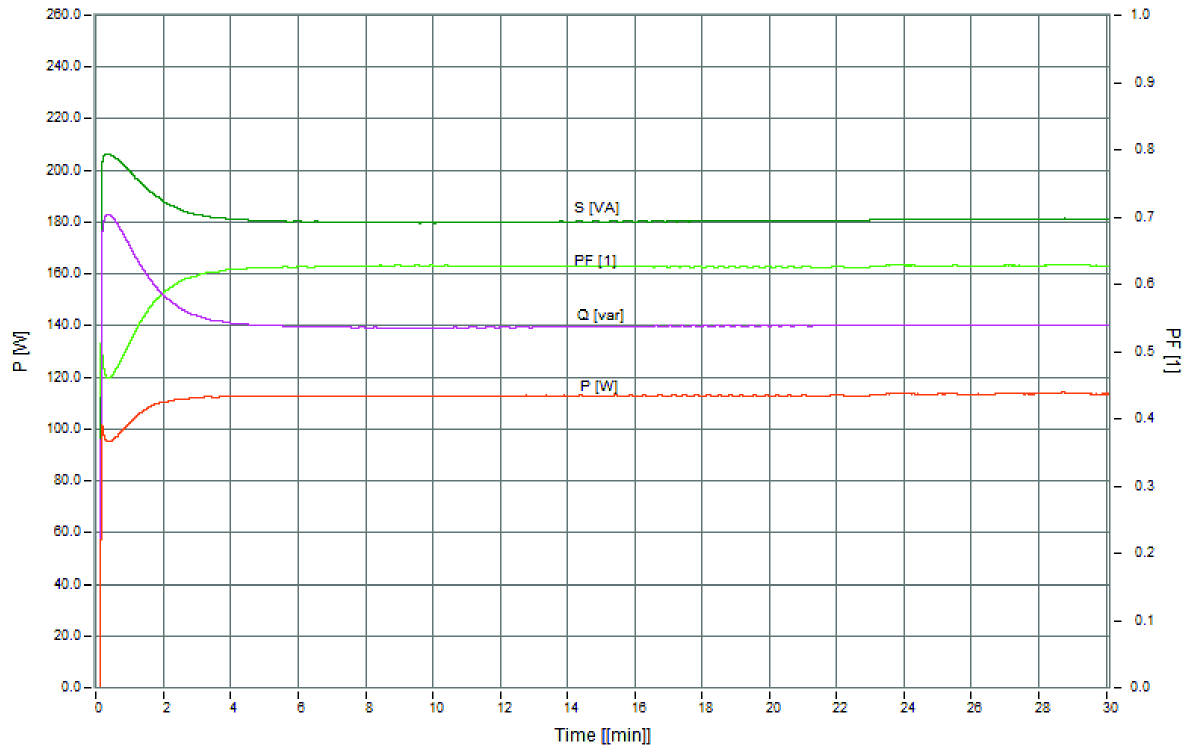


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 209.49	[V]	*****	0.00⁰
I L1 = 0.85	[A]	*****	51.09⁰

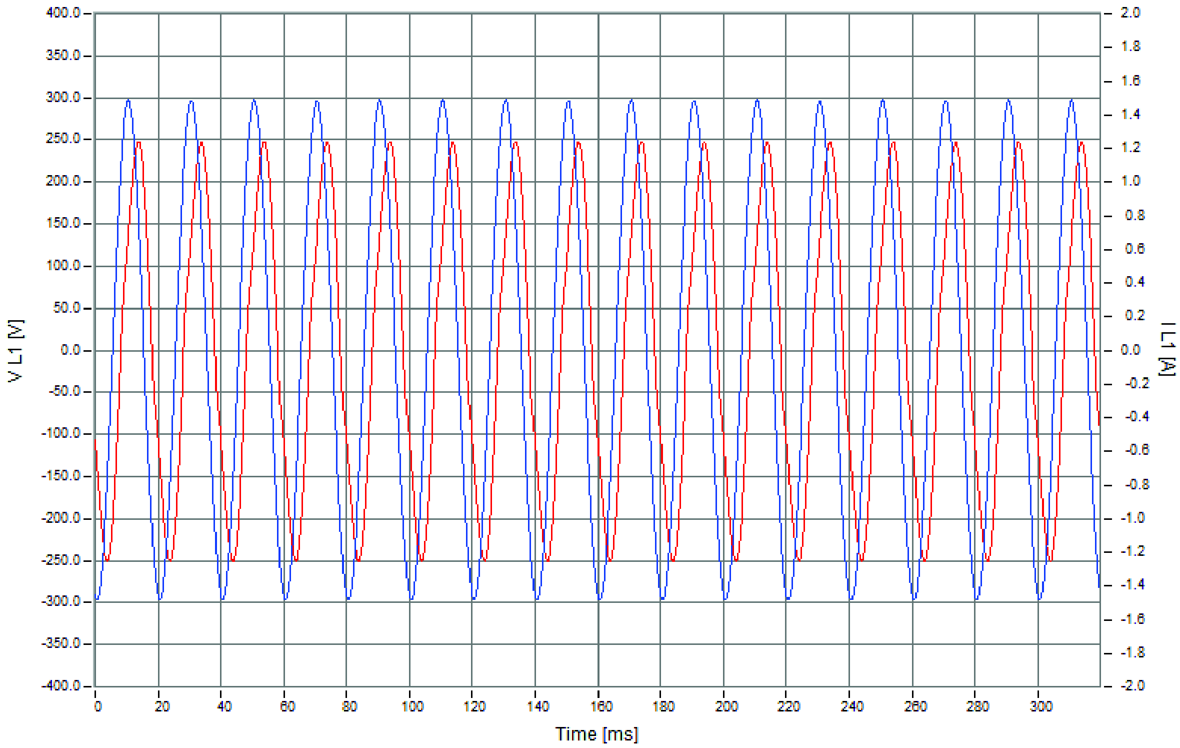


Figure 24. Current and voltage signal curve - 210 V

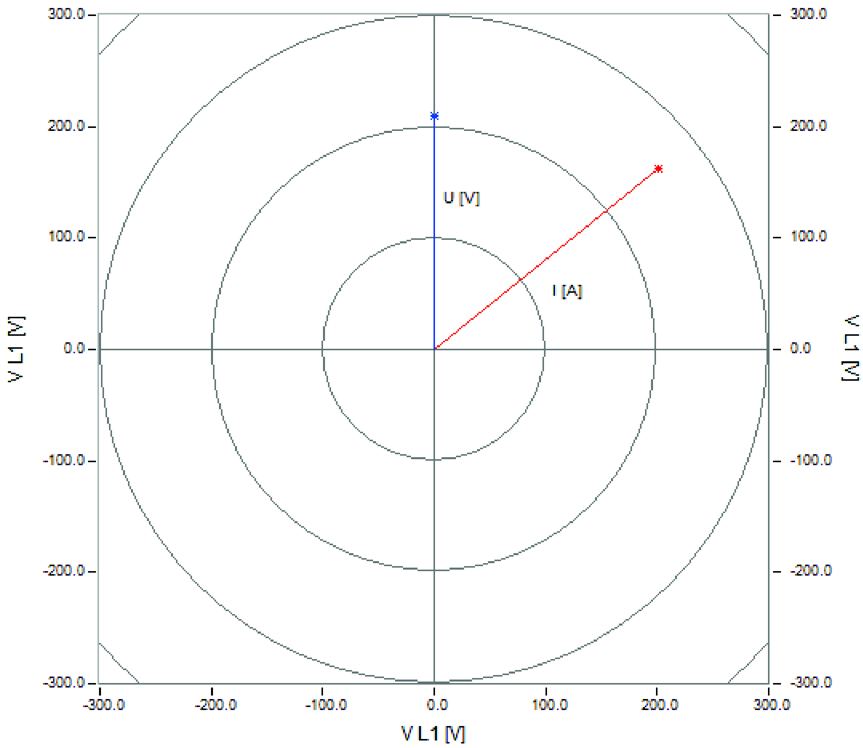


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

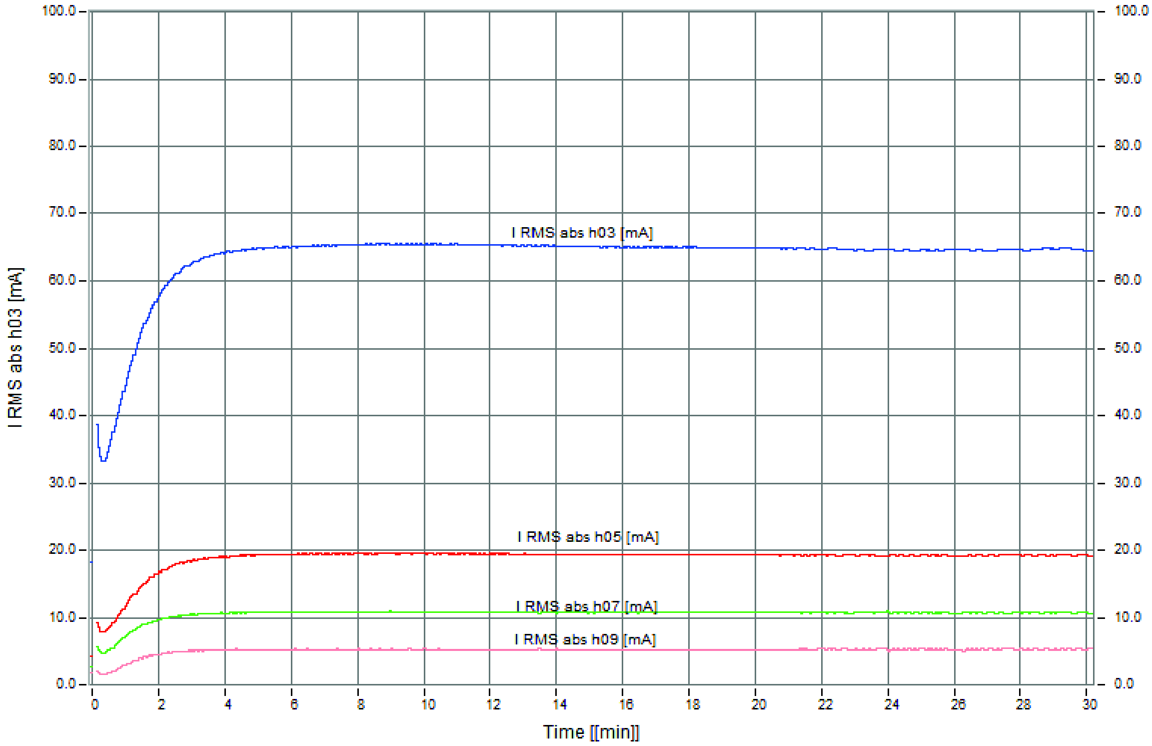


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

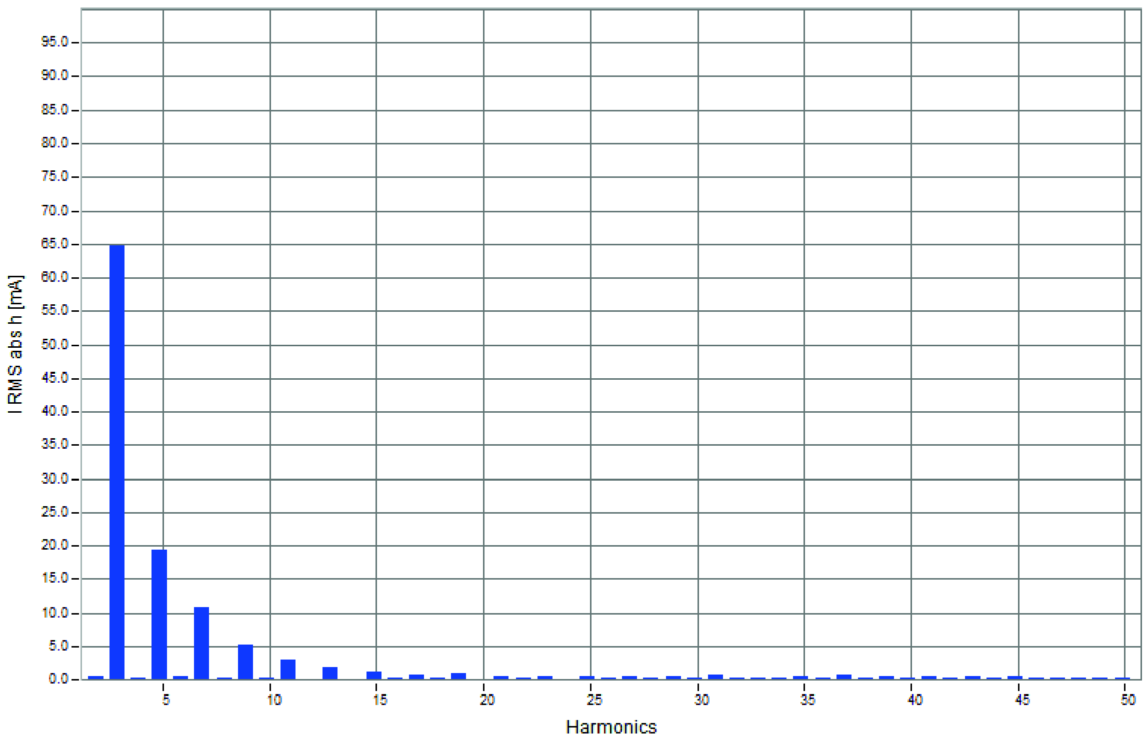


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 7.97\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 7.94\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 219.39 V

Current: I = 0.89 A

Active Power = 125.05 W

Reactive Power = 150.55 var

Apparent Power = 196.43 VA

Power Factor = 0.63

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

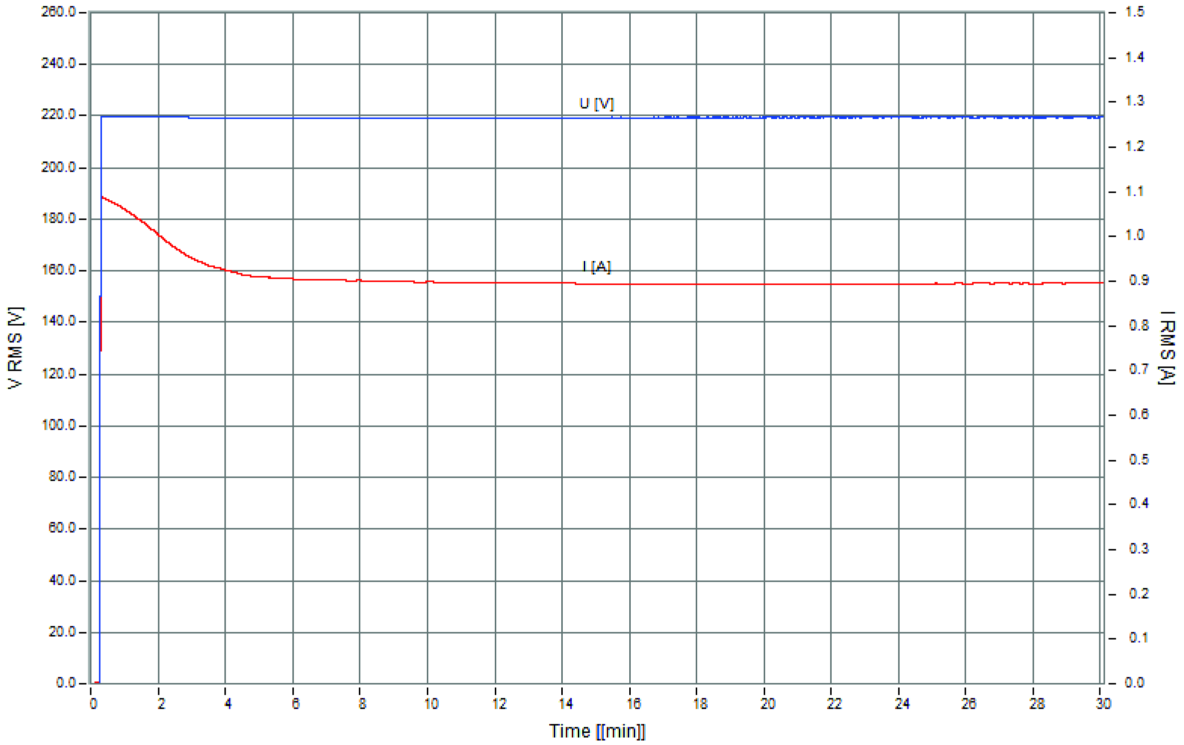


Figure 28. Root Mean Square of voltage and current - 220 V

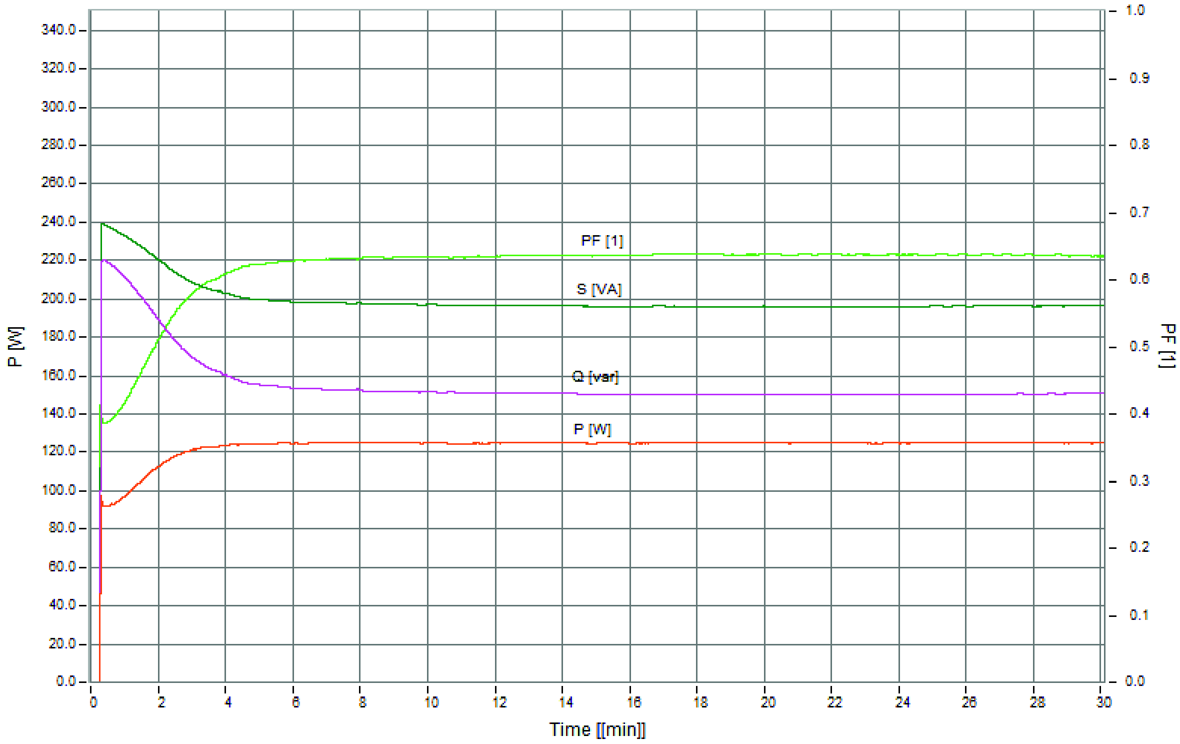


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 219.39	[V]	*****	0.00^0
I L1 = 0.89	[A]	*****	50.34

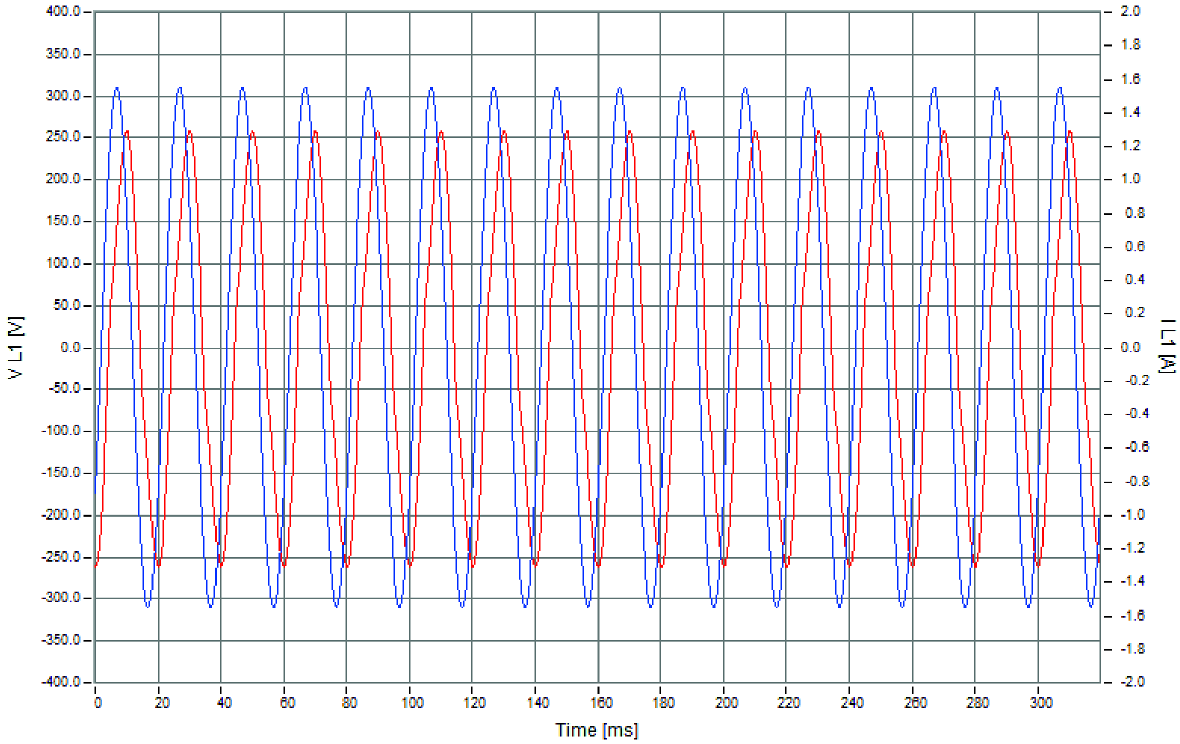


Figure 30. Current and voltage signal curve - 220 V

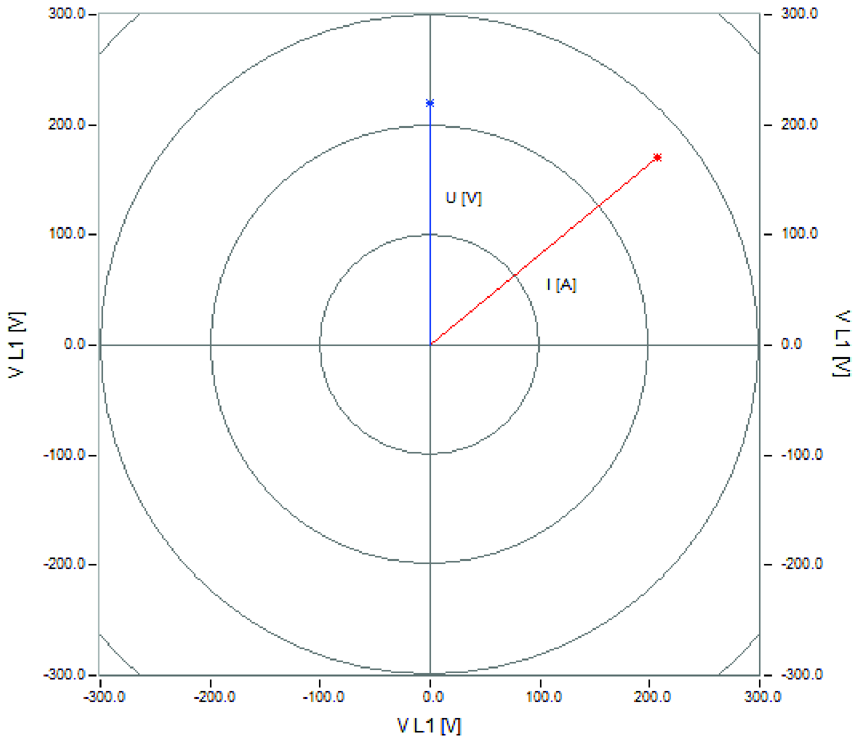


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

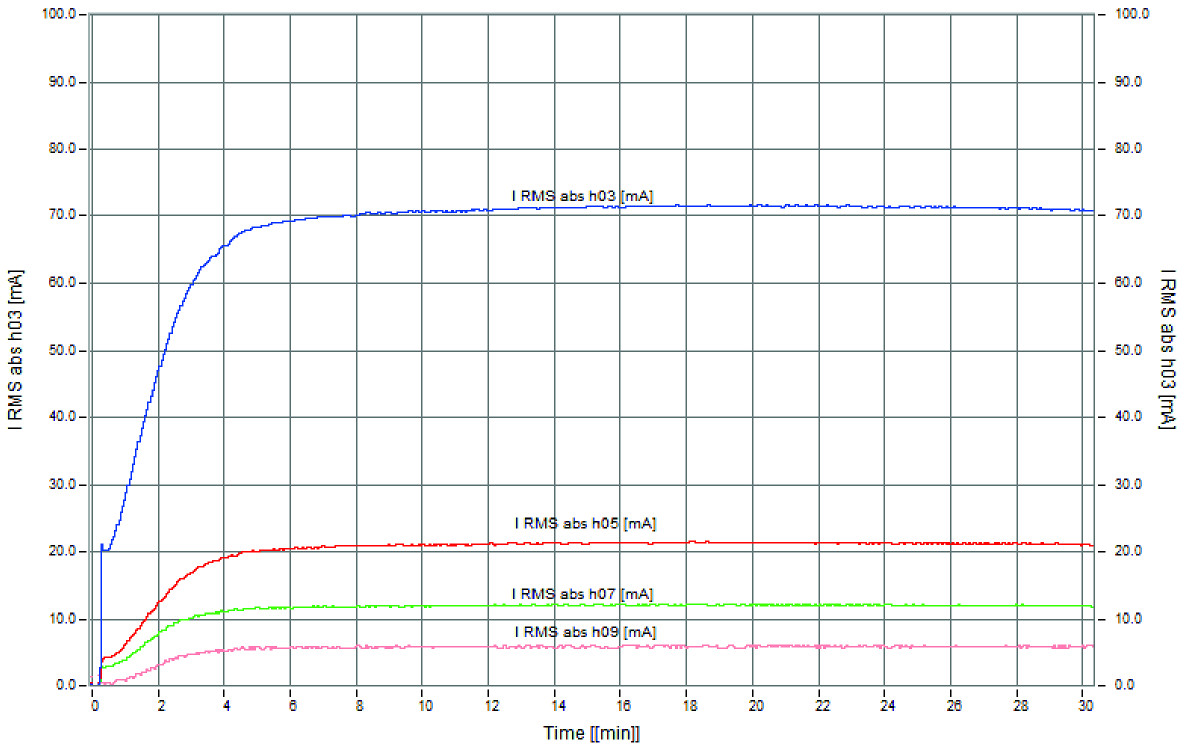


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

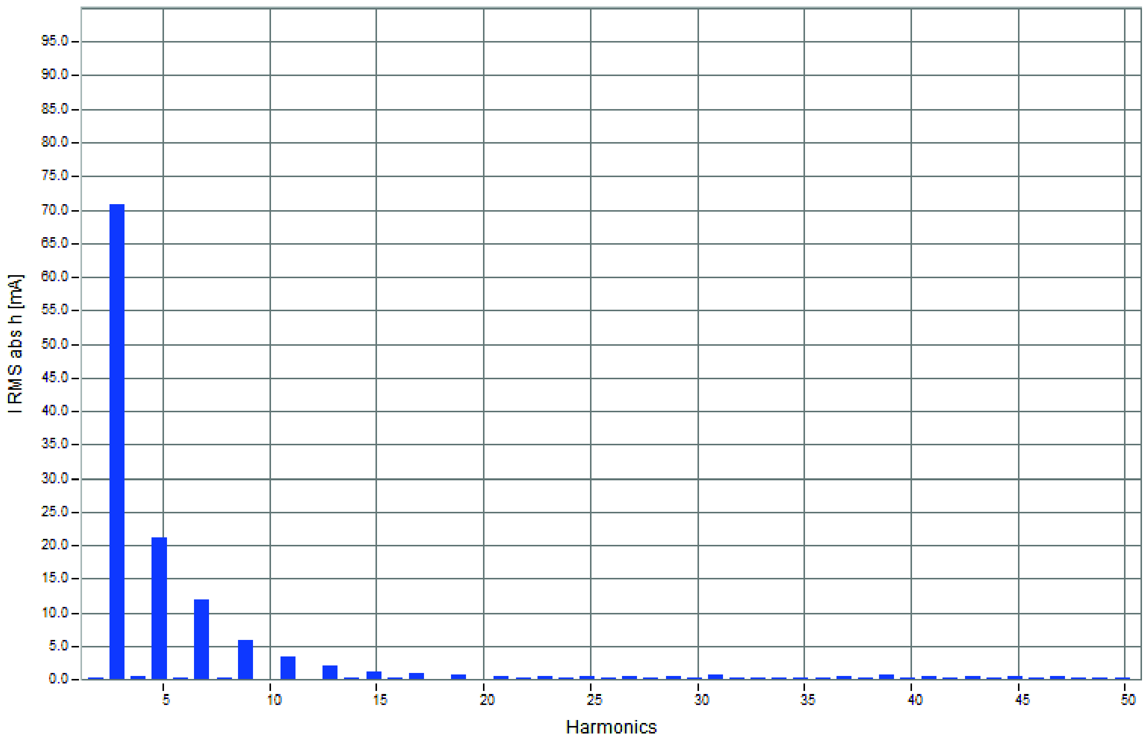


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 8.42\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 8.39\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:

Voltage: U = 239.33 V
Current: I = 0.96 A
Active Power = 148.64 W
Reactive Power = 176.16 var
Apparent Power = 231.44 VA
Power Factor = 0.64

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

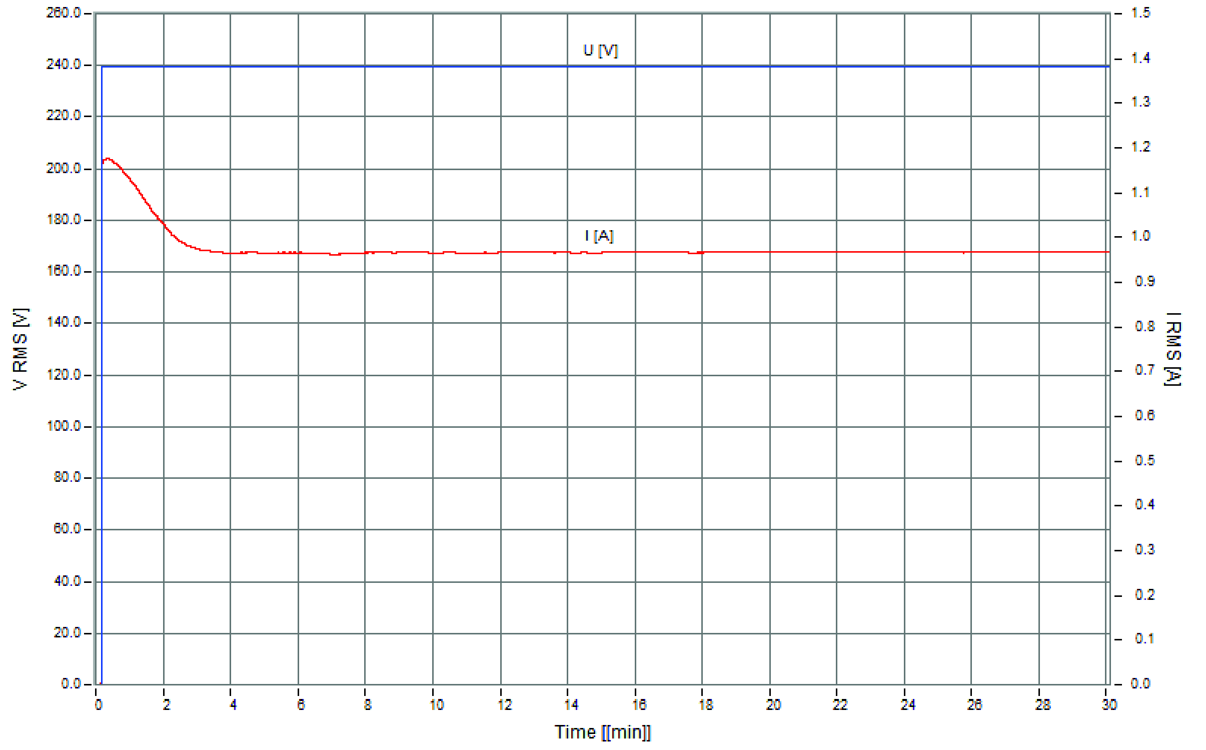


Figure 34. Root Mean Square of voltage and current - 240 V

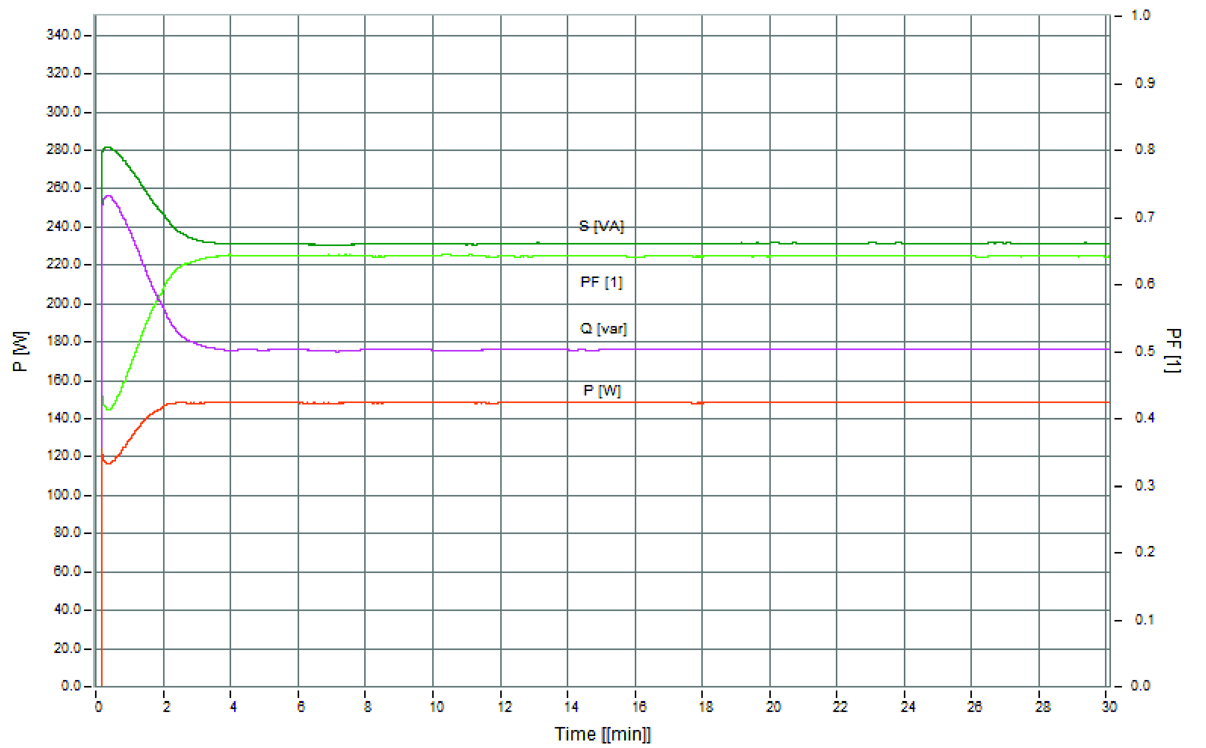


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 239.34	[V]	*****	0.00^0
I L1 = 0.96	[A]	*****	49.71^0

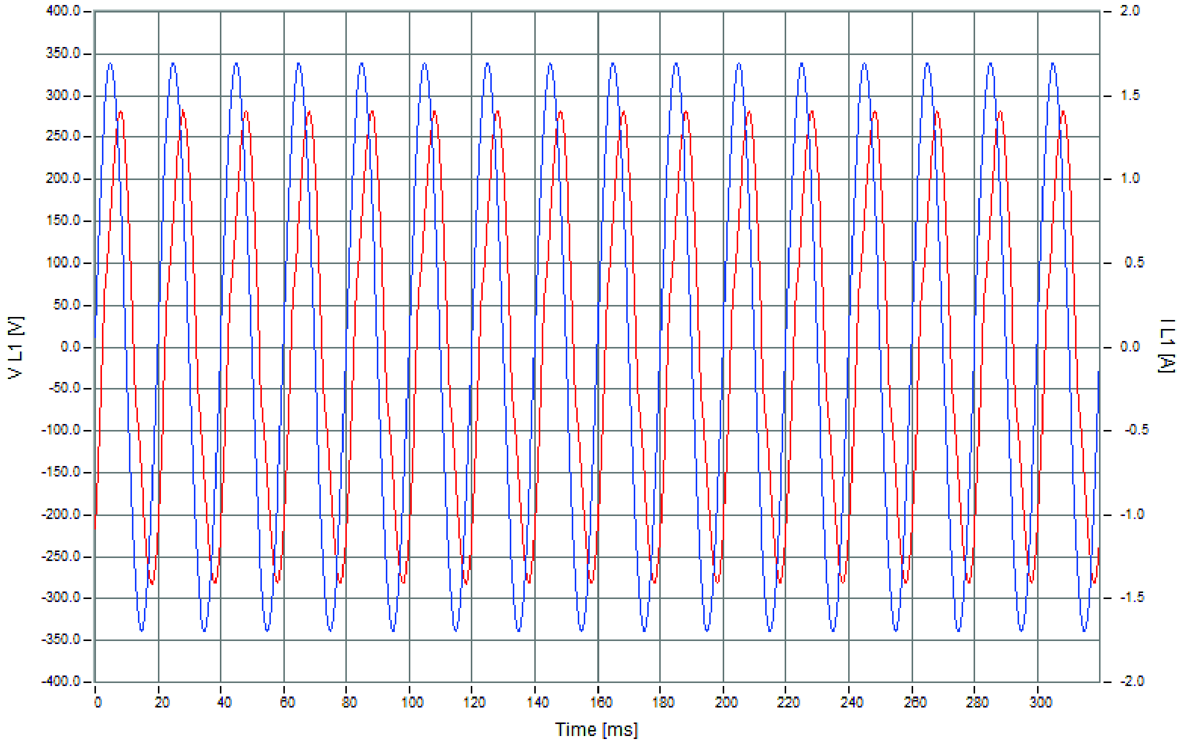


Figure 36. Current and voltage signal curve - 240 V

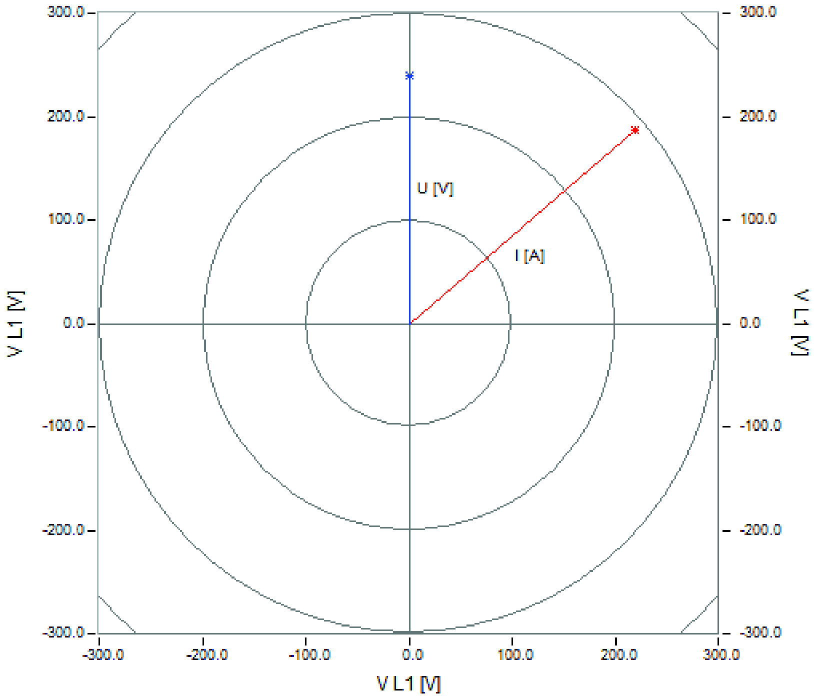


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

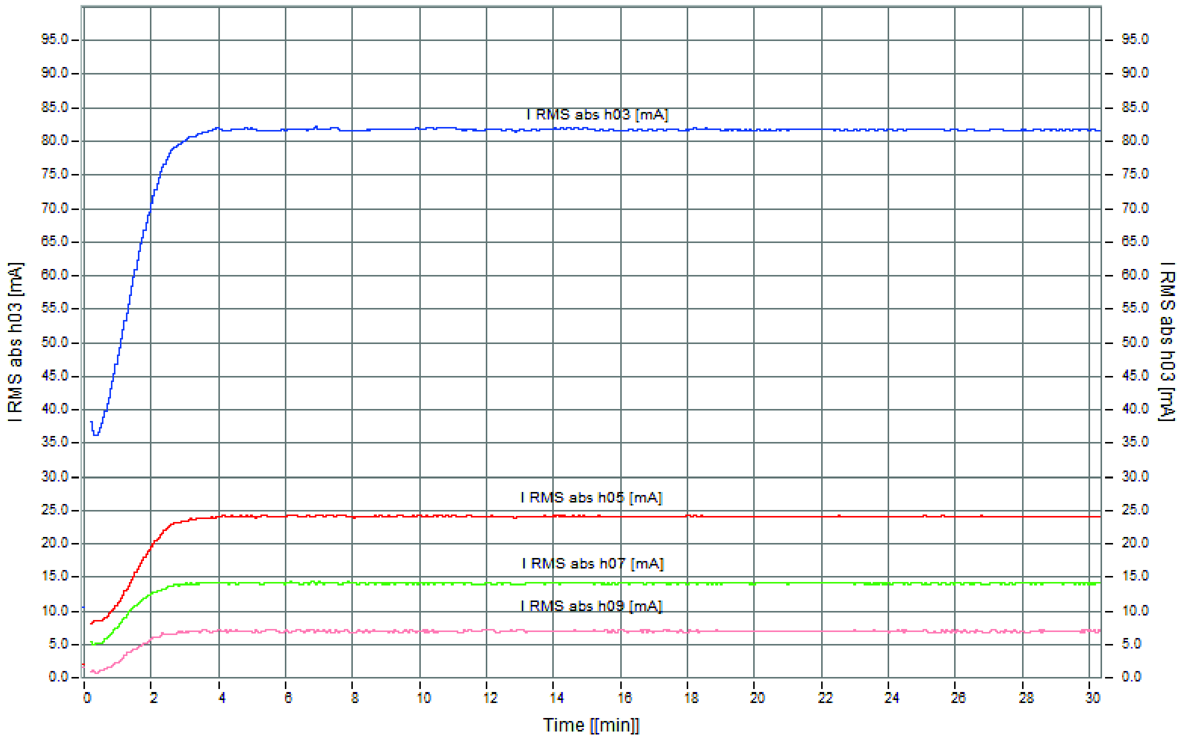


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

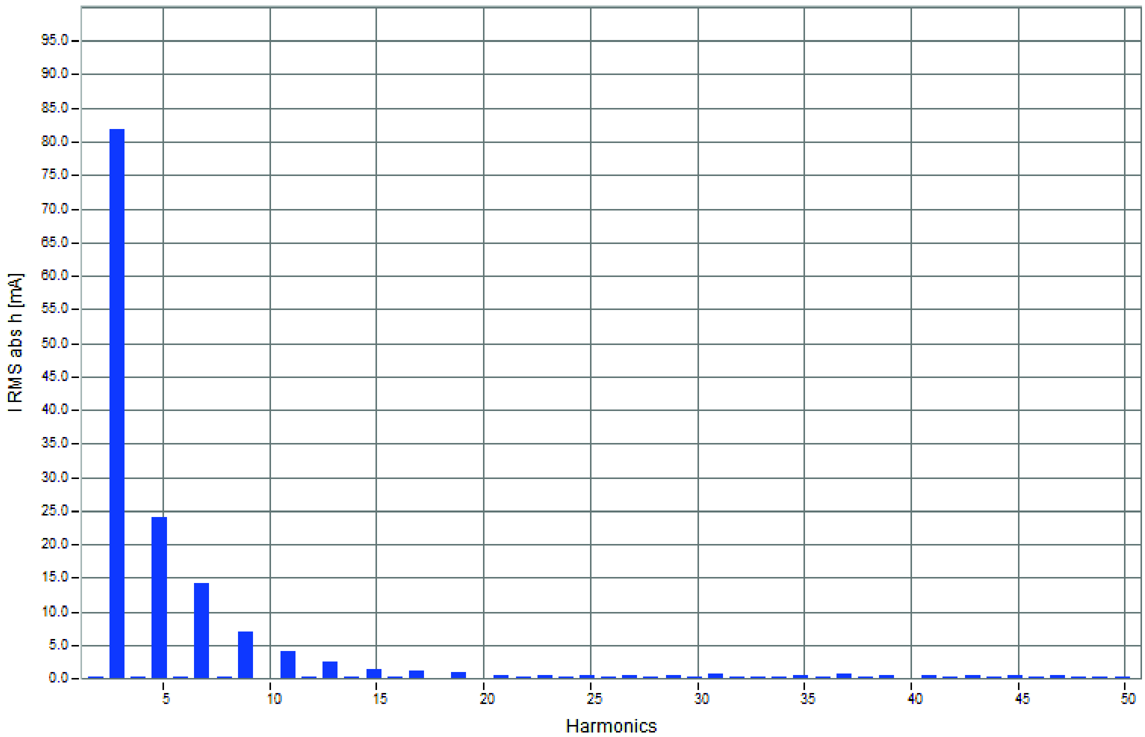


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.0\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 8.97\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 249.30 V
Current: I = 0.99 A
Active Power = 160.85 W
Reactive Power = 187.60 var
Apparent Power = 248.23 VA
Power Factor = 0.64

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

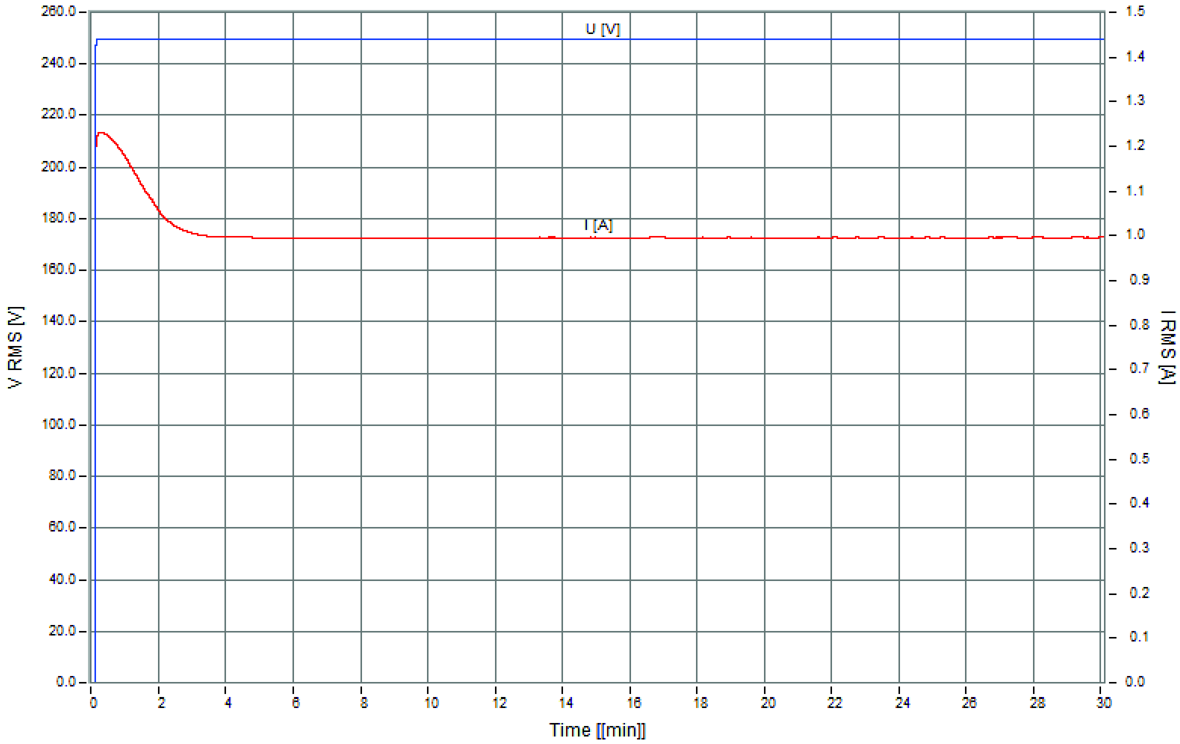


Figure 40. Root Mean Square of voltage and current - 250 V

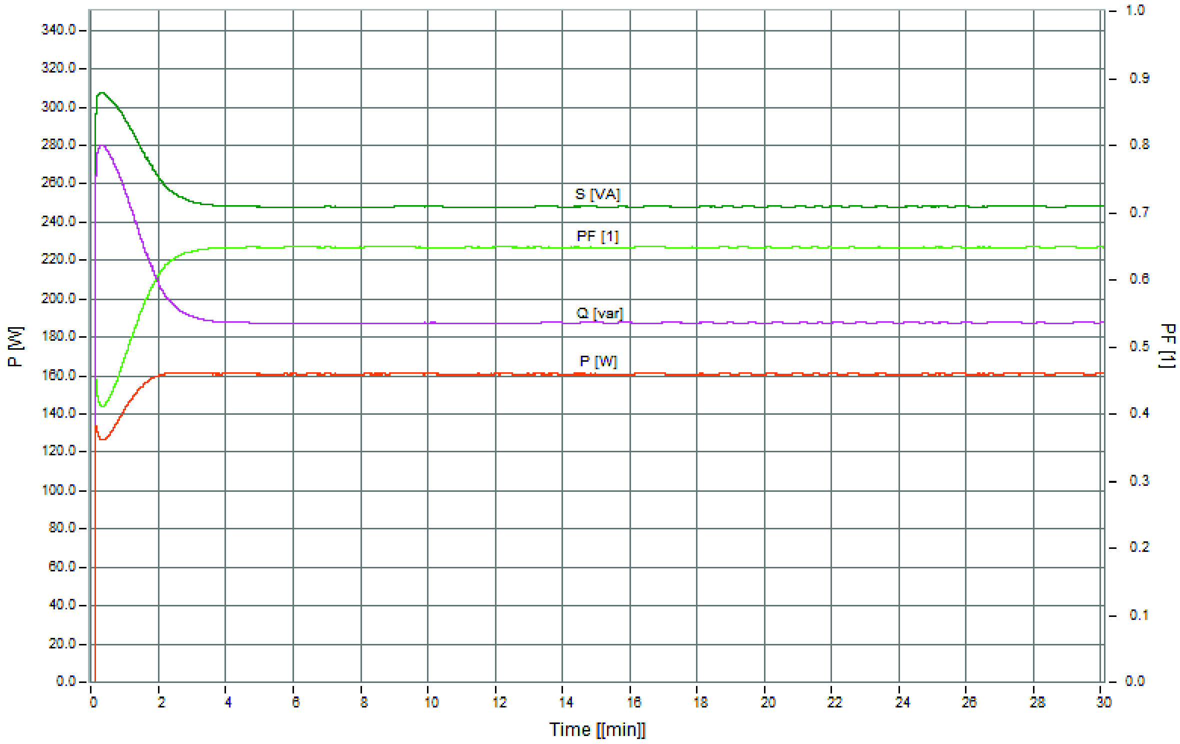


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 249.56	[V]	*****	$0{,}00^0$
I L1 = 1.11	[A]	*****	57.37^0

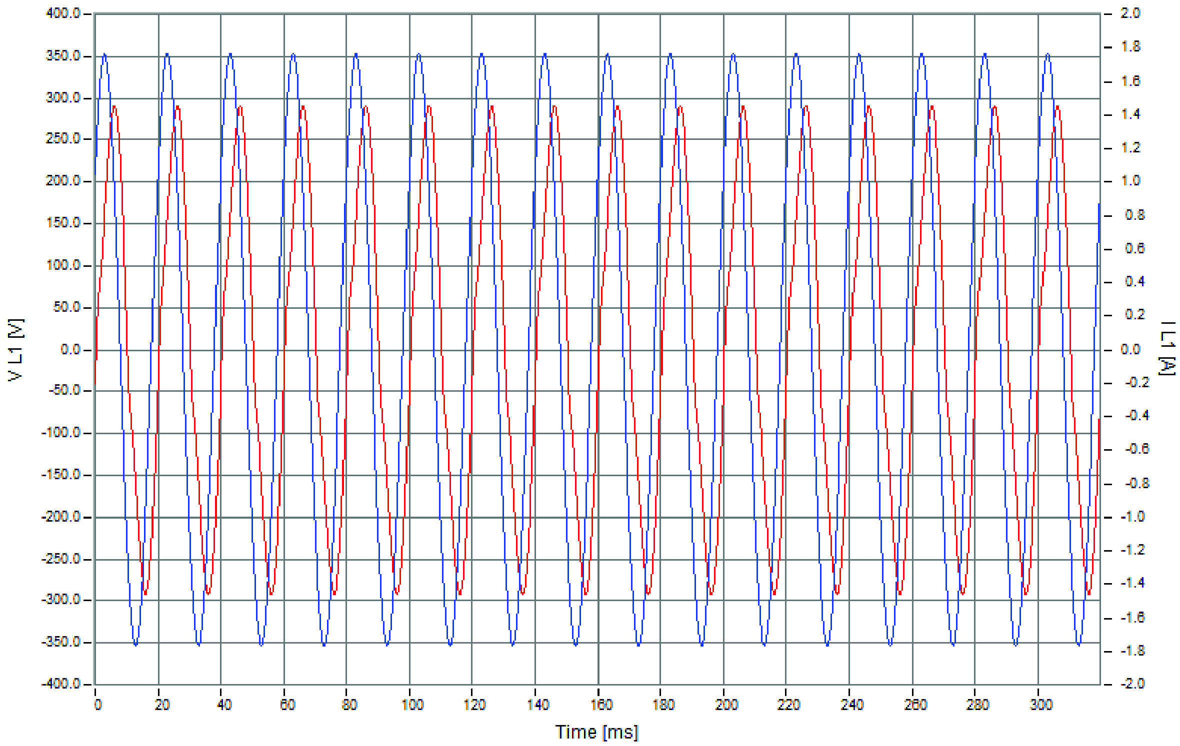


Figure 42. Current and voltage signal curve - 250 V

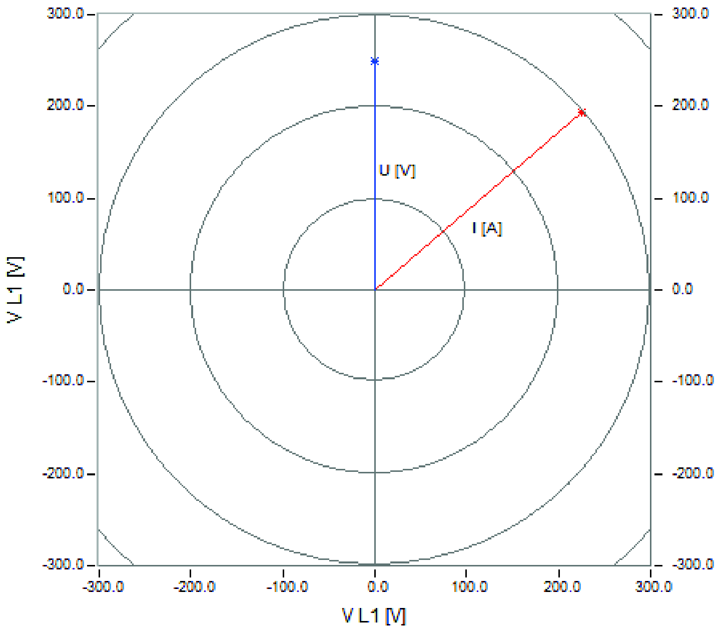


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

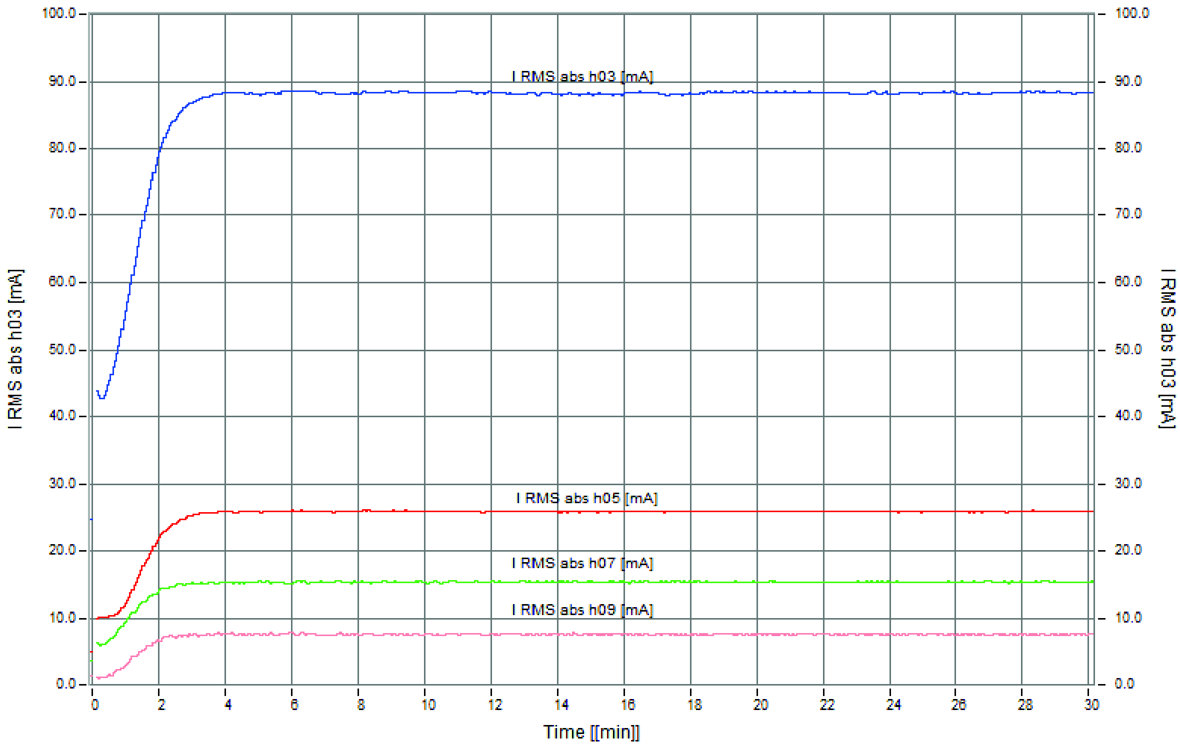


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

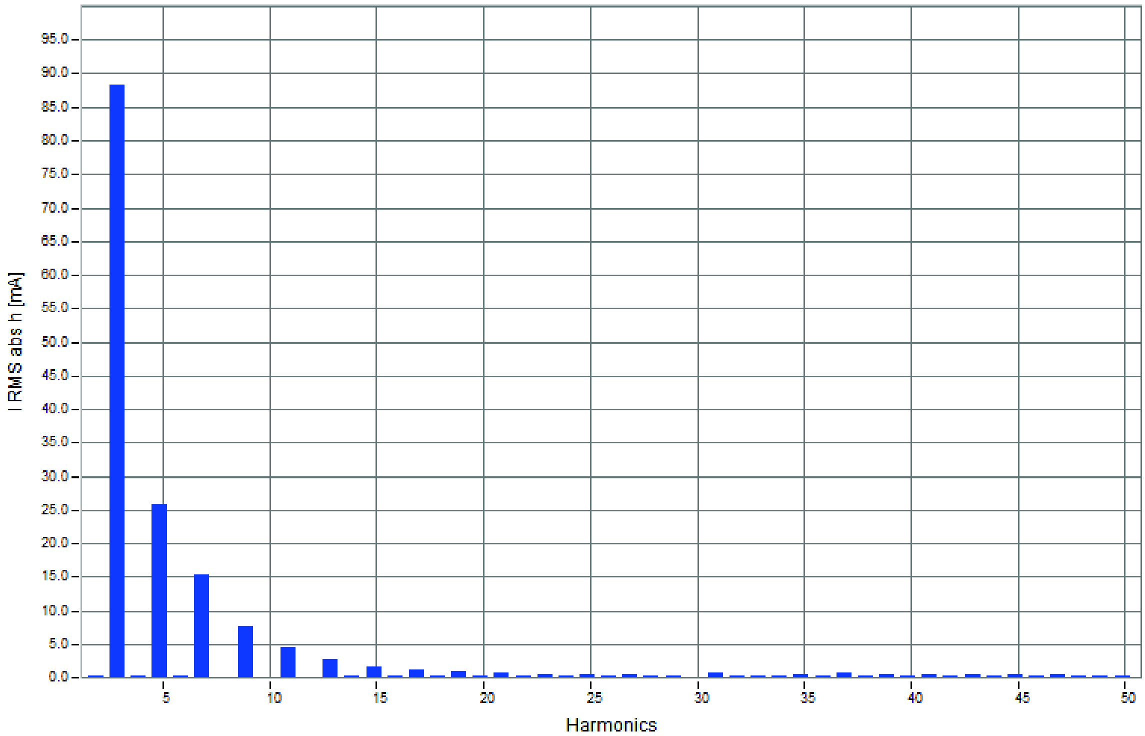


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.44\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.40\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 9.44%, for the maximum voltage, 1.09 p.u.. The minimum THD, 7.71%, is measured for the voltage 0.87 p.u.. Further increase of the voltage causes a slight increase of the THD.

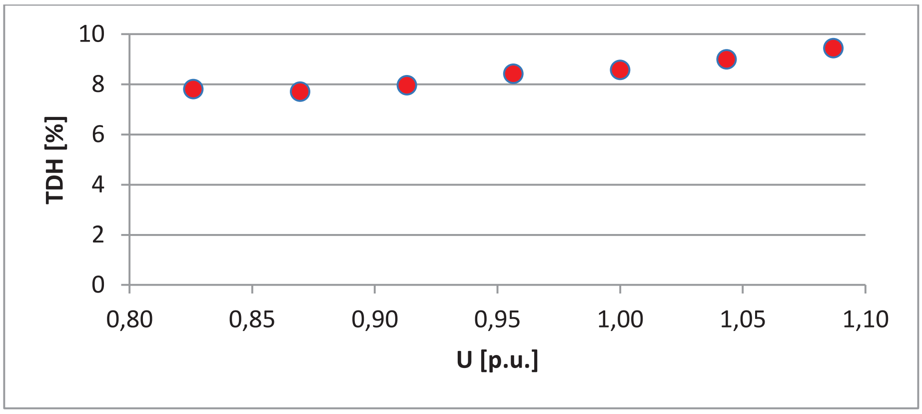
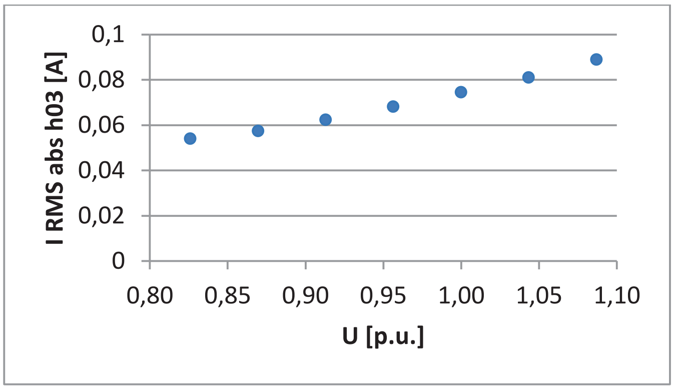
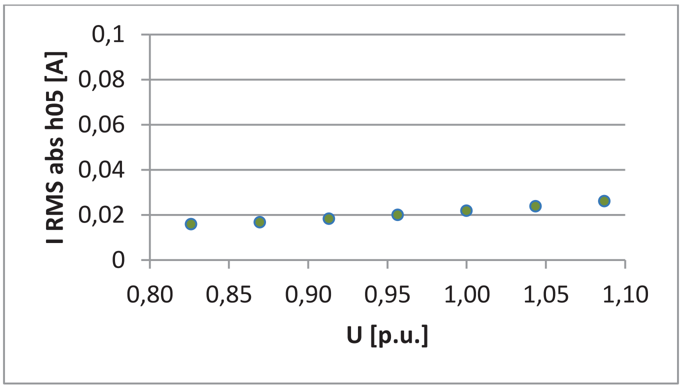


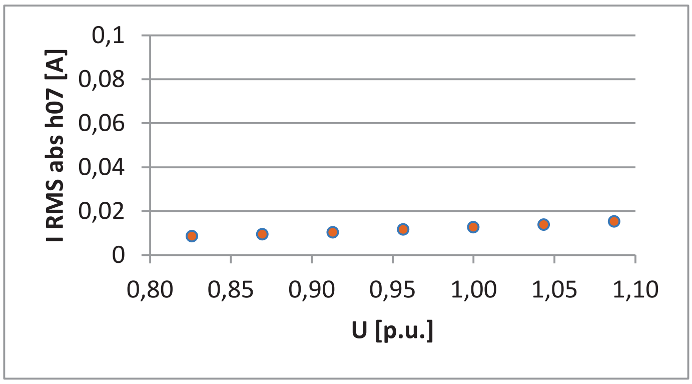
Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature



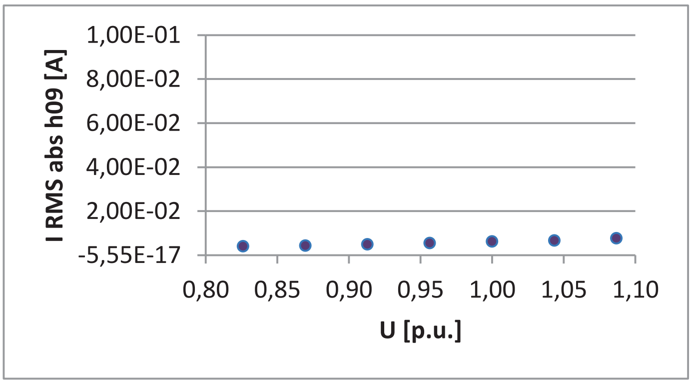
a)



b)



c)



d)

Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which increases with the voltage increase. Figures 47. b) and d) show the 5th and the 9th harmonic respectively, which have exponential rising behaviour . In both cases the harmonic values are increasing with the voltage increase. Figure 47. c) shows 7th harmonic which increases marginally with the voltage increase.

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MEASUREMENT PROTOCOL 6

High pressure Sodium lamp-old
Lamp: NARVA
Ballast: VOSSLOH SOHVABE

Vienna 03.February 2016

1. Content

2. List of figures

3. Light type

High pressure sodium lamp
1X light source
Status: old

4. Technical data

NARVA NAT-S 150 W
Voltage: 230 V
Real power: 150 W
Lamp operating current: 1.8 A
Lamp starting current: 2.2 A
Run-up time: 5 min
Reignition time: 2 min

Maximum overall length L: 211 mm
Diameter d: 46 mm

Ballast and Ignitron:
VOSSLOH SOHVABE
Voltage: 220 V
Real Power: 150 W
Current: 1.8 A

5. Measurement

5.1. Schema

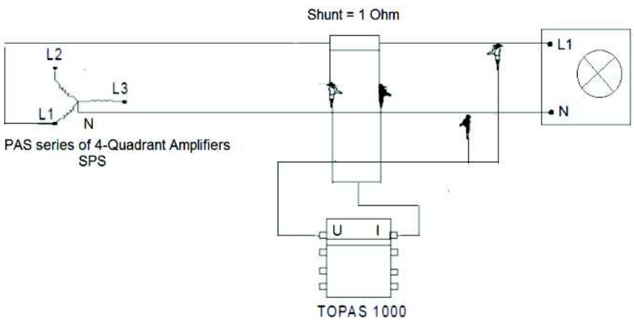


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside **Temperature**: 21.4^{0}C
Voltage range: 190-250 V **Shunt:** 0.5 Ω
Measurement interval: 30 min

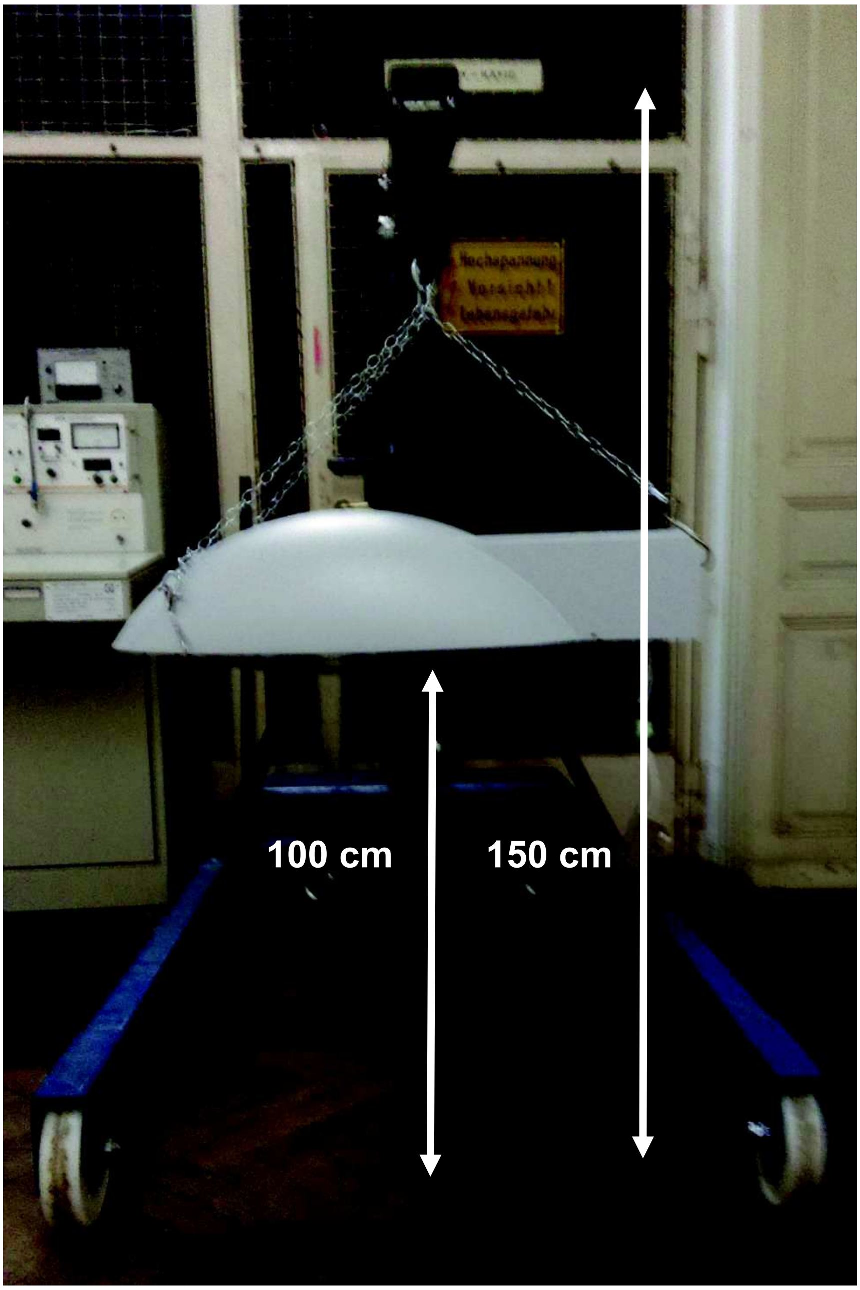


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 229.52 V
Current: I = 1.02 A
Active Power = 125.59 W
Reactive Power = 198.75 var
Apparent Power = 235.63 VA
Power Factor = 0.53

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

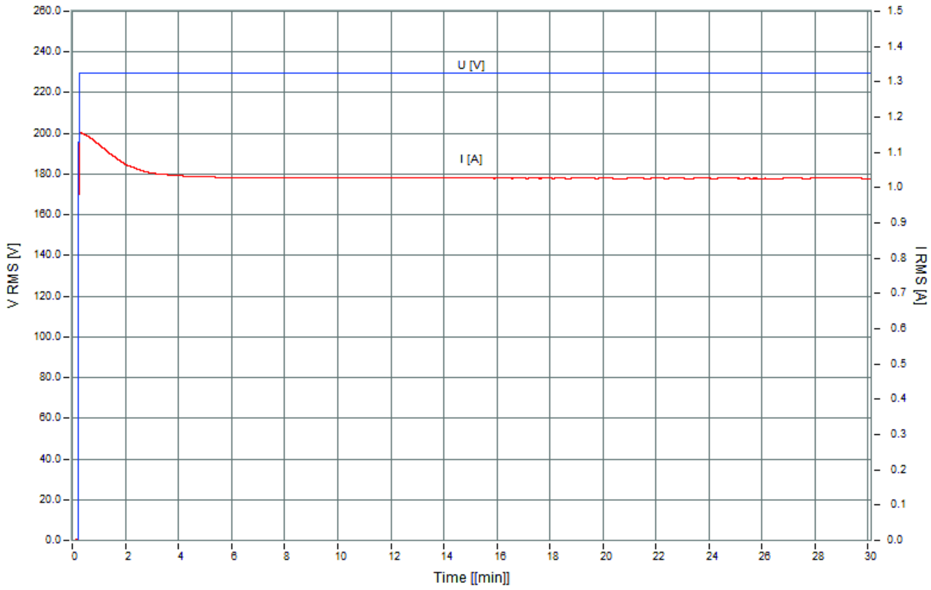


Figure 3. Root Mean Square of voltage and current - 230 V

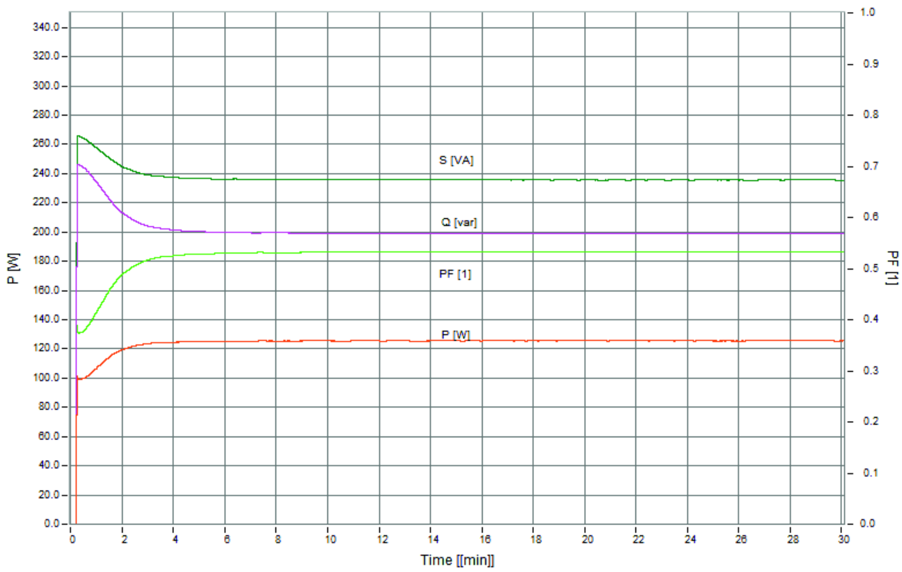


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 229.72	[V]	*****	0.00^0
I L1 = 1.1	[A]	*****	63.92

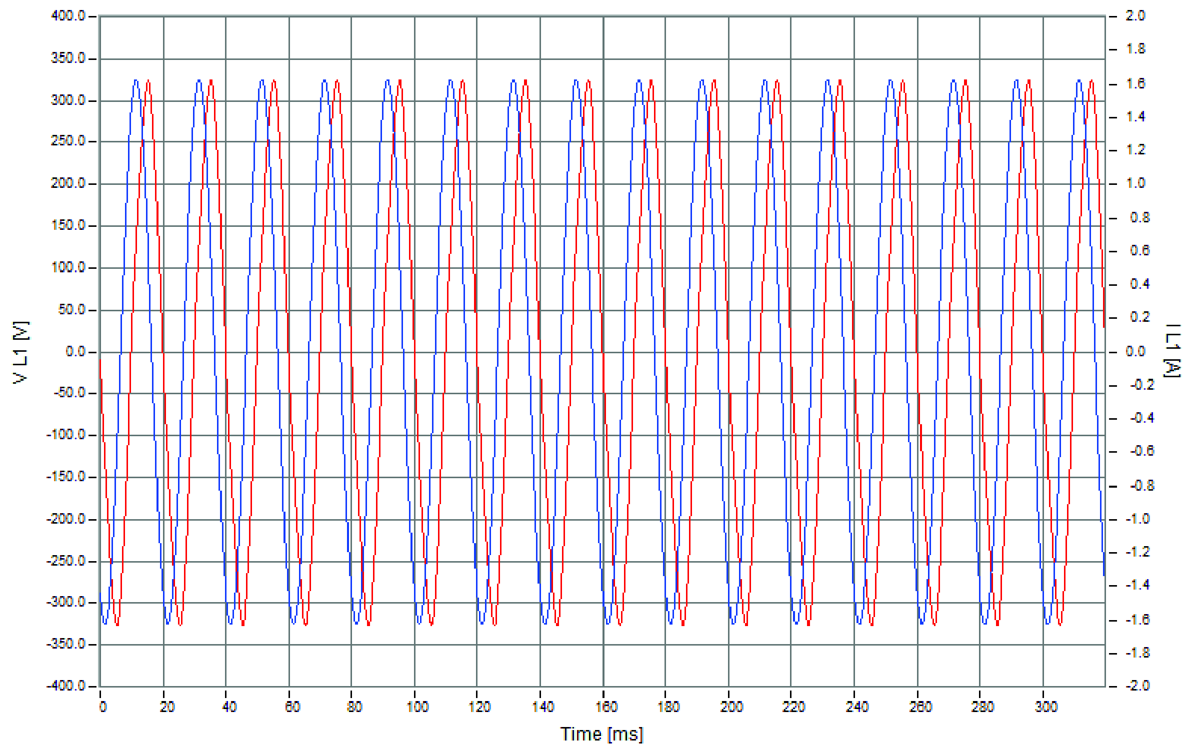


Figure 5. Current and voltage signal curve - 230 V

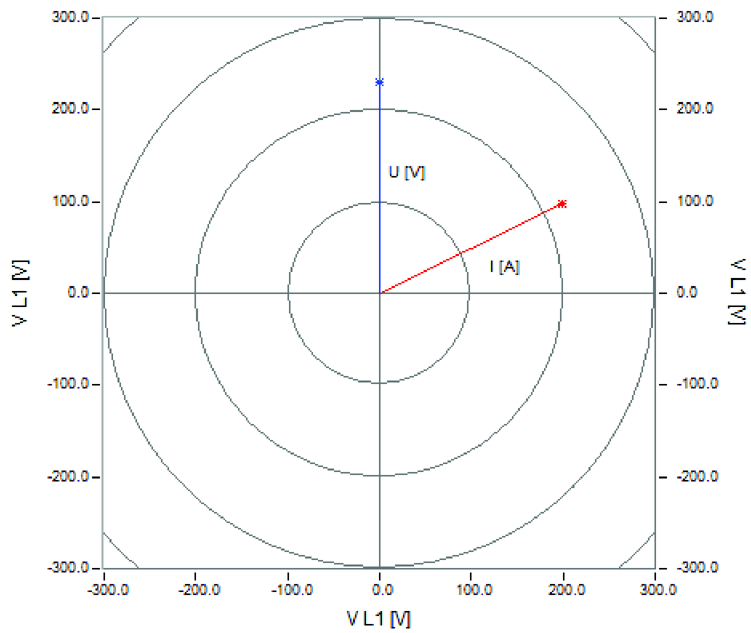


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

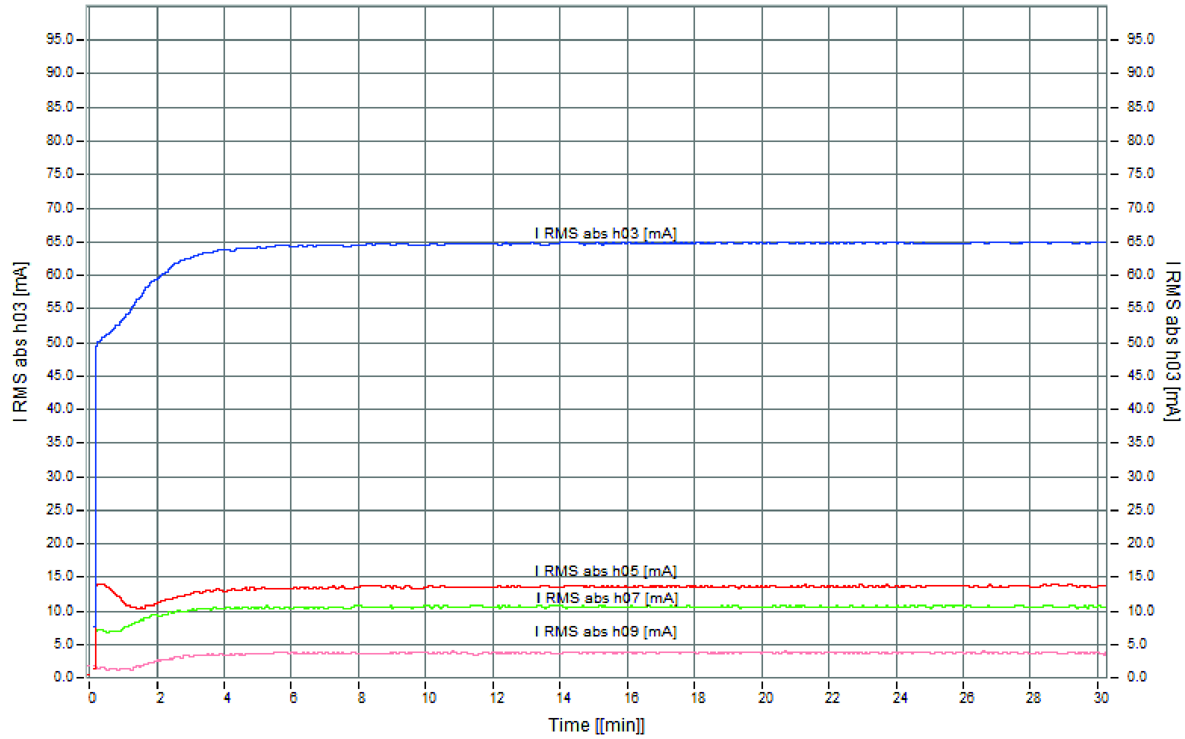


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

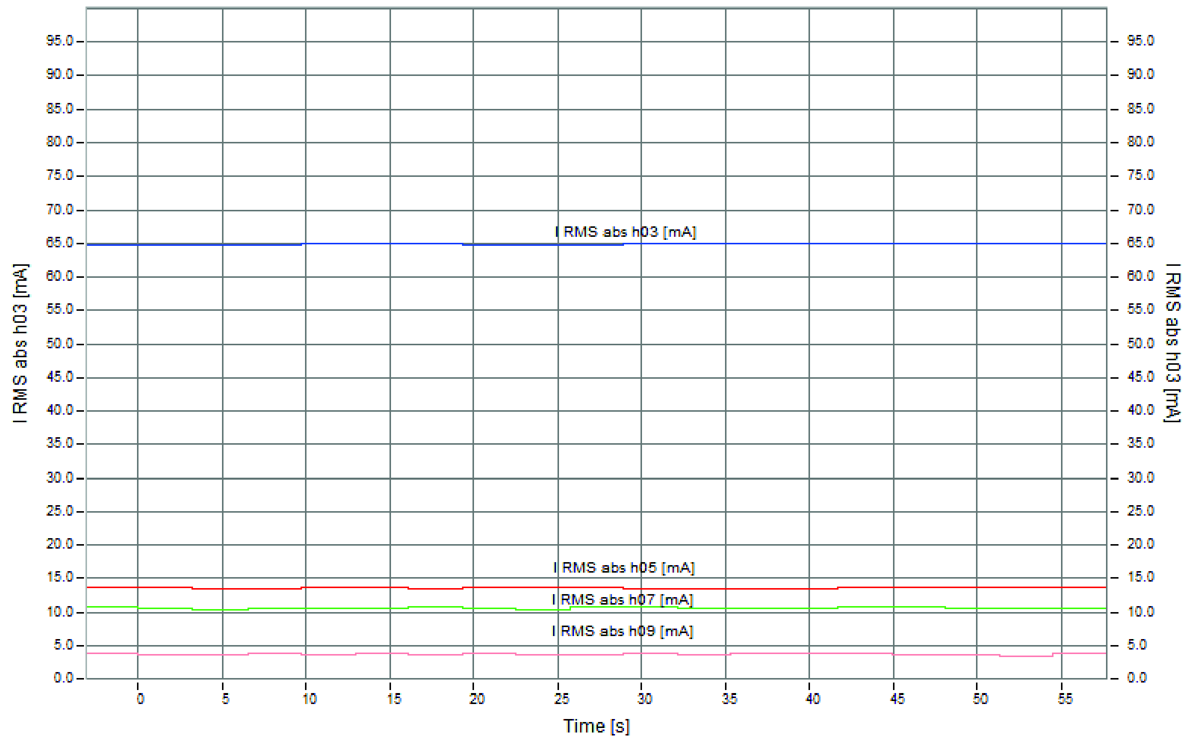


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

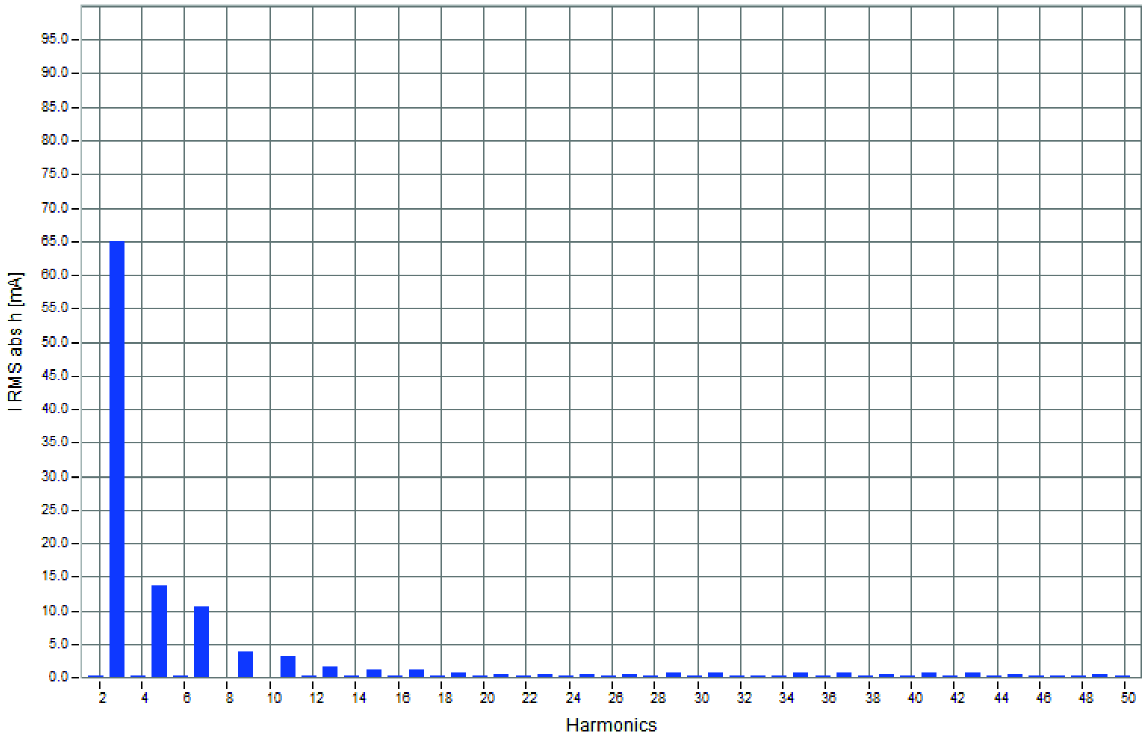


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 6.58\,\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 6.56\,\%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 189.58 V
Current: I = 0.82 A
Active Power = 86.17 W
Reactive Power = 131.12 var
Apparent Power = 157.19 VA
Power Factor = 0.54

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

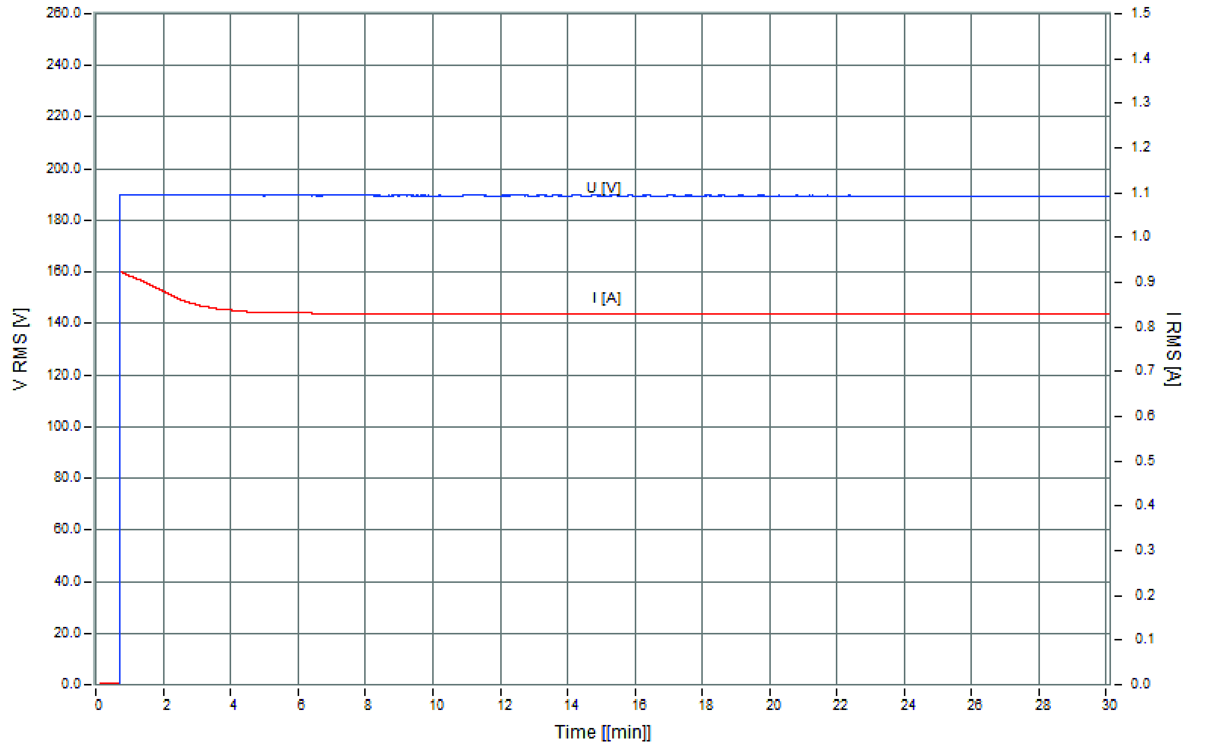


Figure 10. Root Mean Square of voltage and current - 190 V

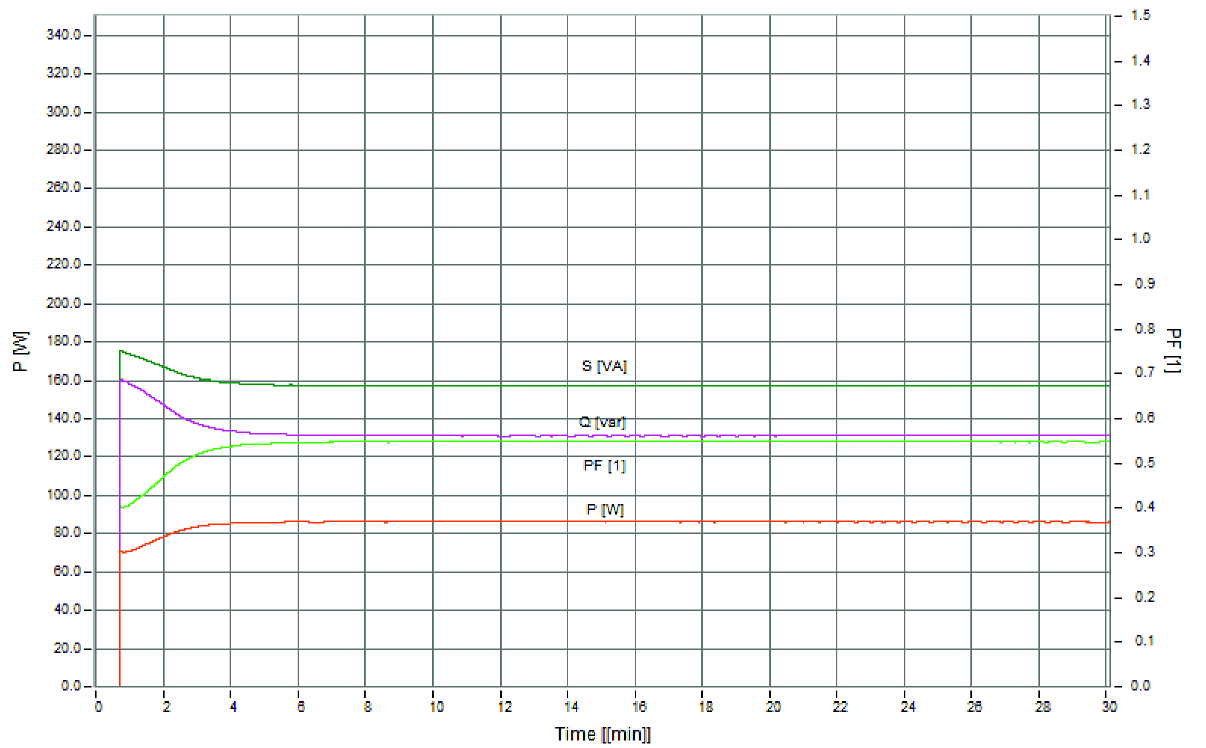


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 189.61	[V]	*****	0.00^0
I L1 = 0.82	[A]	*****	56.64^0

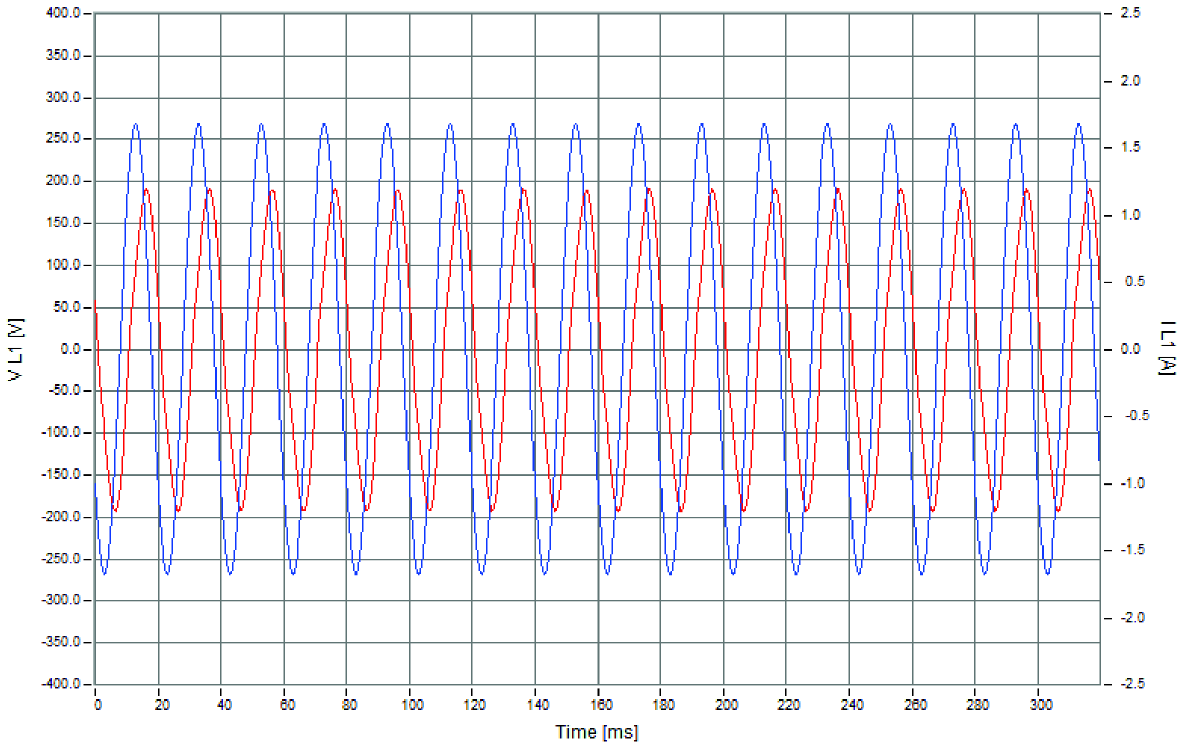


Figure 12. Current and voltage signal curve - 190 V

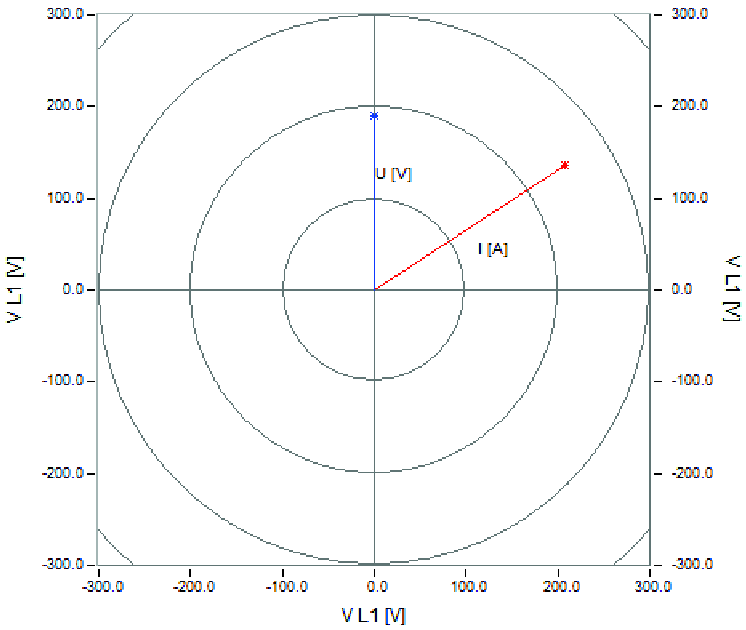


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

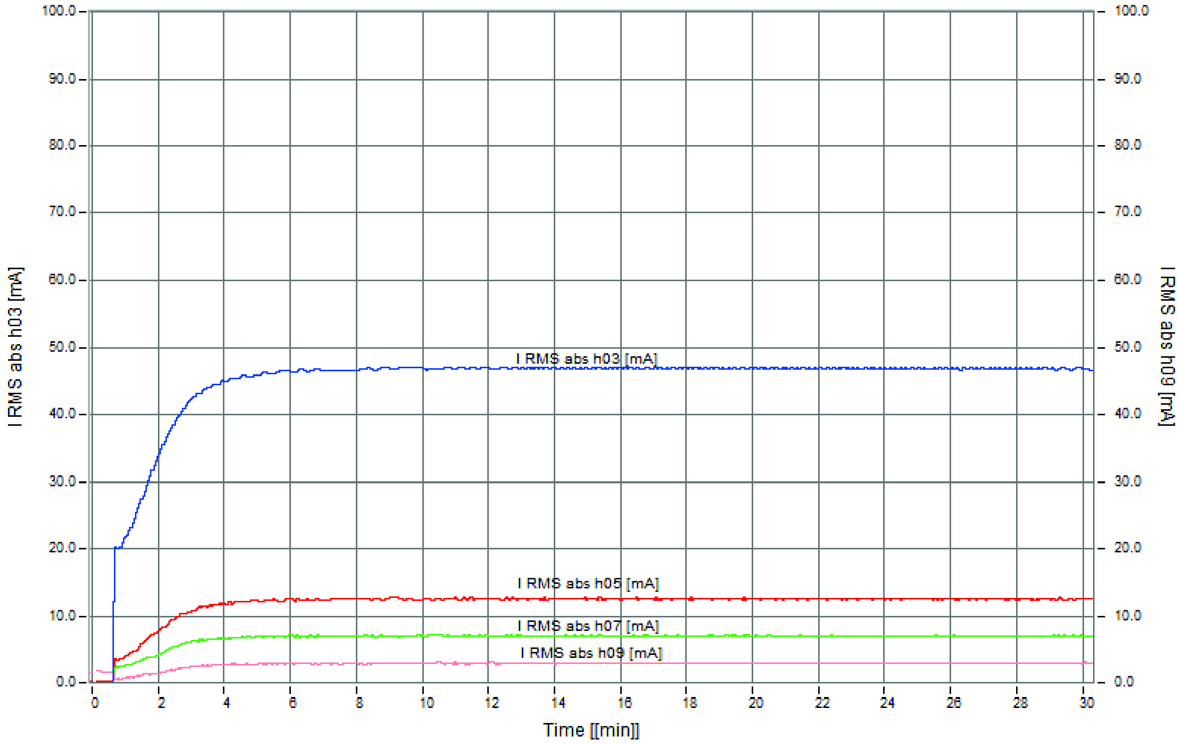


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

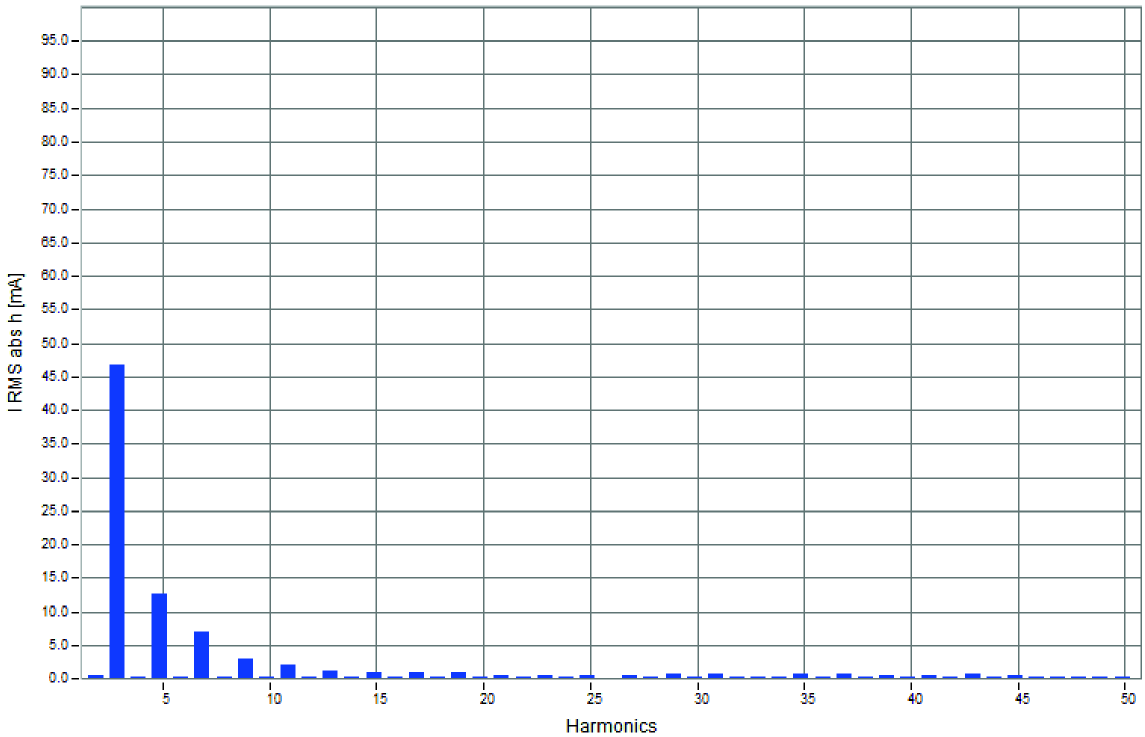


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 5.93\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 5.92\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 199.56 V
Current: I = 0.87 A
Active Power = 92.24 W
Reactive Power = 146.55 var
Apparent Power = 175.10 VA
Power Factor = 0.54

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

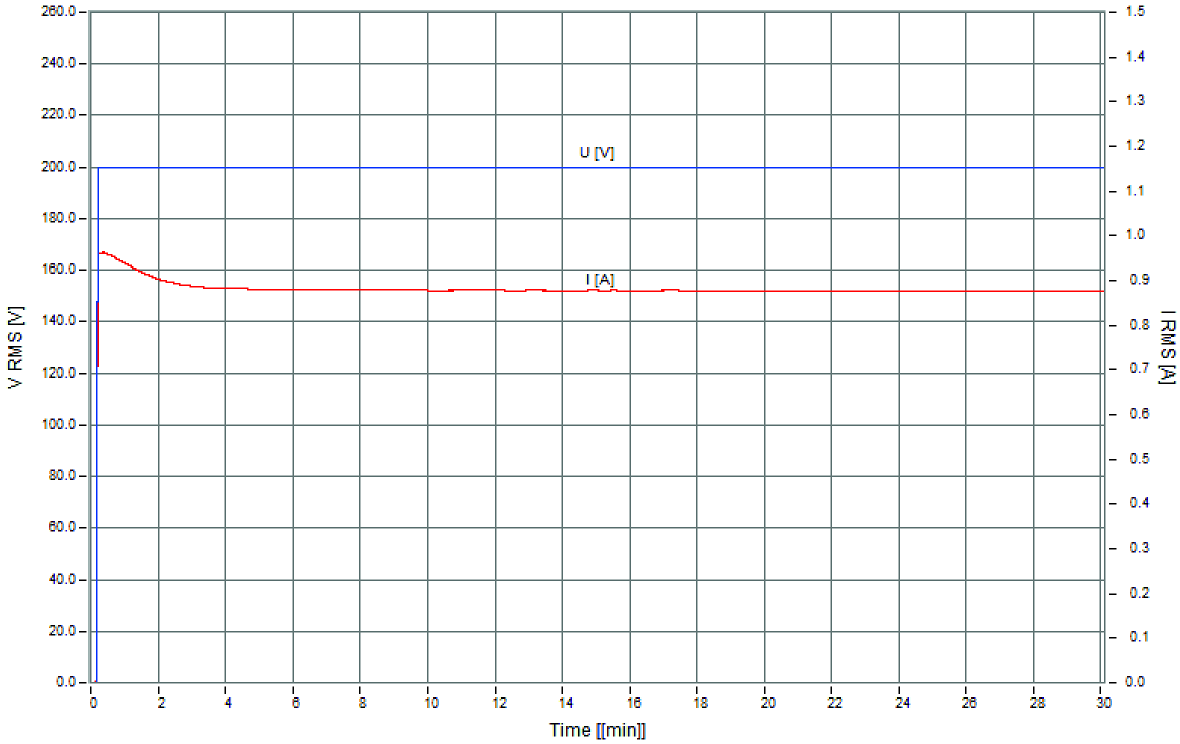


Figure 16. Root Mean Square of voltage and current - 200 V

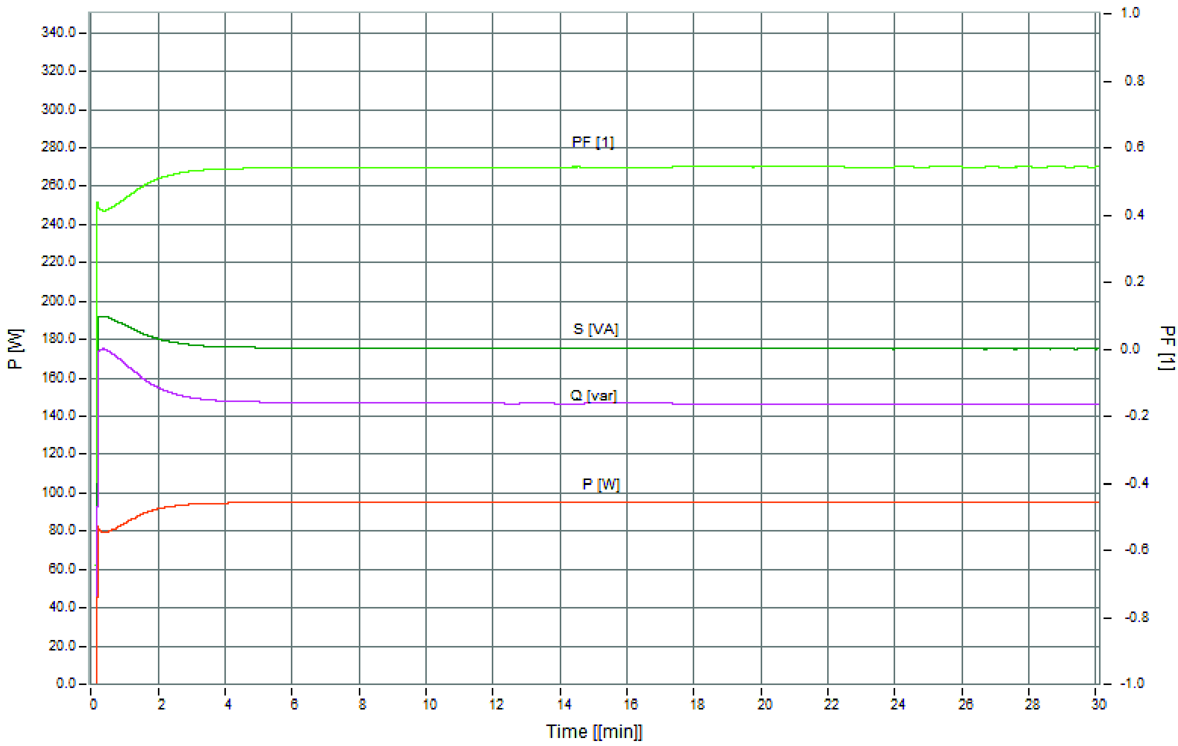


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 199.61	[V]	*****	0.00⁰
I L1 = 0.90	[A]	*****	59.59⁰

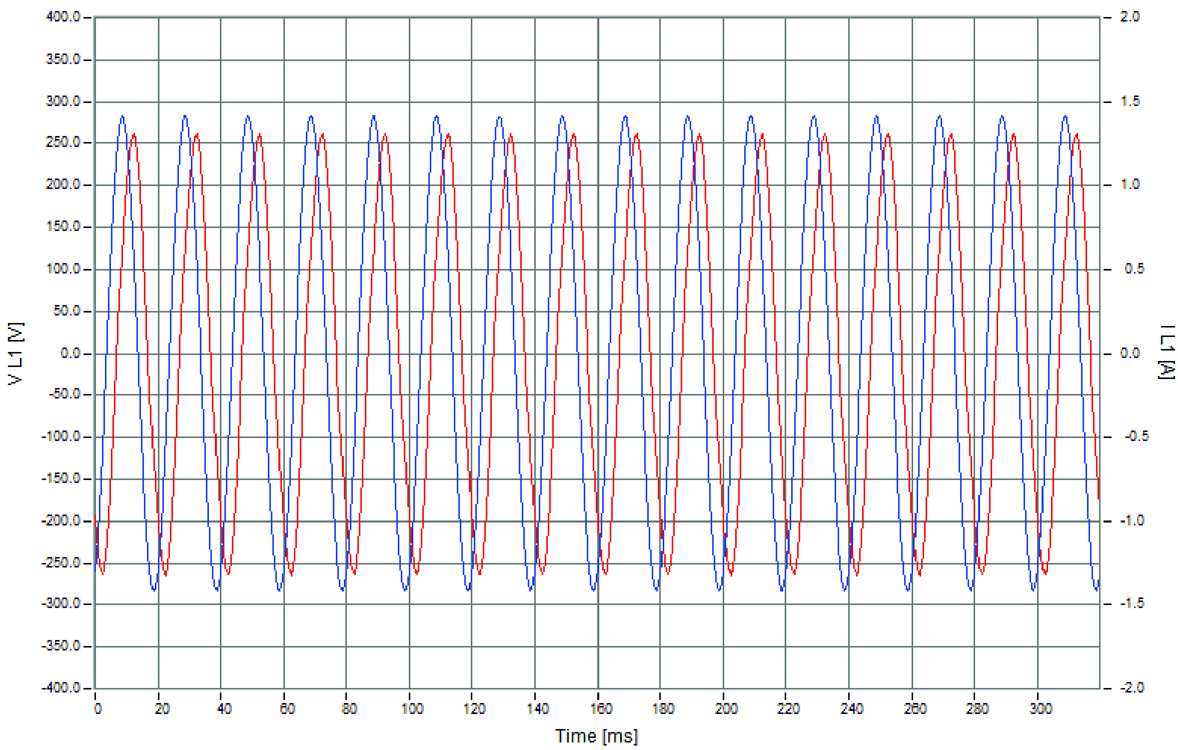


Figure 18. Current and voltage signal curve - 200 V

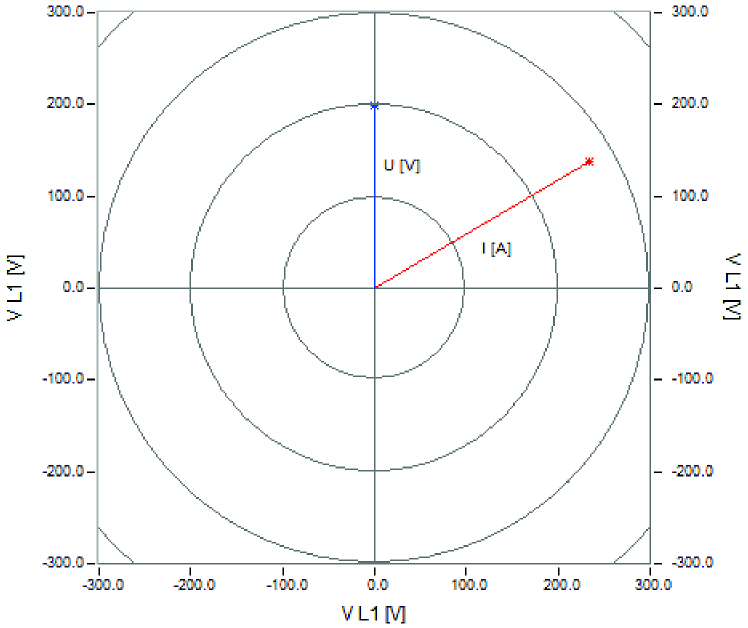


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

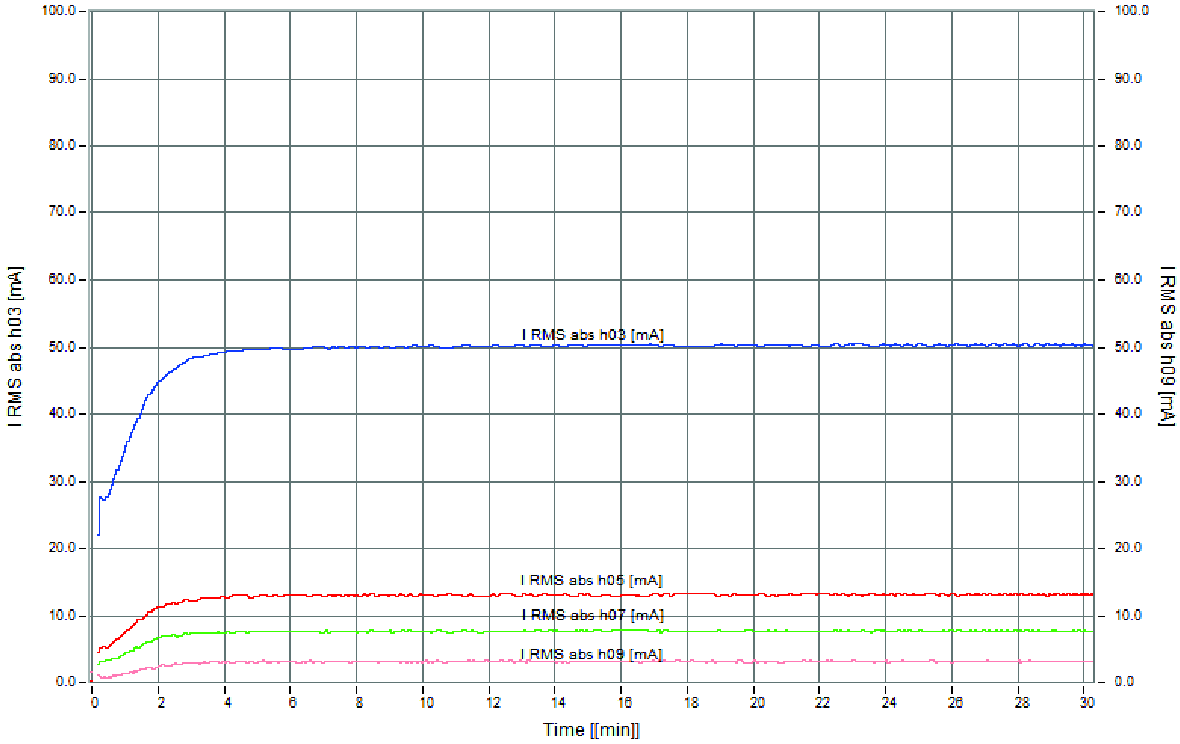


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

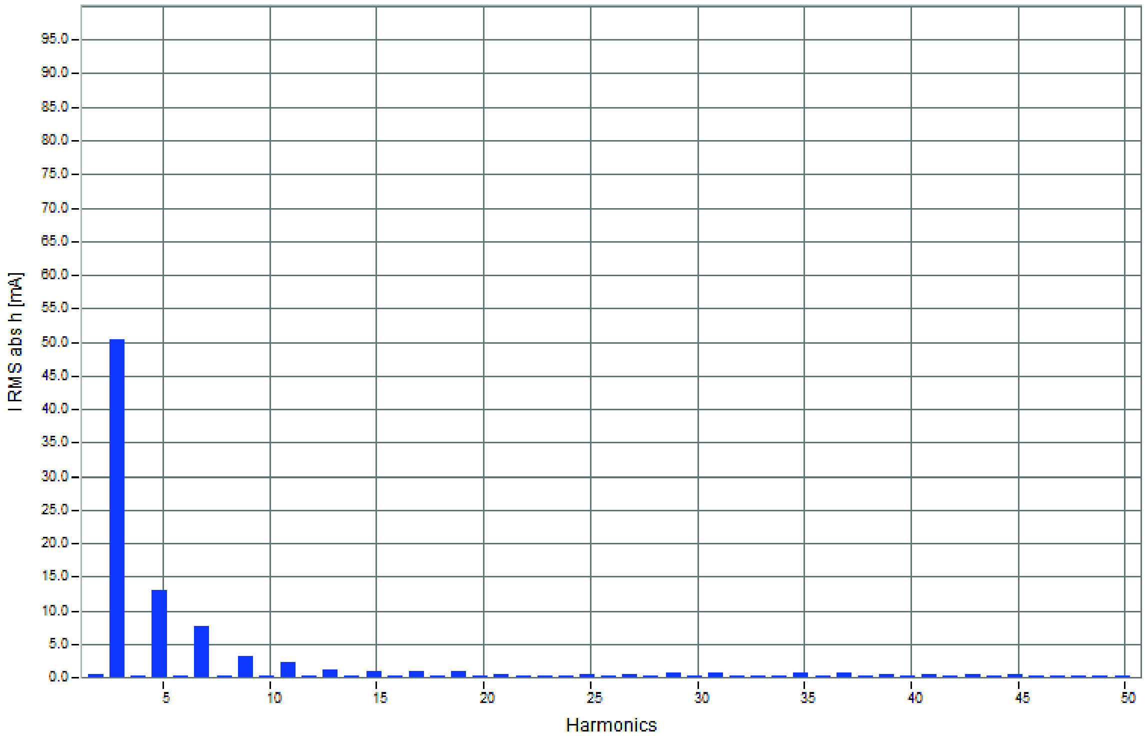


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 6.02\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 6.01\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:
Voltage: U = 20.53 V
Current: I = 0.92A
Active Power = 104.50 W
Reactive Power = 163.64 var
Apparent Power = 194.53 VA
Power Factor = 0.53

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

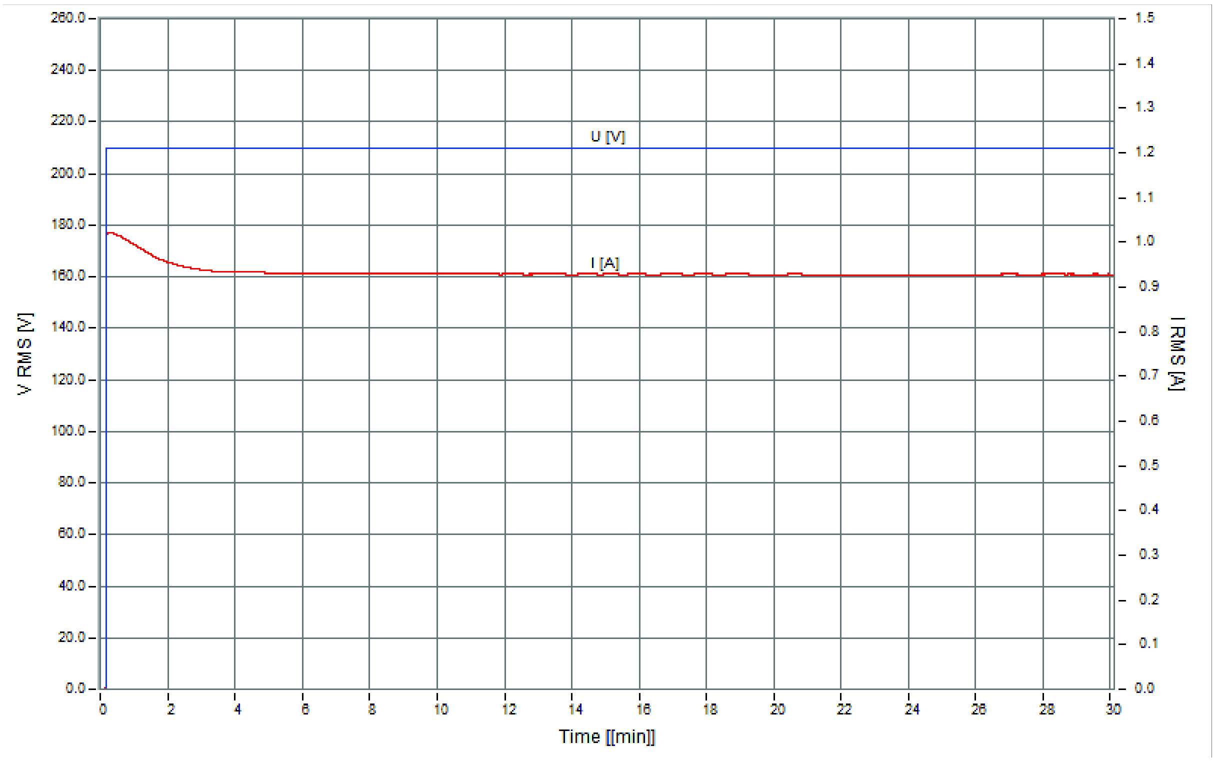


Figure 22. Root Mean Square of voltage and current - 210 V

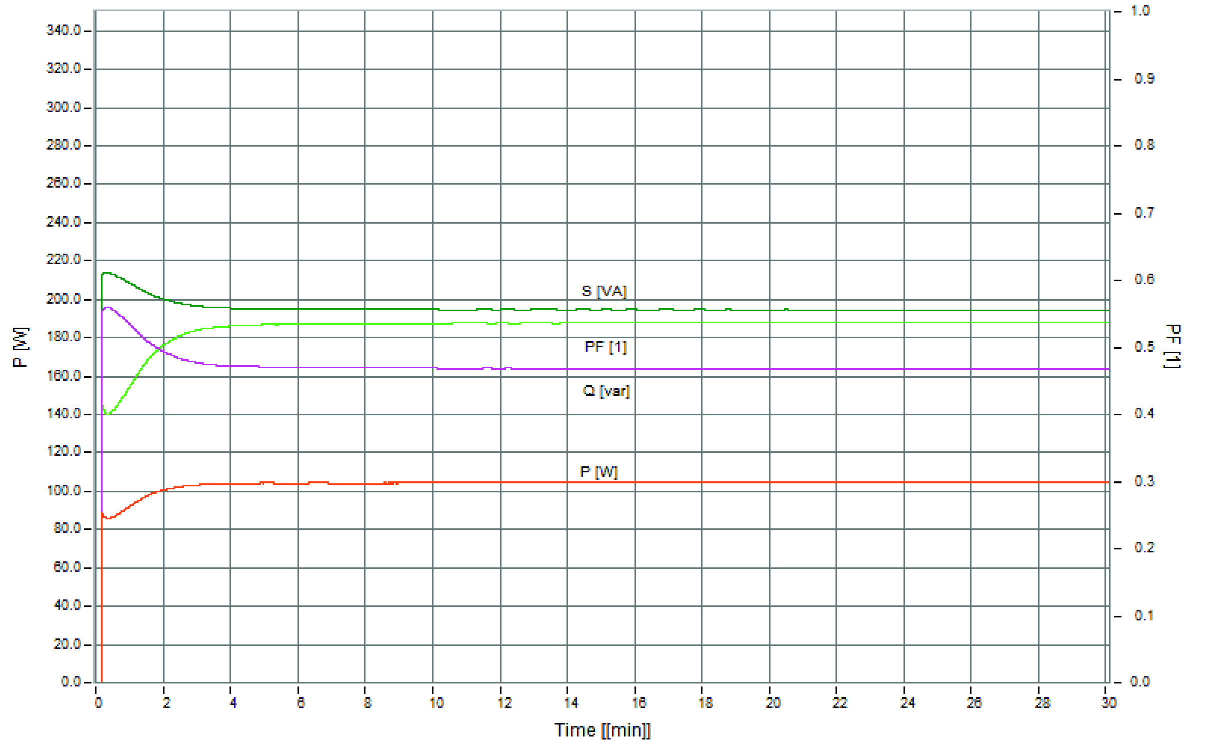


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 209.54	[V]	*****	0.00⁰
I L1 = 0.92	[A]	*****	57.48⁰

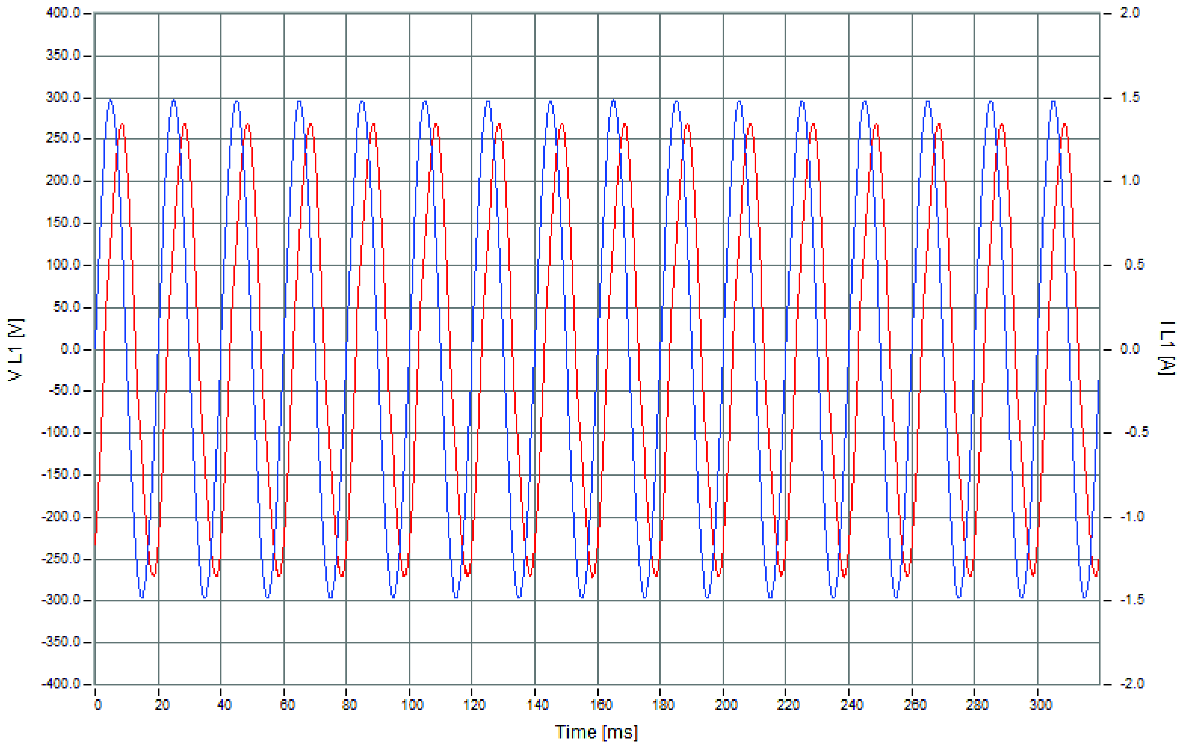


Figure 24. Current and voltage signal curve - 210 V

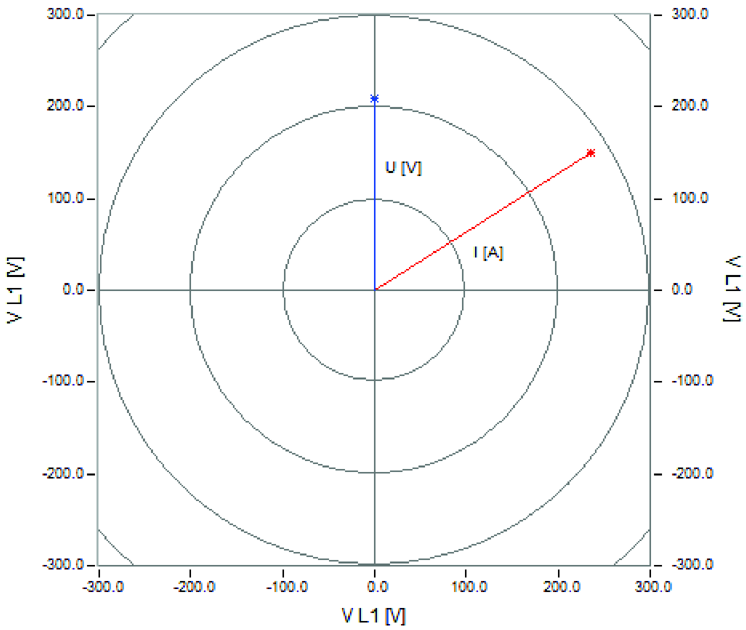


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

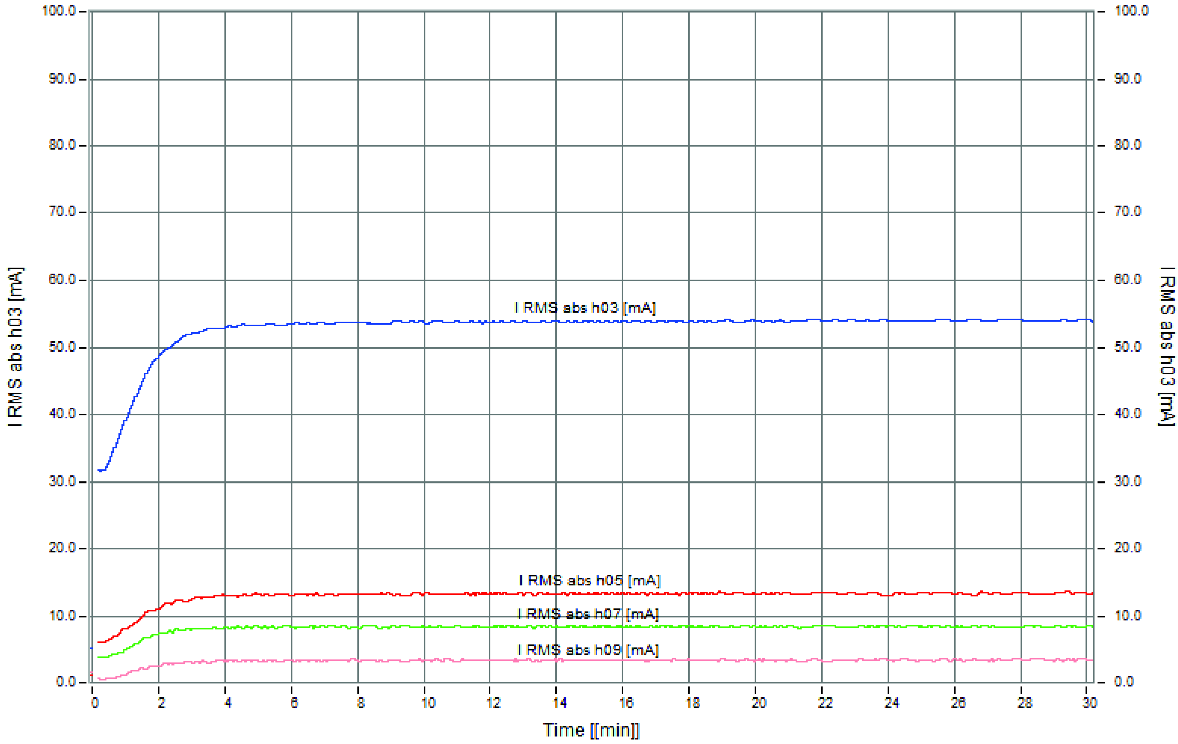


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

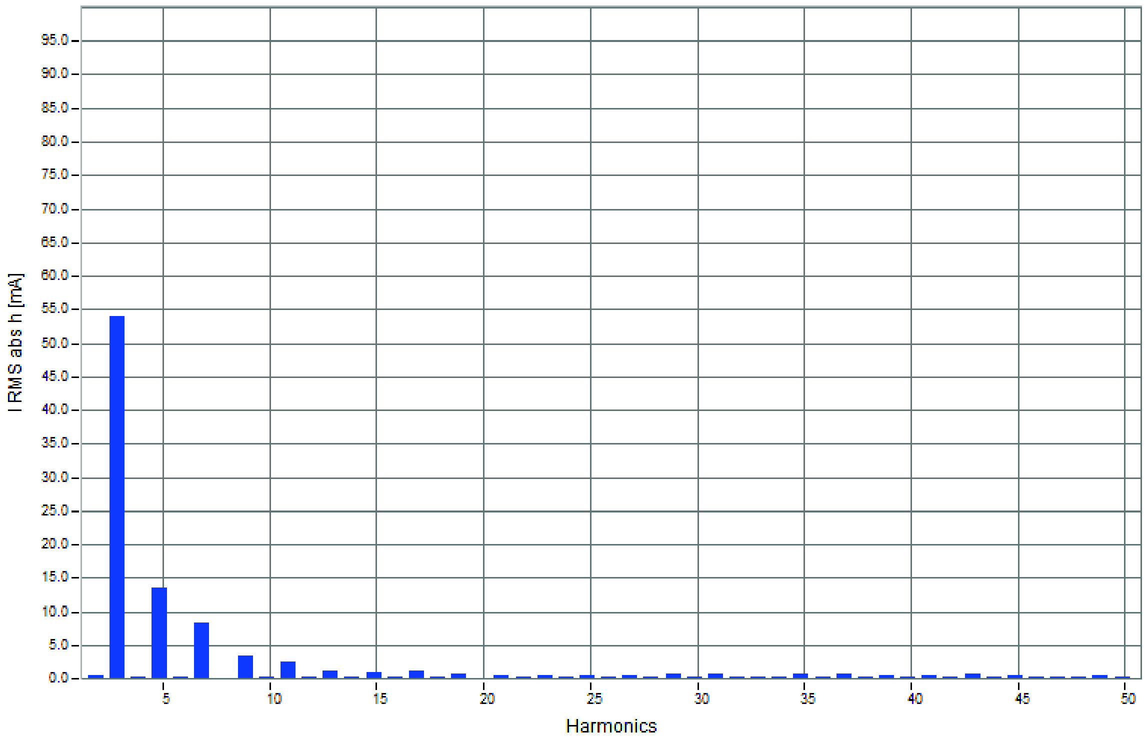


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 6.09\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 6.08\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 219.53 V

Current: I = 0.97 A

Active Power = 114.54 W

Reactive Power = 181.30 var

Apparent Power = 214.88 VA

Power Factor = 0.53

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

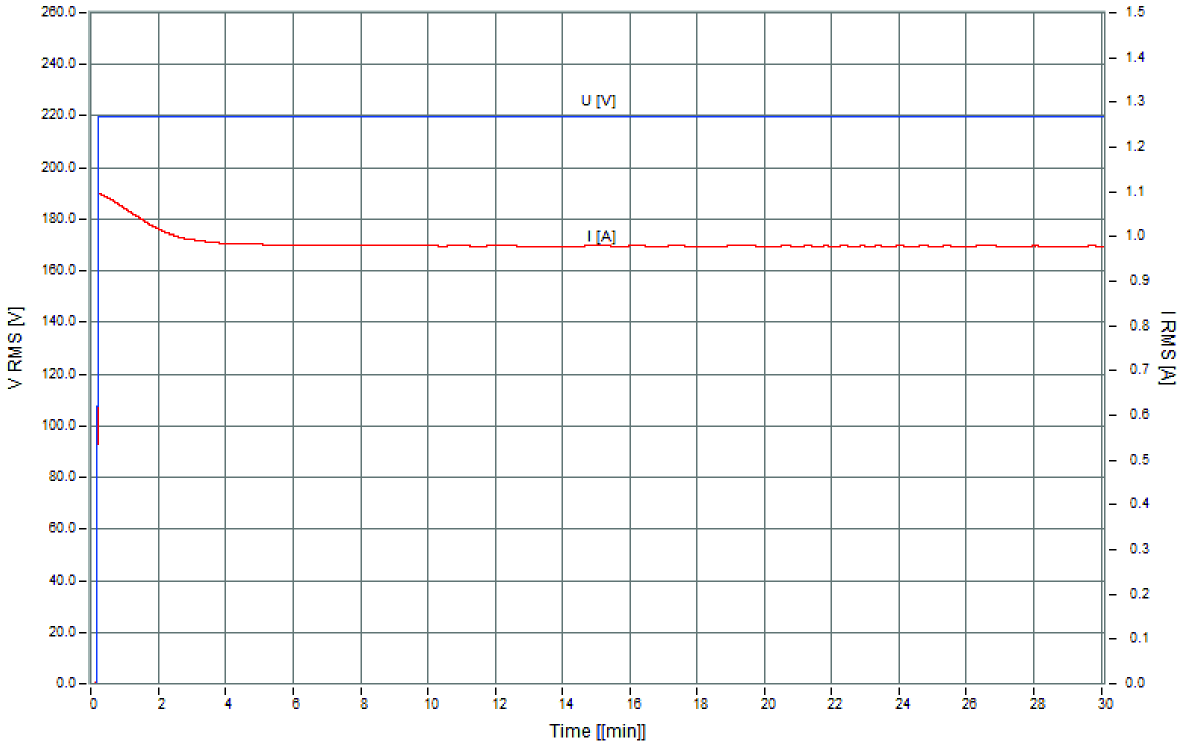


Figure 28. Root Mean Square of voltage and current - 220 V

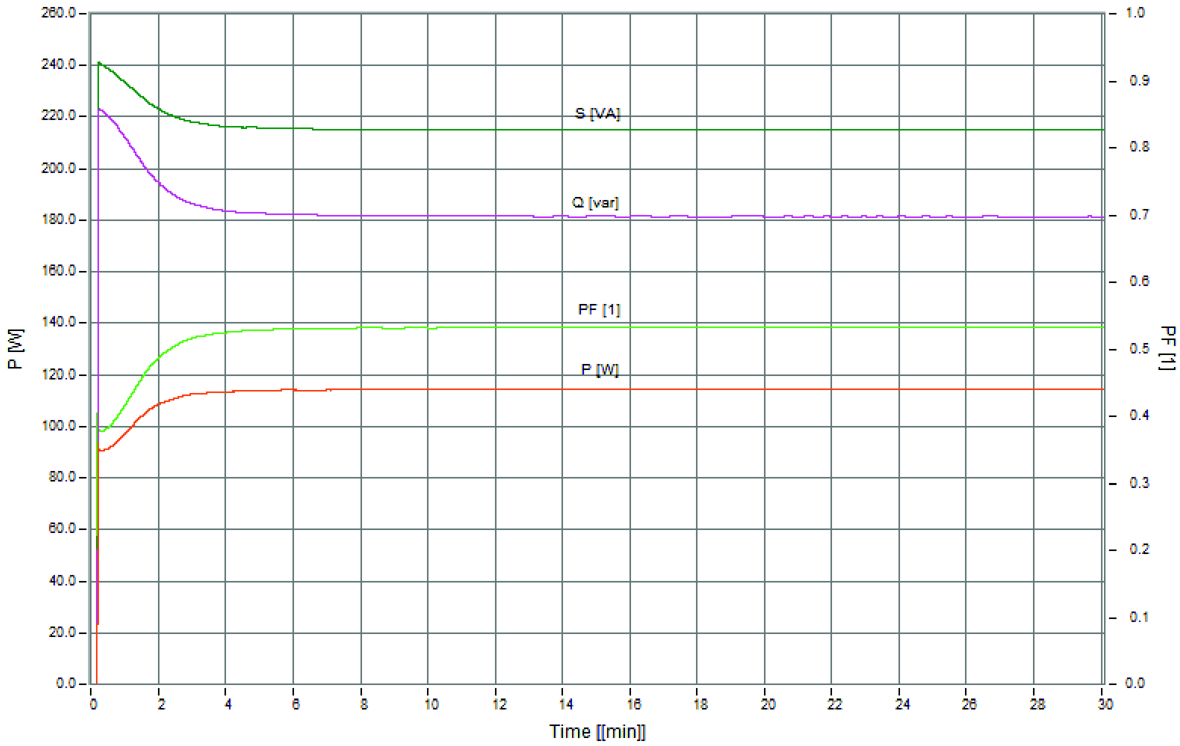


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 219.53	[V]	*****	0.00⁰
I L1 = 0.97	[A]	*****	57.73⁰

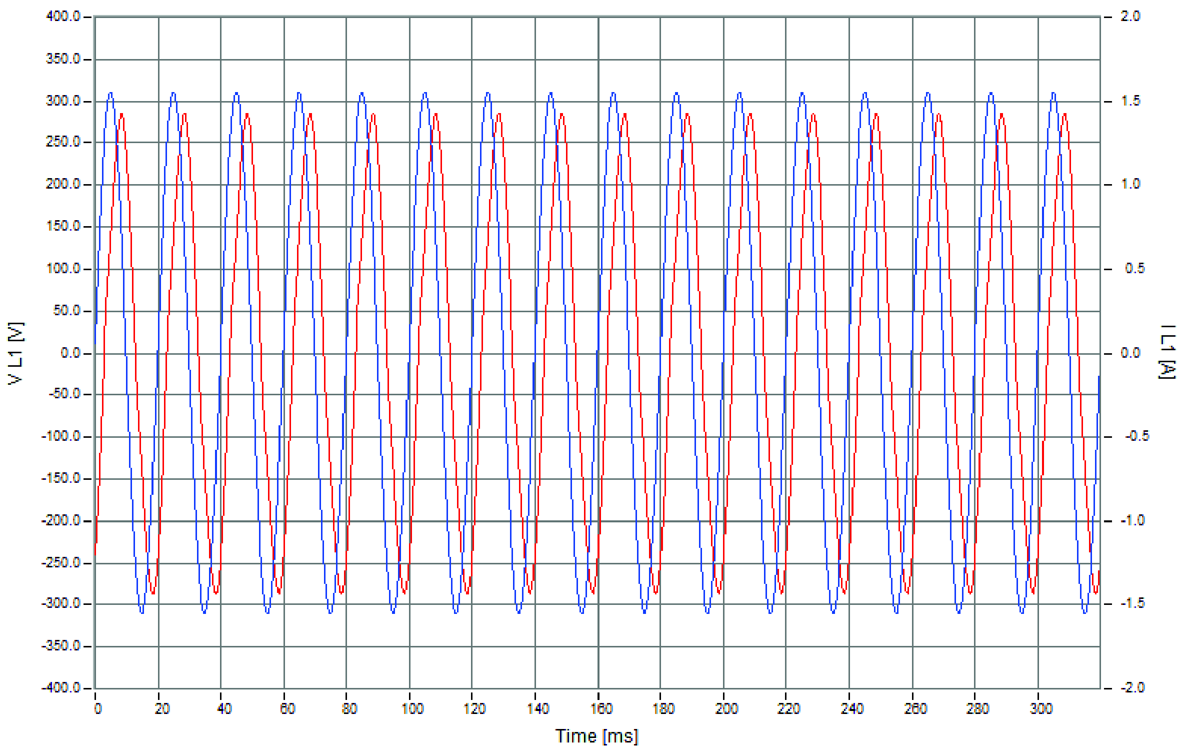


Figure 30. Current and voltage signal curve - 220 V

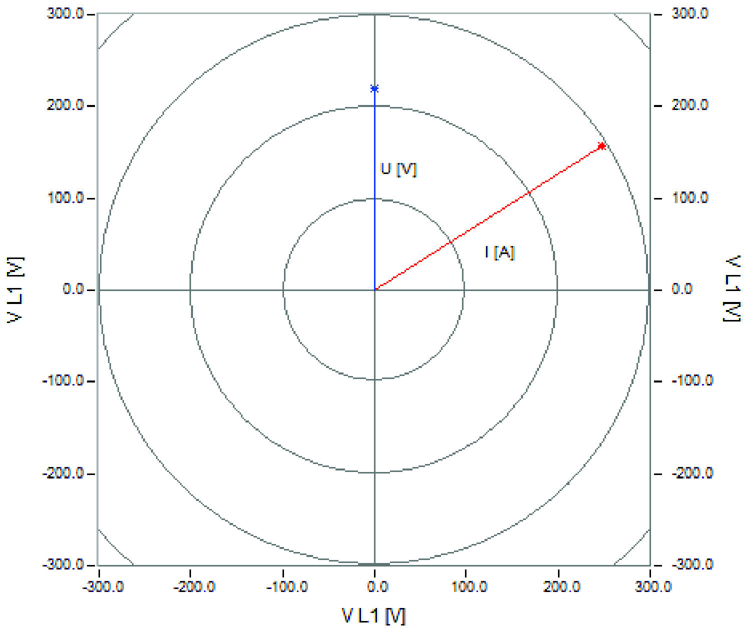


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

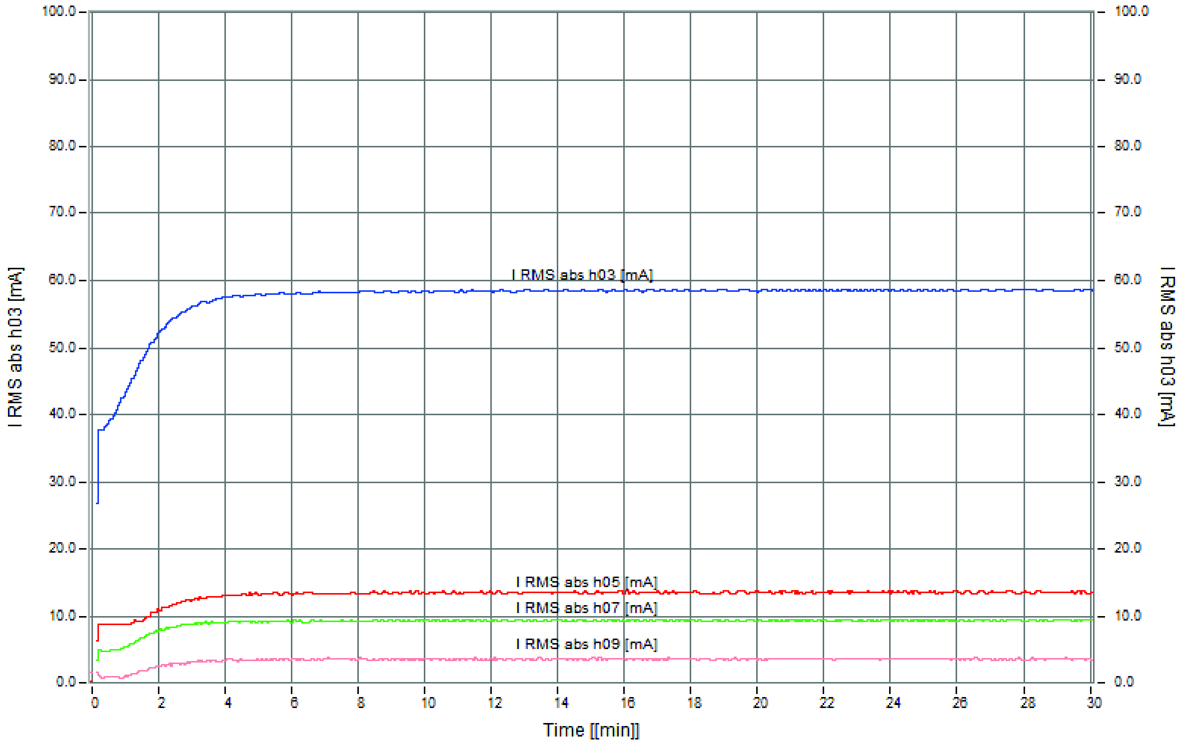


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

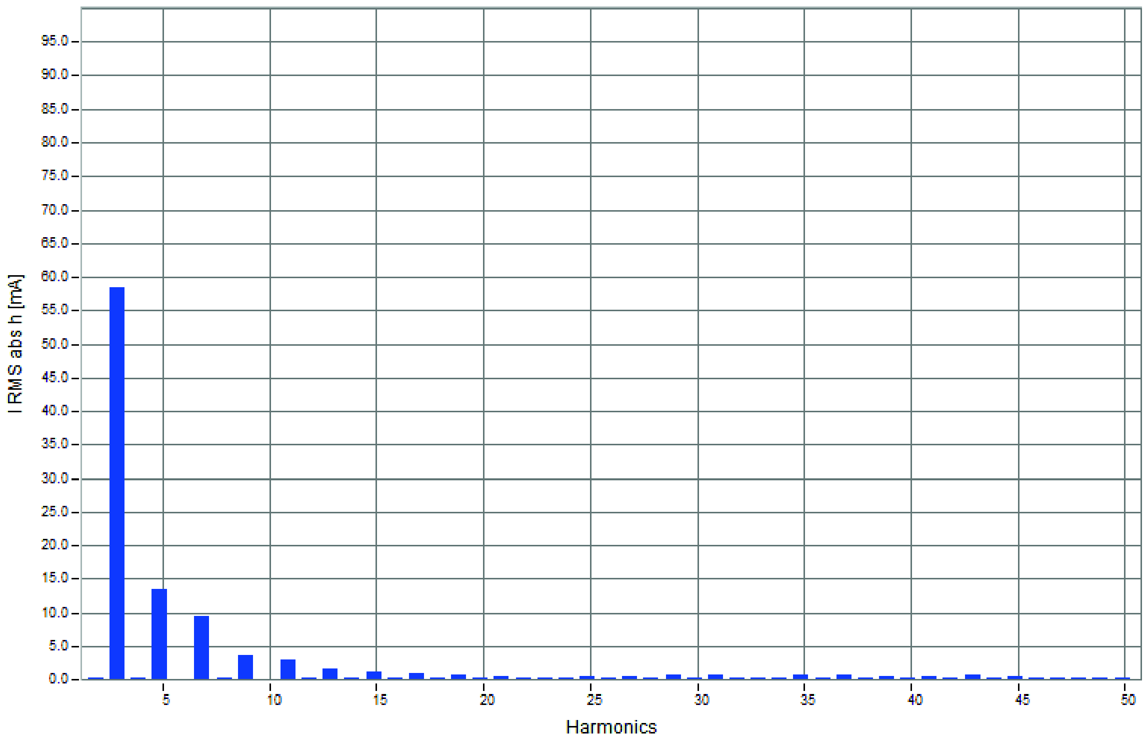


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 6.24\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 6.23\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 239.50 V
Current: I = 1.07 A
Active Power = 137.71 W
Reactive Power = 215.64 var
Apparent Power = 256.51 VA
Power Factor = 0.53

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

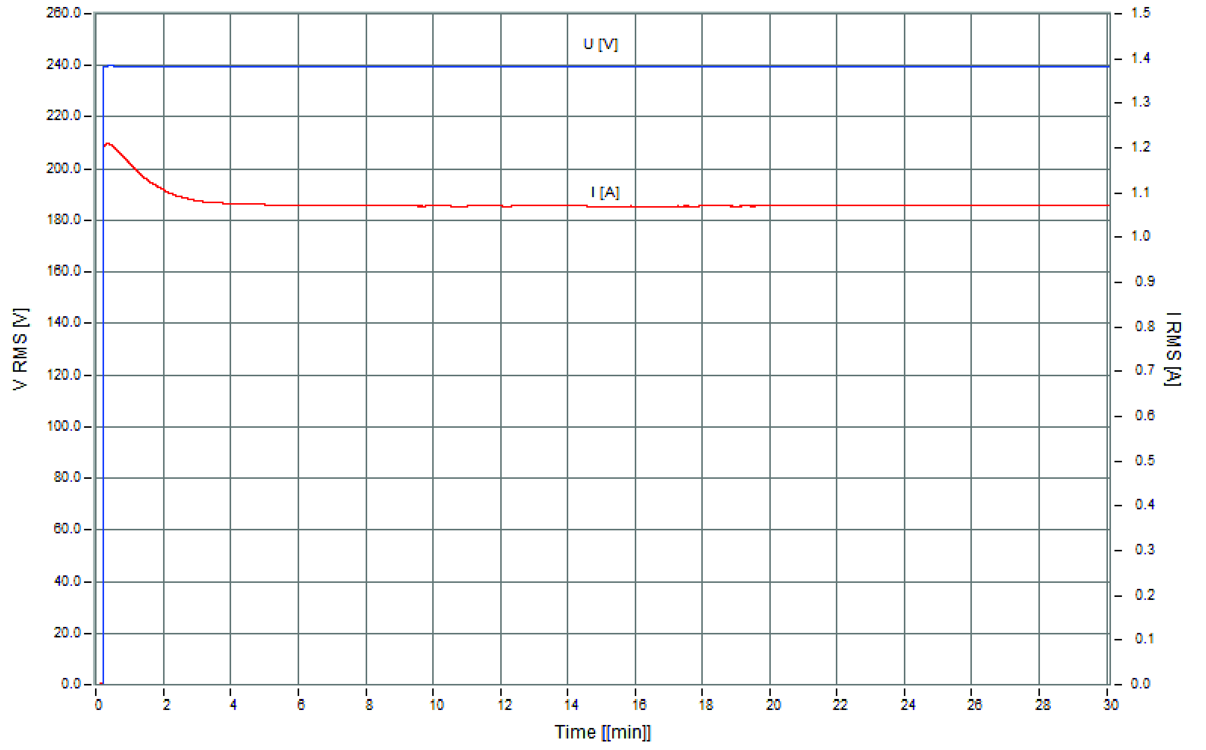


Figure 34. Root Mean Square of voltage and current - 240 V

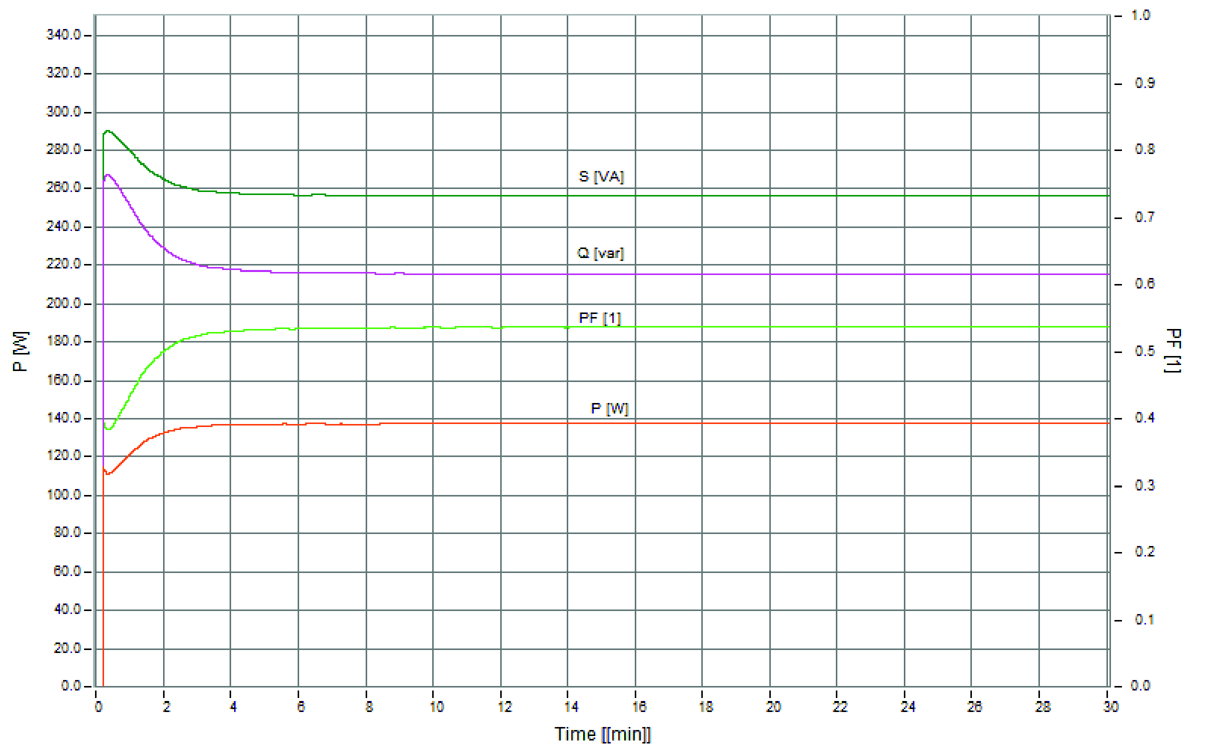


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 239.55	[V]	*****	0.00^0
I L1 = 1.06	[A]	*****	57.47^0

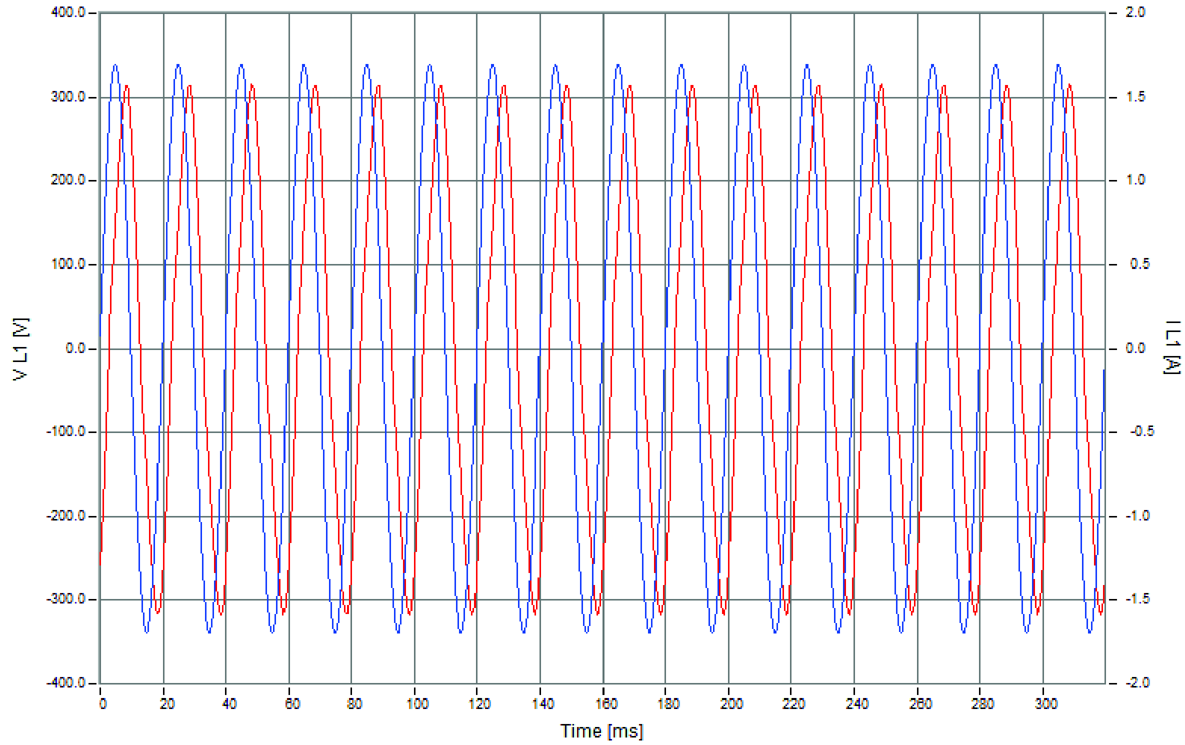


Figure 36. Current and voltage signal curve - 240 V

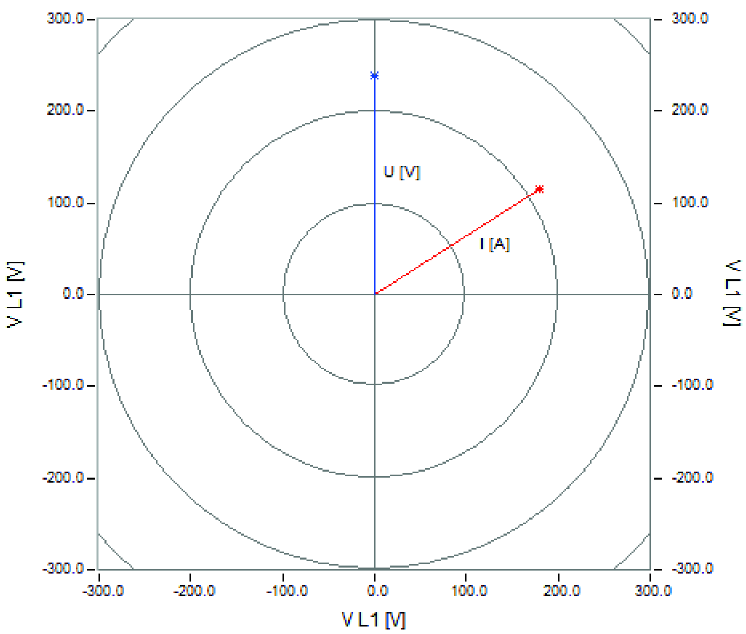


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

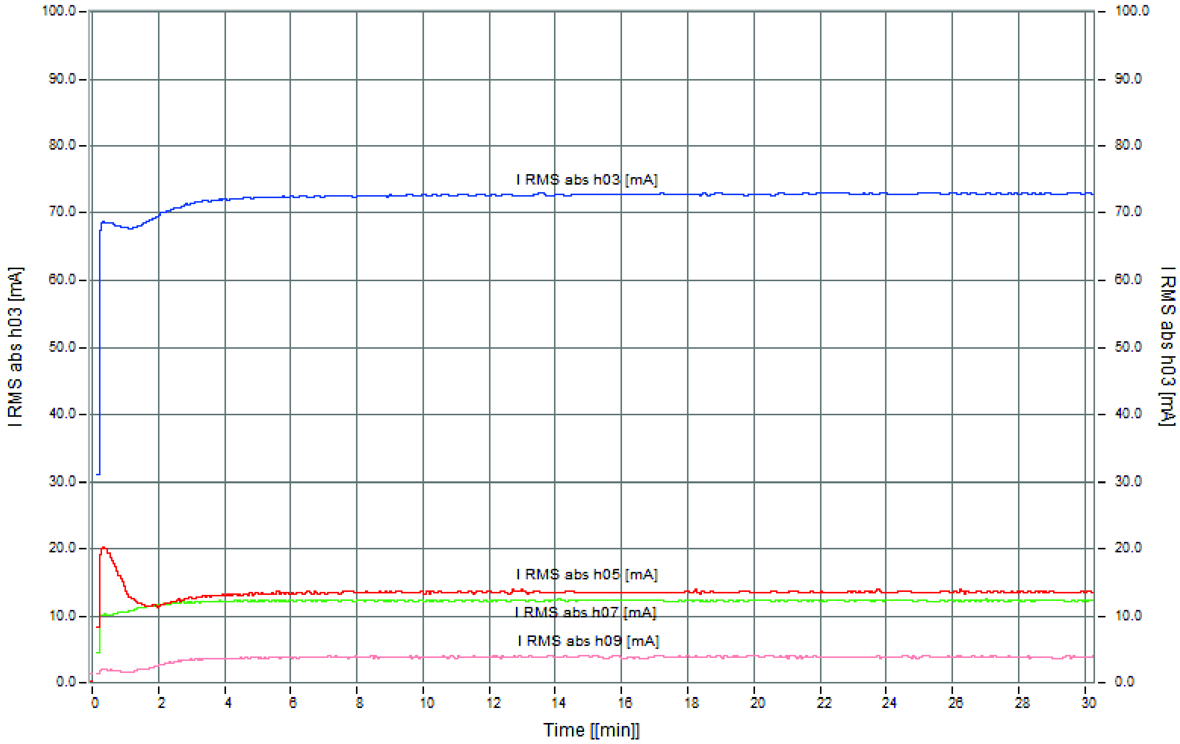


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

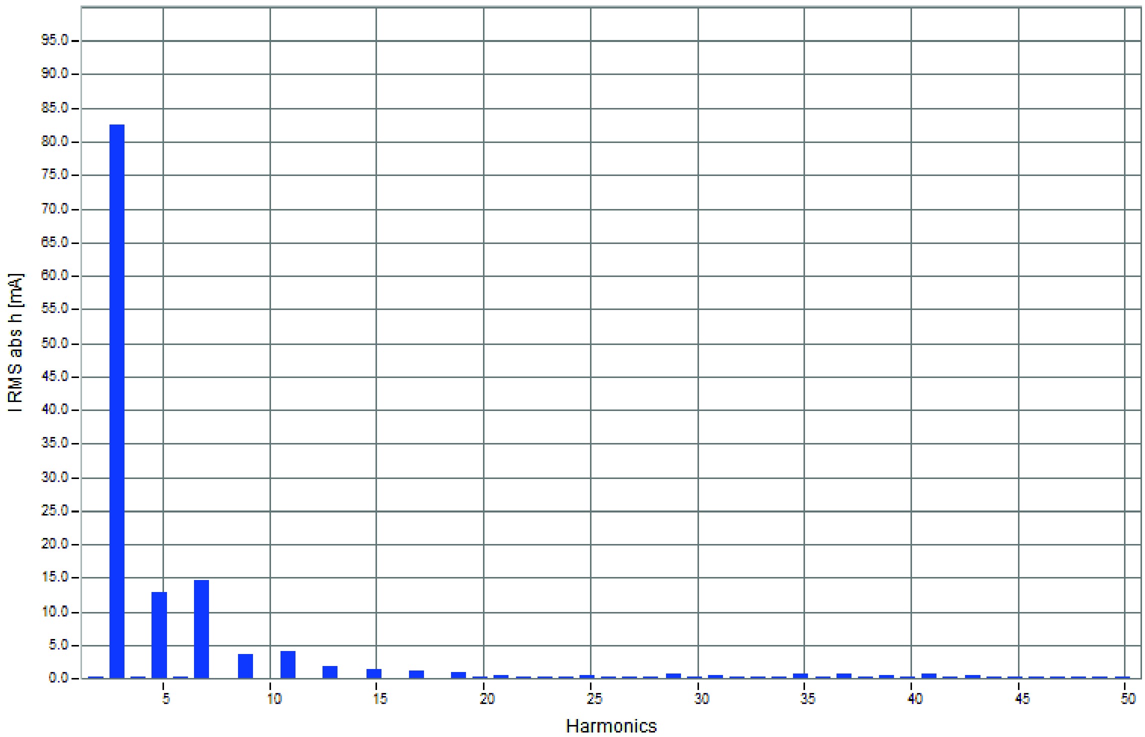


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 7.06\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 7.04\,\%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 249.55 V
Current: I = 1.11 A
Active Power = 149.94 W
Reactive Power = 234.50 var
Apparent Power = 279.16 VA
Power Factor = 0.53

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

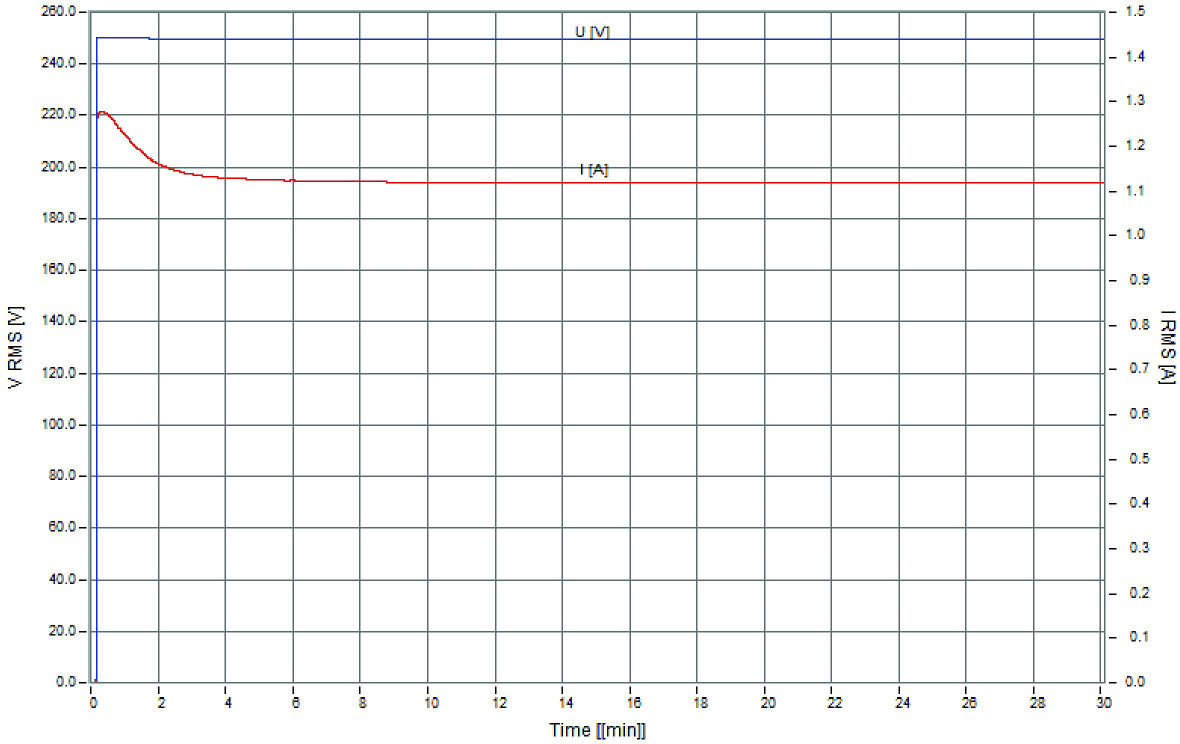


Figure 40. Root Mean Square of voltage and current - 250 V

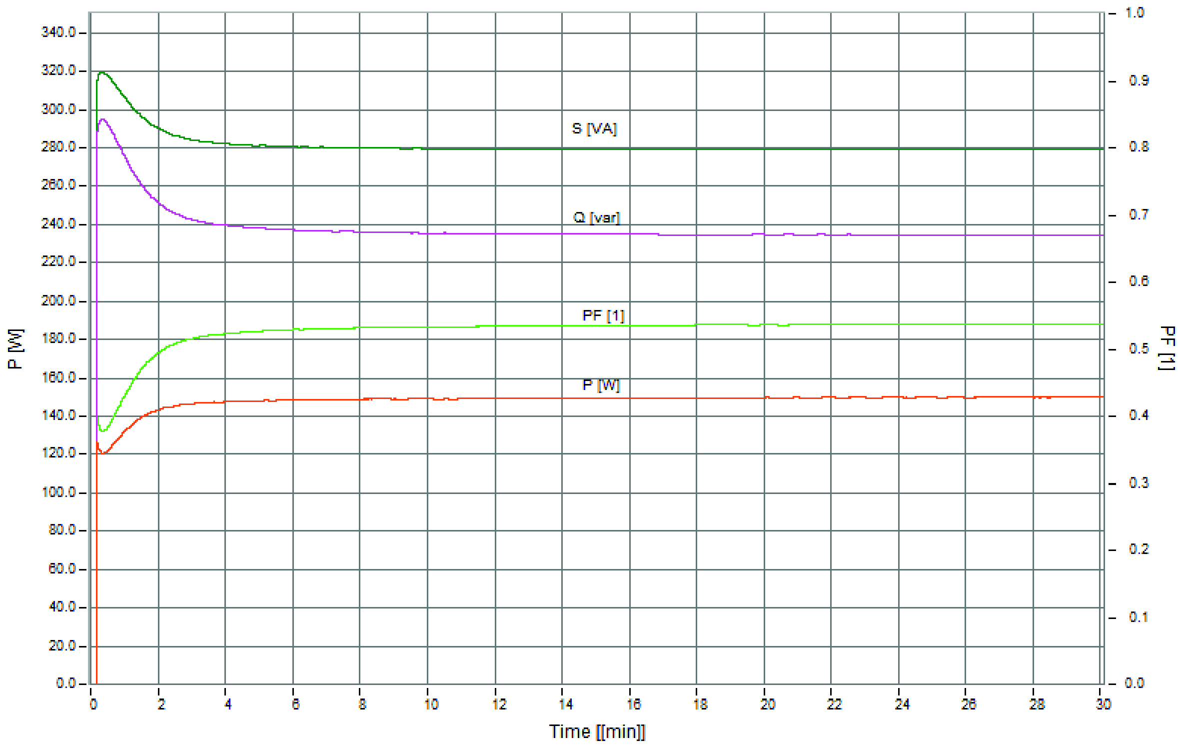


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 249.56	[V]	*****	0,00^0
I L1 = 1.11	[A]	*****	57.37^0

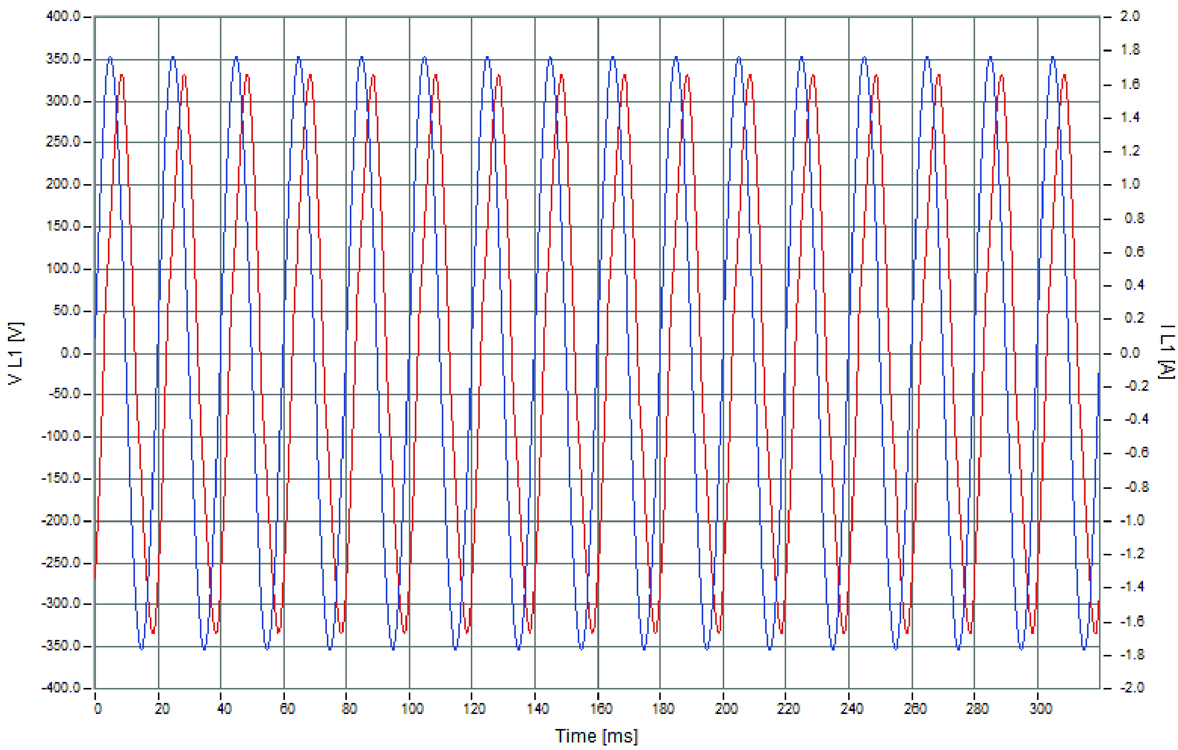


Figure 42. Current and voltage signal curve - 250 V

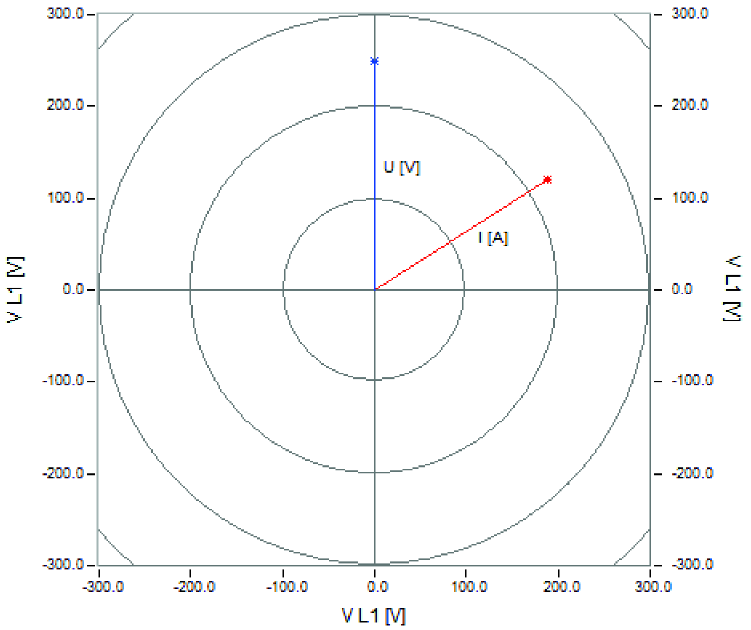


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

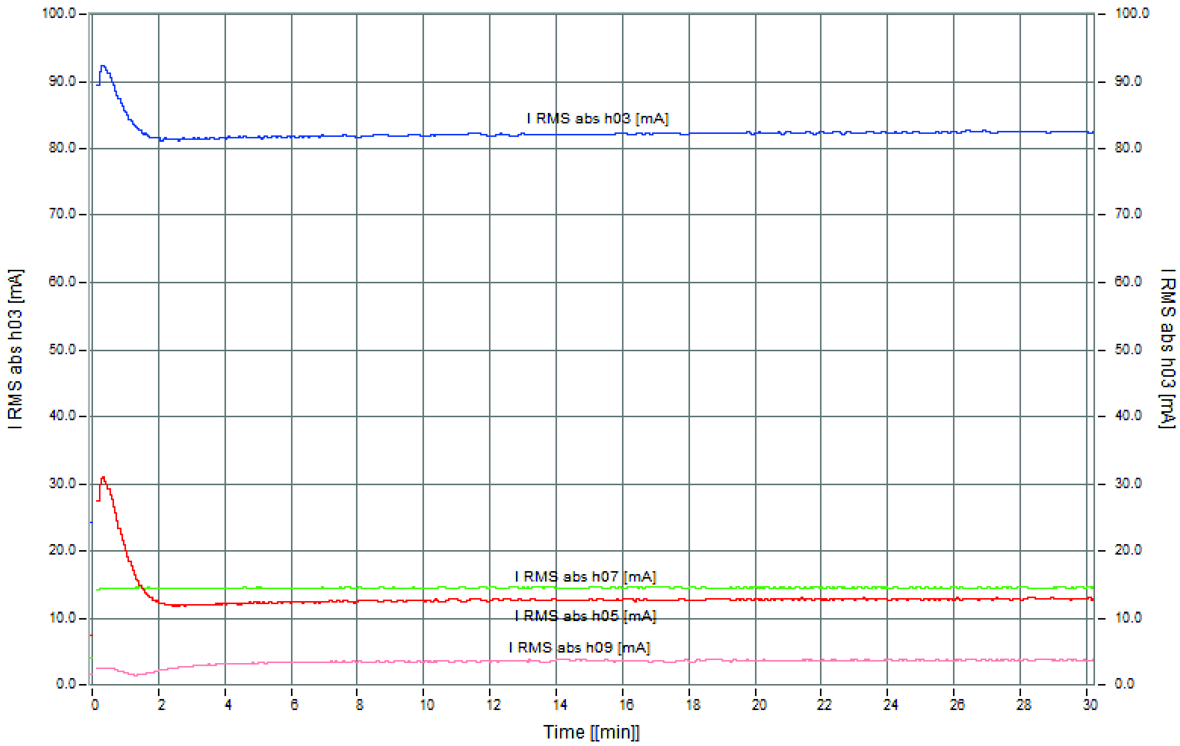


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

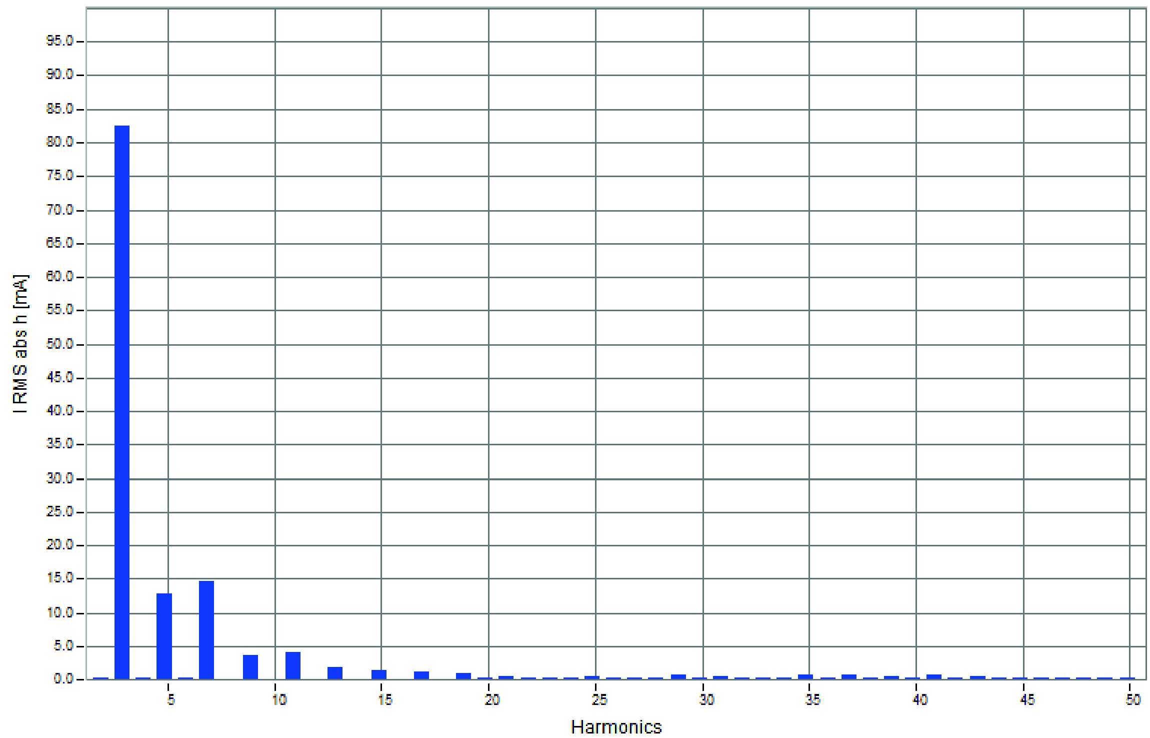


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 7.61\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 7.59\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 7.61%, for the maximum voltage, 1.09 p.u.. The minimum THD, 5.93%, is measured for the minimum voltage 0.82 p.u.. Further increase of the voltage causes a slight increase of the THD.

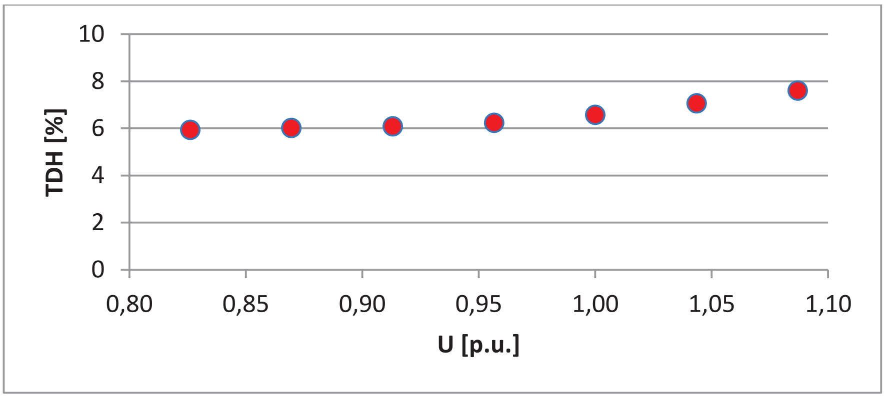
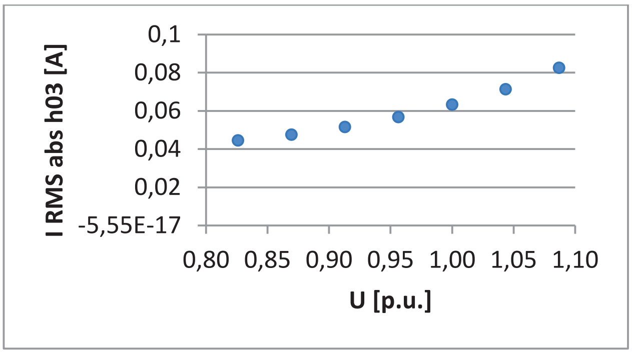
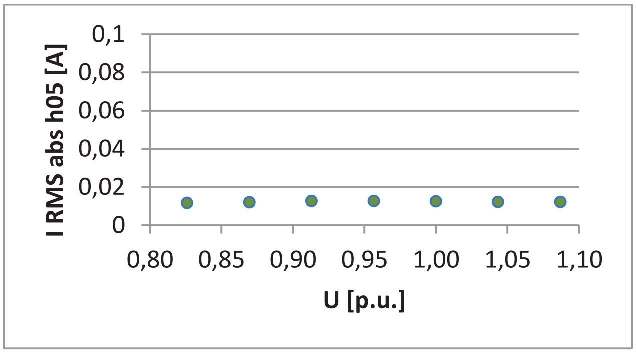


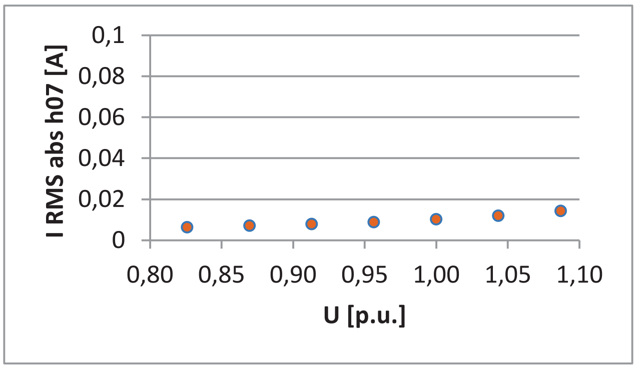
Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature



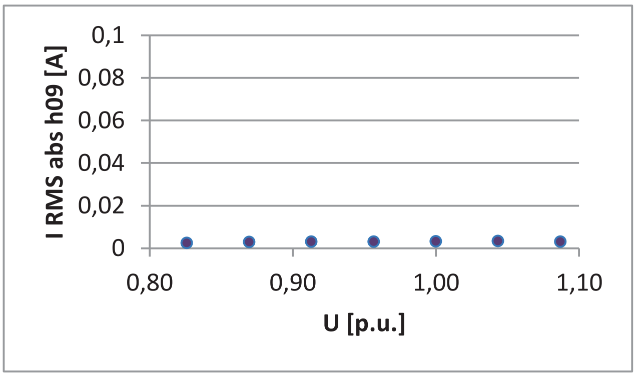
a)



b)



c)



d)

Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which increases with the voltage increase. Figures 47. b) and d) shows the 5th and the 9th harmonic respectively, which have exponential falling behaviour . In both cases the harmonic values are decreasing with the voltage increase. Figure 47. c) shows 7th harmonic which increases marginally with the voltage increase.

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Institut für Energiesysteme und Elektrische Antriebe
Gußhausstraße 25/370-1
A - 1040 Wien

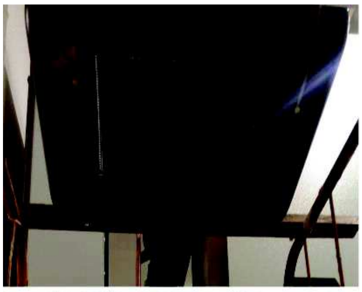
MEASUREMENT PROTOCOL 7

LEDWAY
5X20 LED light bar

Vienna 01.February 2016

1. Content

2. List of figures



3. Light type

LEDs
5X 20 light Source
Status: new

4. Technical data

LEDWAY 20 LED light bar
Voltage: 120-277 V
Real power : 110 W
Frequency : 50-60 Hz

5. Measurement

5.1. Schema

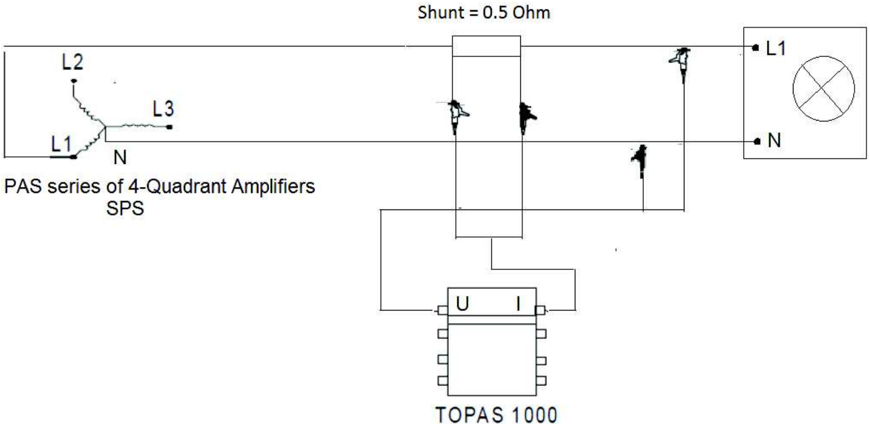


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside
Voltage range: 190-250 V
Measurement interval: 15 min

Temperature: 23.1^{0}C
Shunt: 0.5 Ω

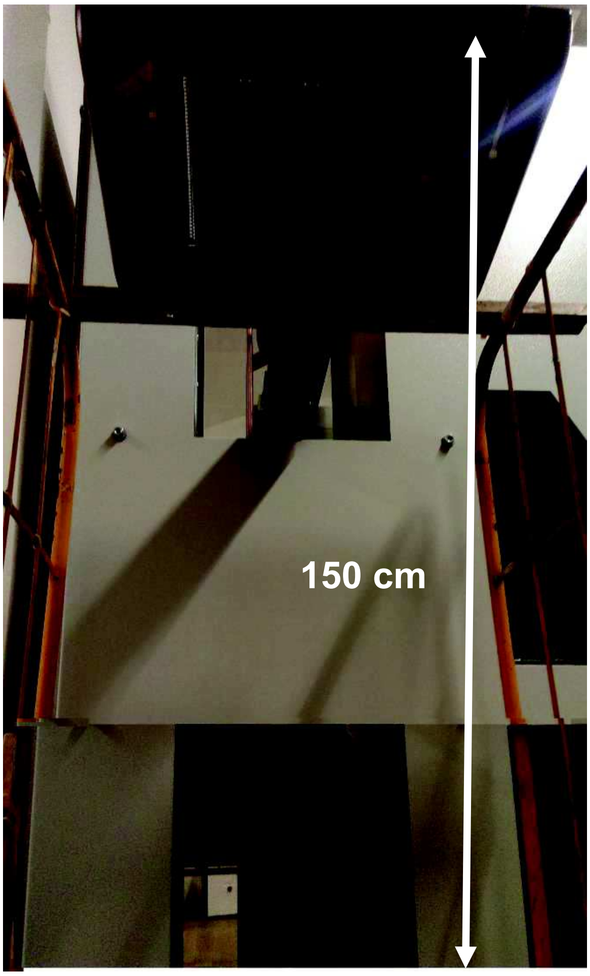


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 229.80 V
Current: I = 0.77 A
Active Power = 102.62 W
Reactive Power = 146.32 var
Apparent Power = 178.92 VA
Power Factor = 0.57

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

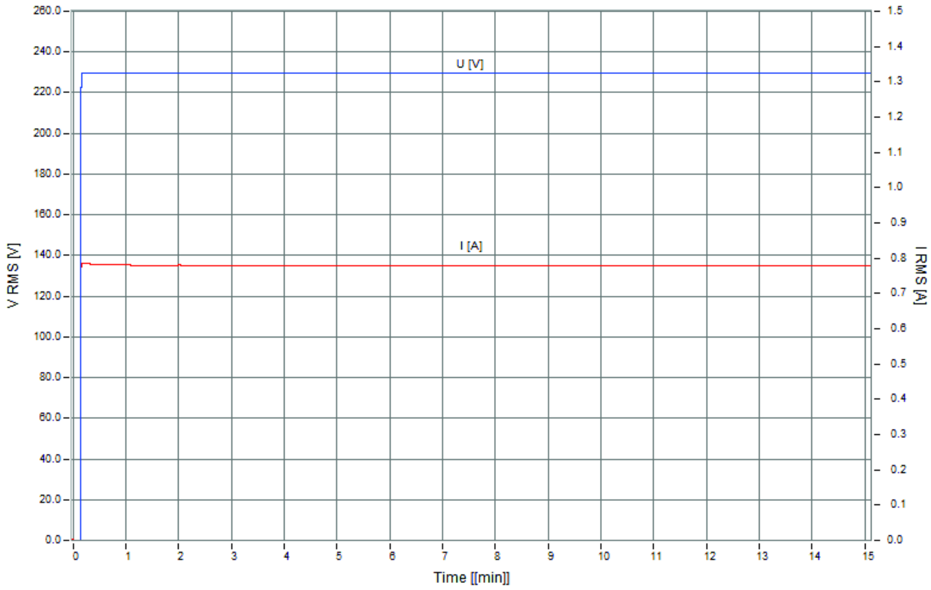


Figure 3. Root Mean Square of voltage and current - 230 V

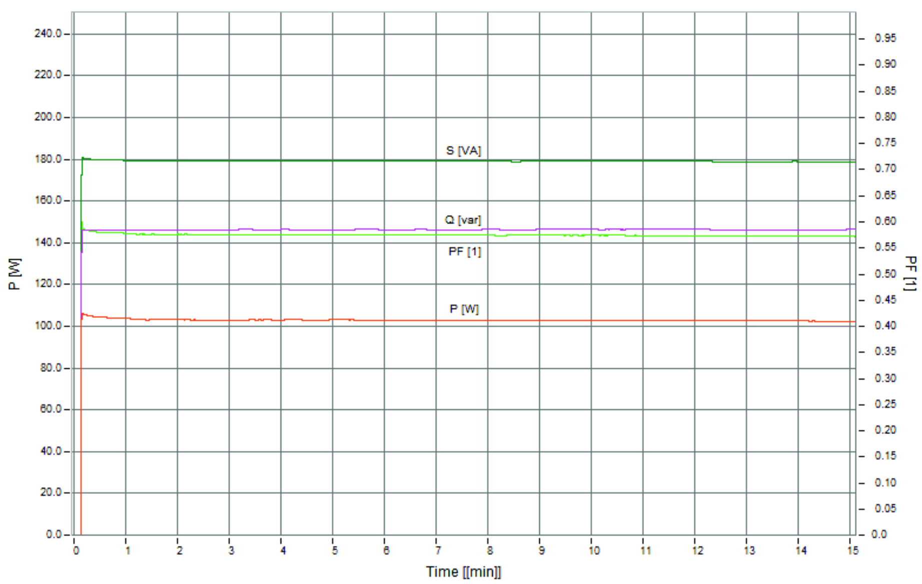


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 229.80	[V]	*****	0.00^0
I L1 = 0.77	[A]	*****	54.98^0

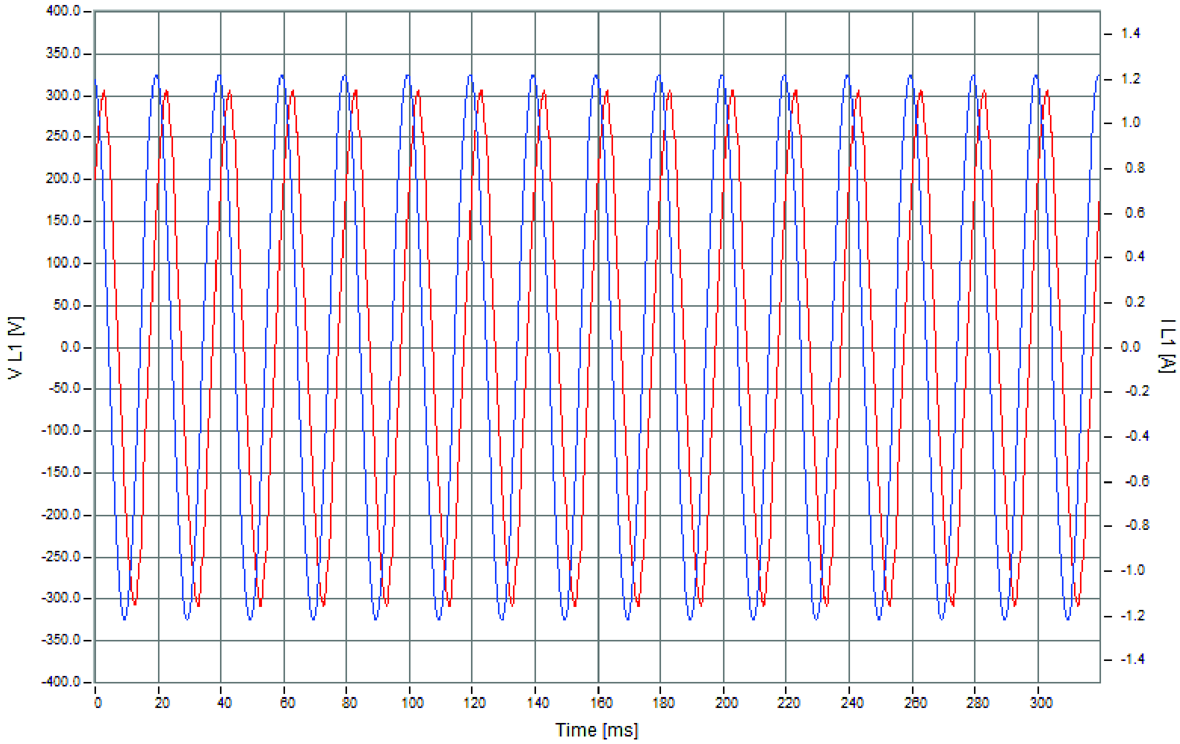


Figure 5. Current and voltage signal curve - 230 V

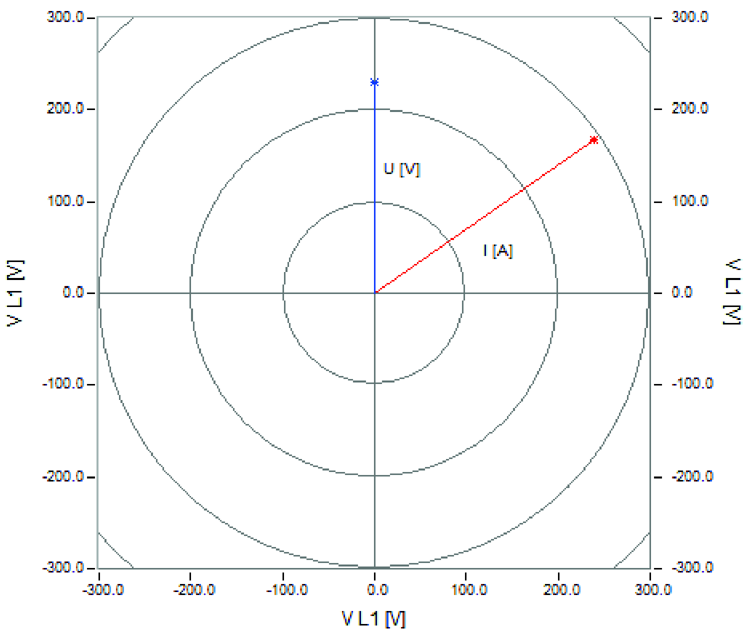


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

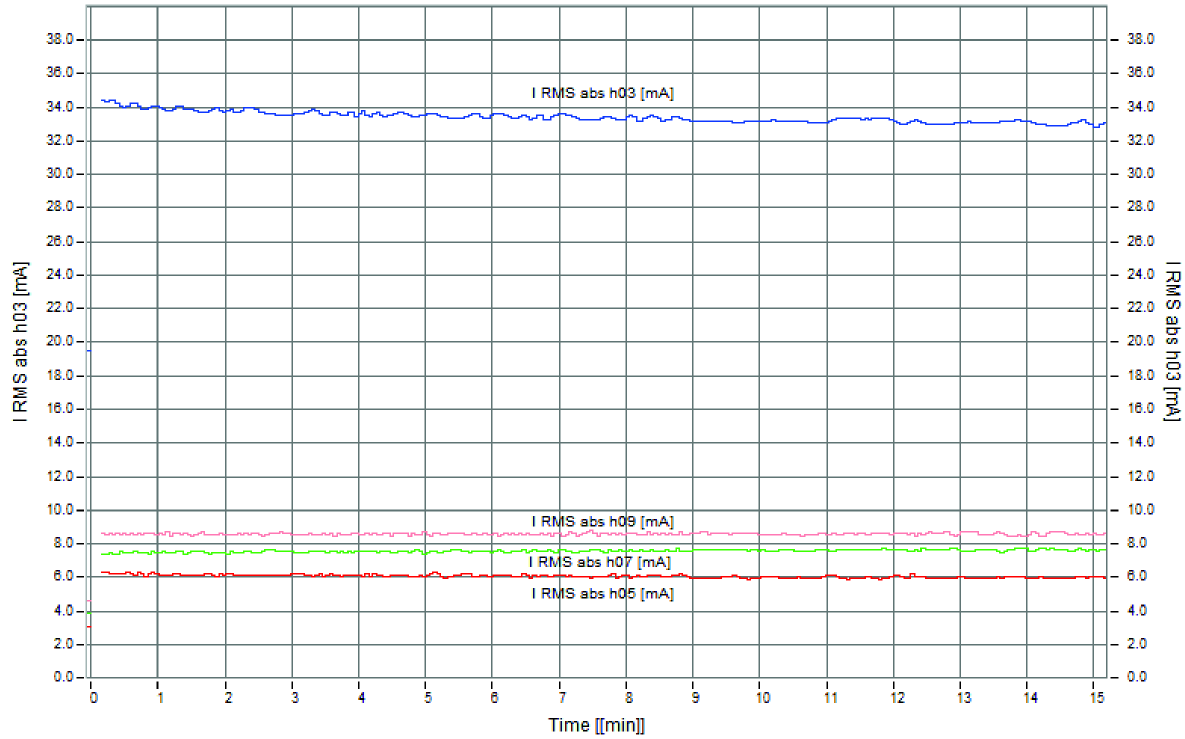


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

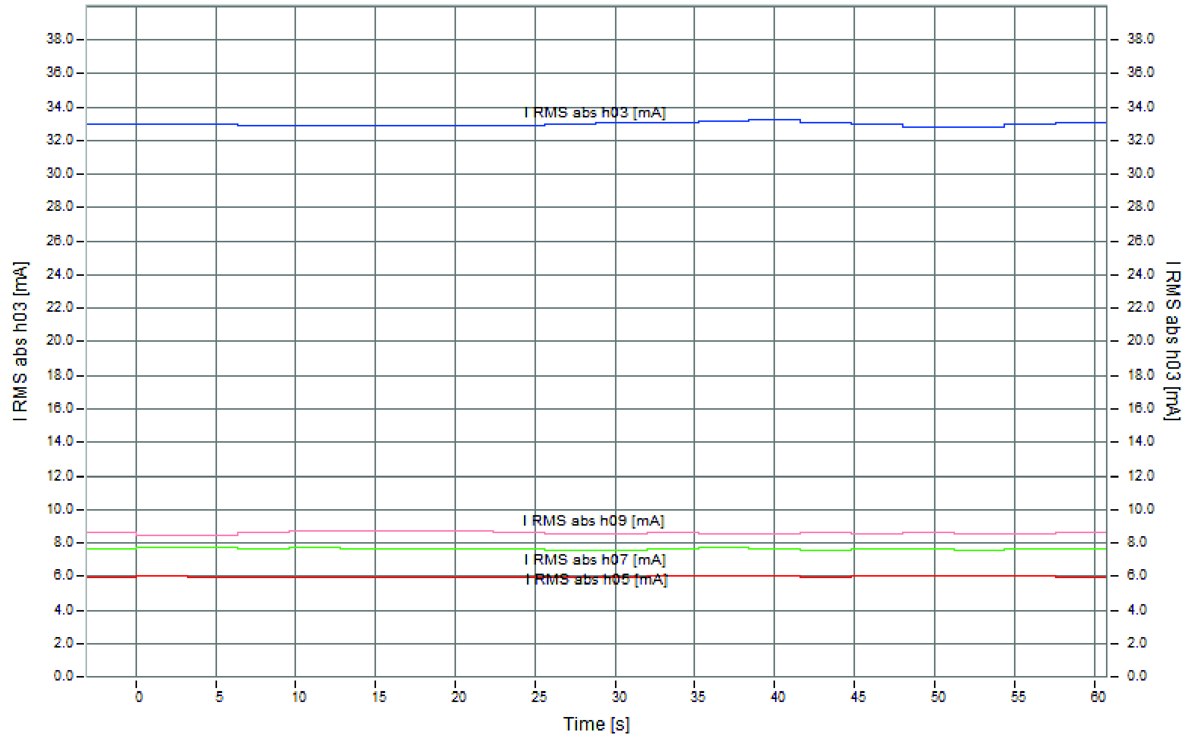


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

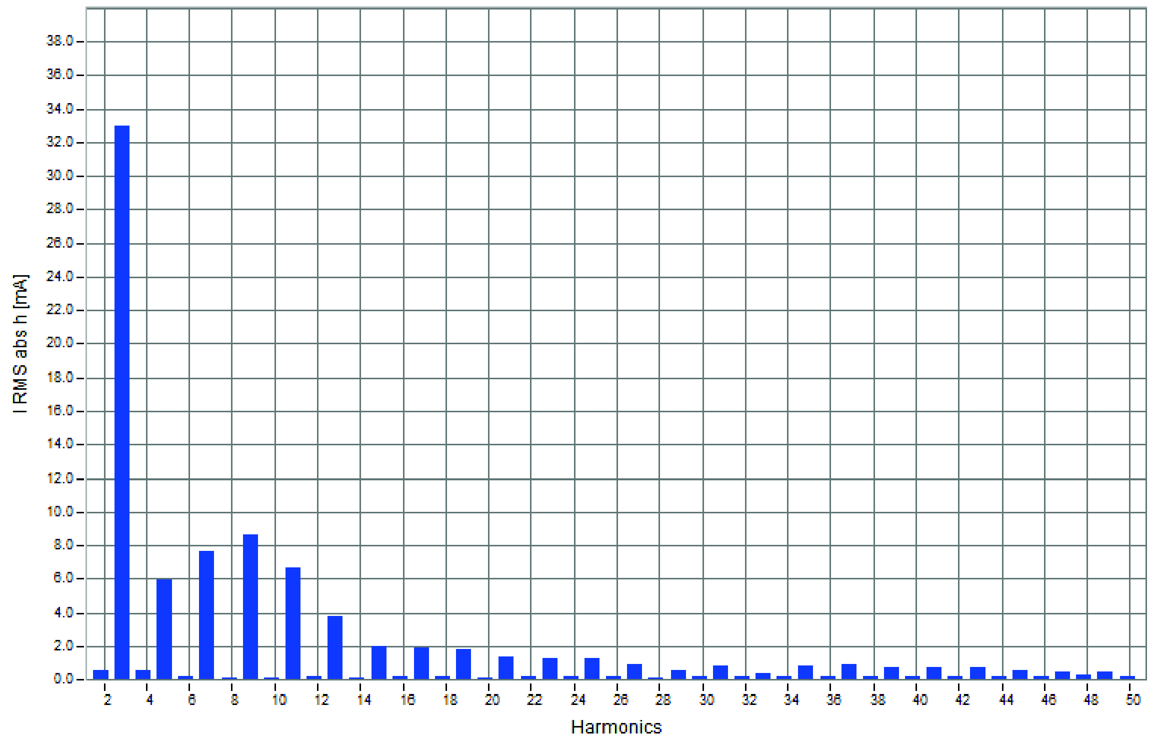


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.7\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.69\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 189.53 V
Current: I = 0.71 A
Active Power = 90.60 W
Reactive Power = 99.93 var
Apparent Power = 135.14 VA
Power Factor = 0.67

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

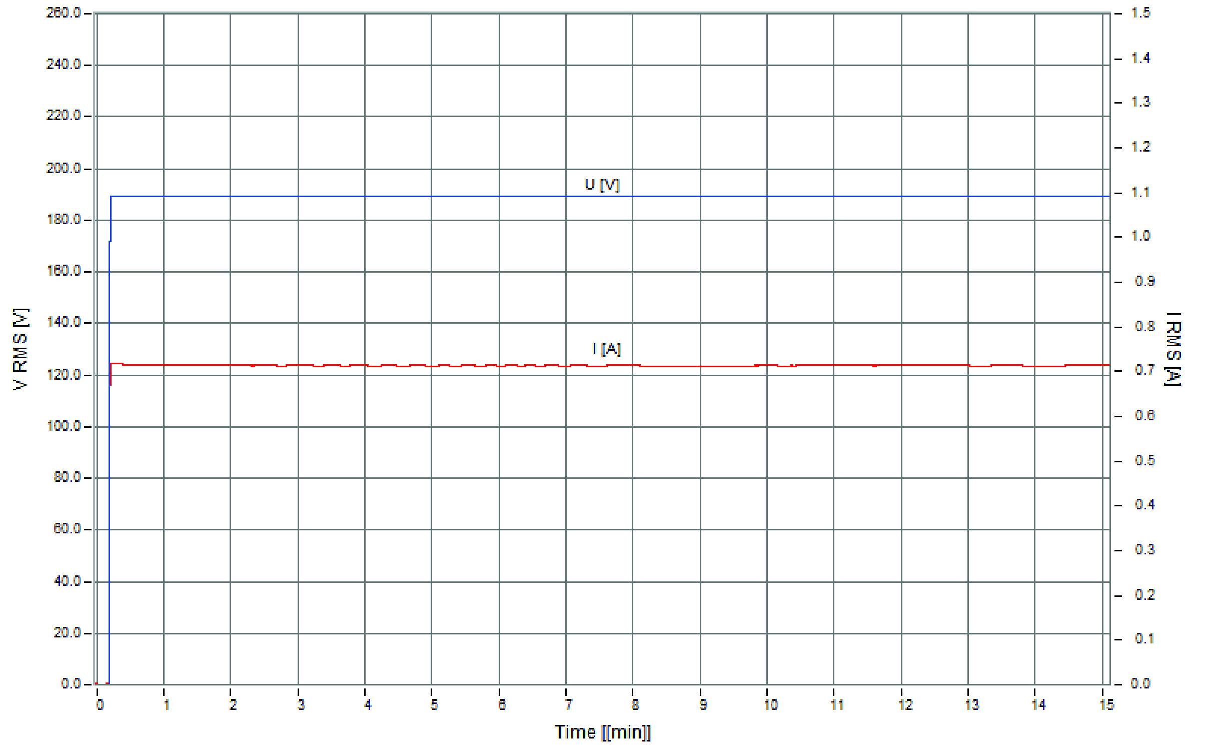


Figure 10. Root Mean Square of voltage and current - 190 V

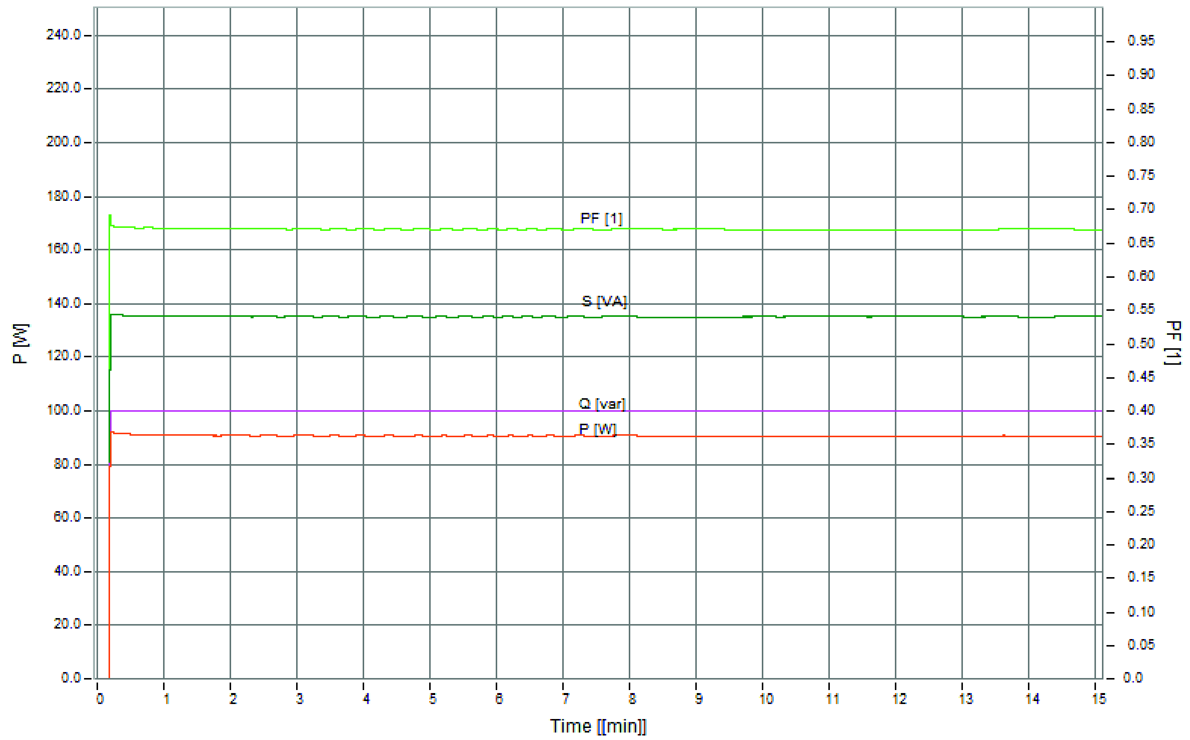


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 189.53	[V]	*****	0.00^0
I L1 = 0.71	[A]	*****	47.68^0

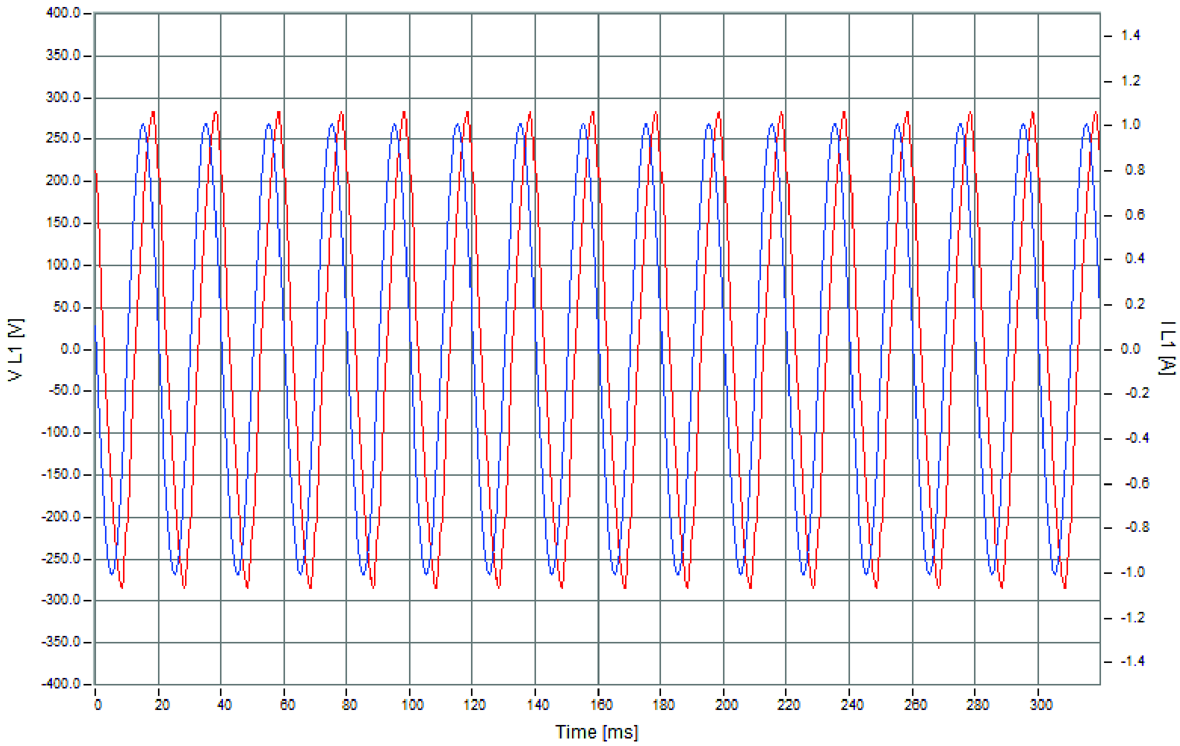


Figure 12. Current and voltage signal curve - 190 V

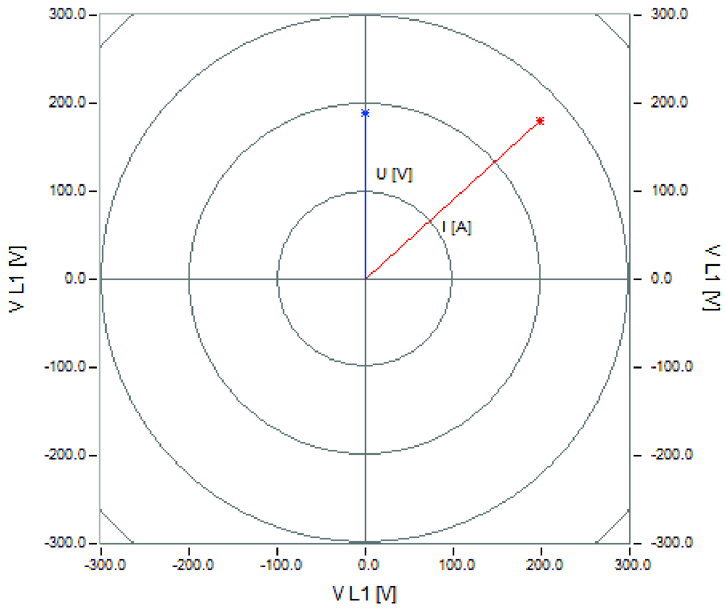


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

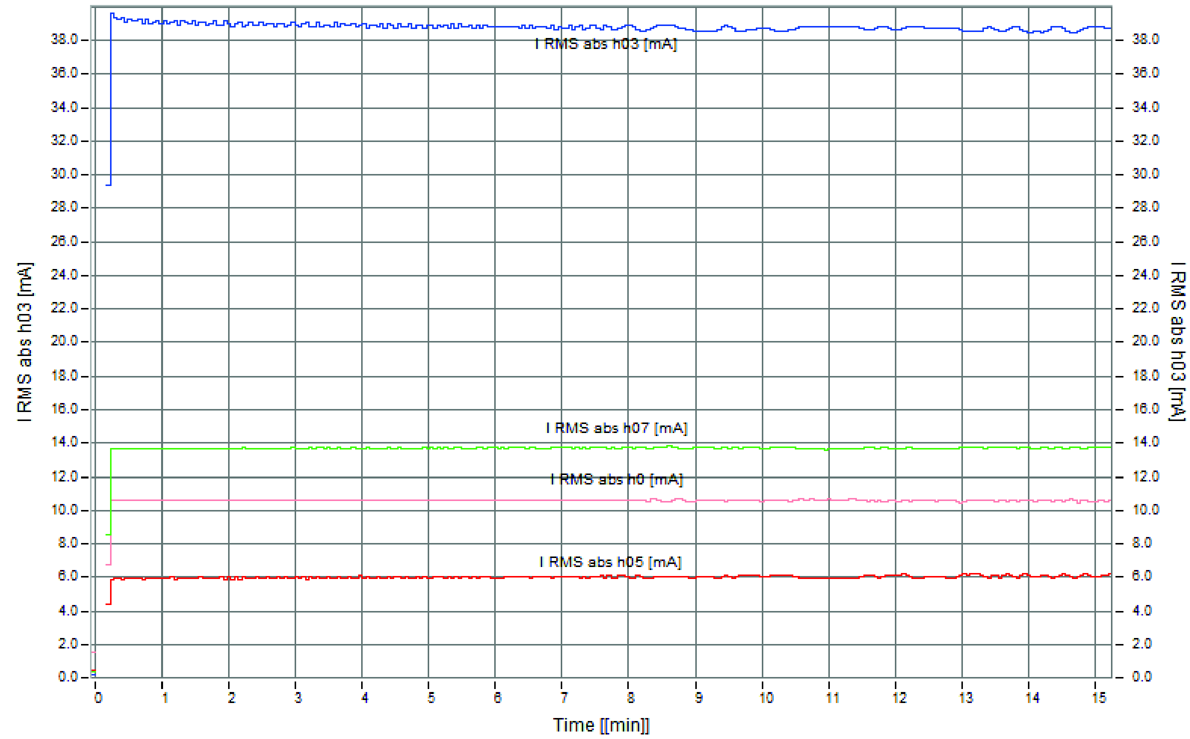


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

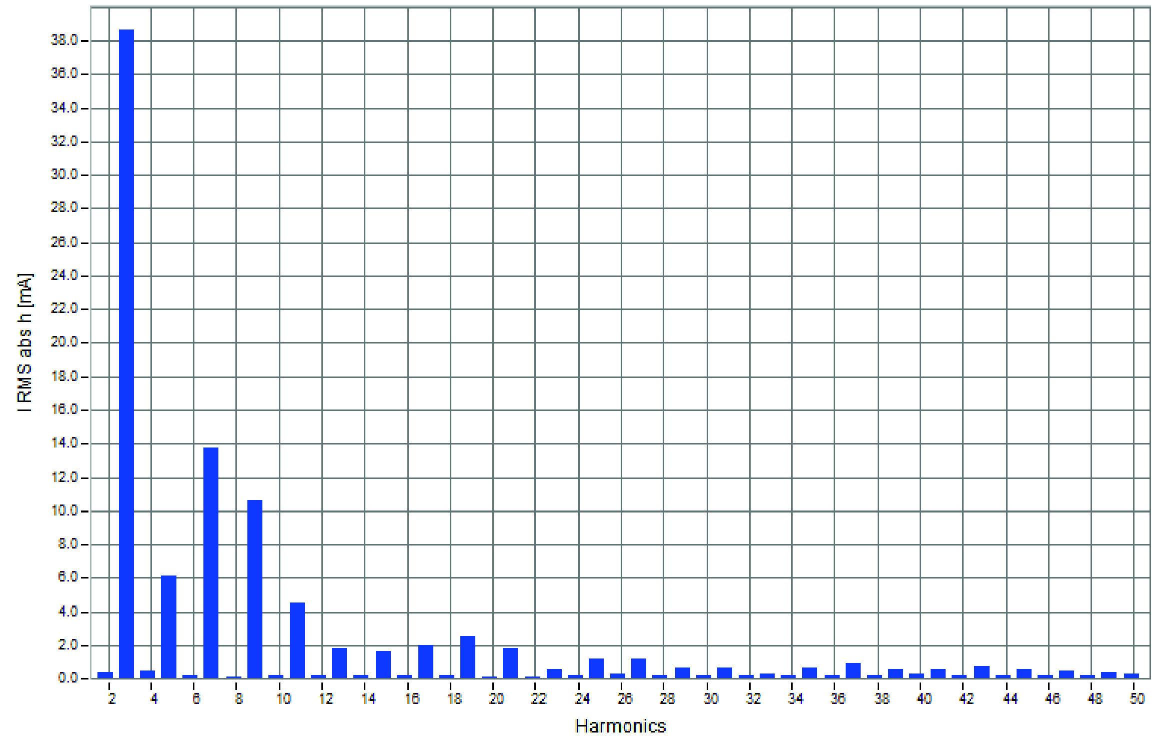


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 6.09\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 6.08\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 199.59 V
Current: I = 0.72 A
Active Power = 93.36 W
Reactive Power = 110.67 var
Apparent Power = 145.03
Power Factor = 0.64

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

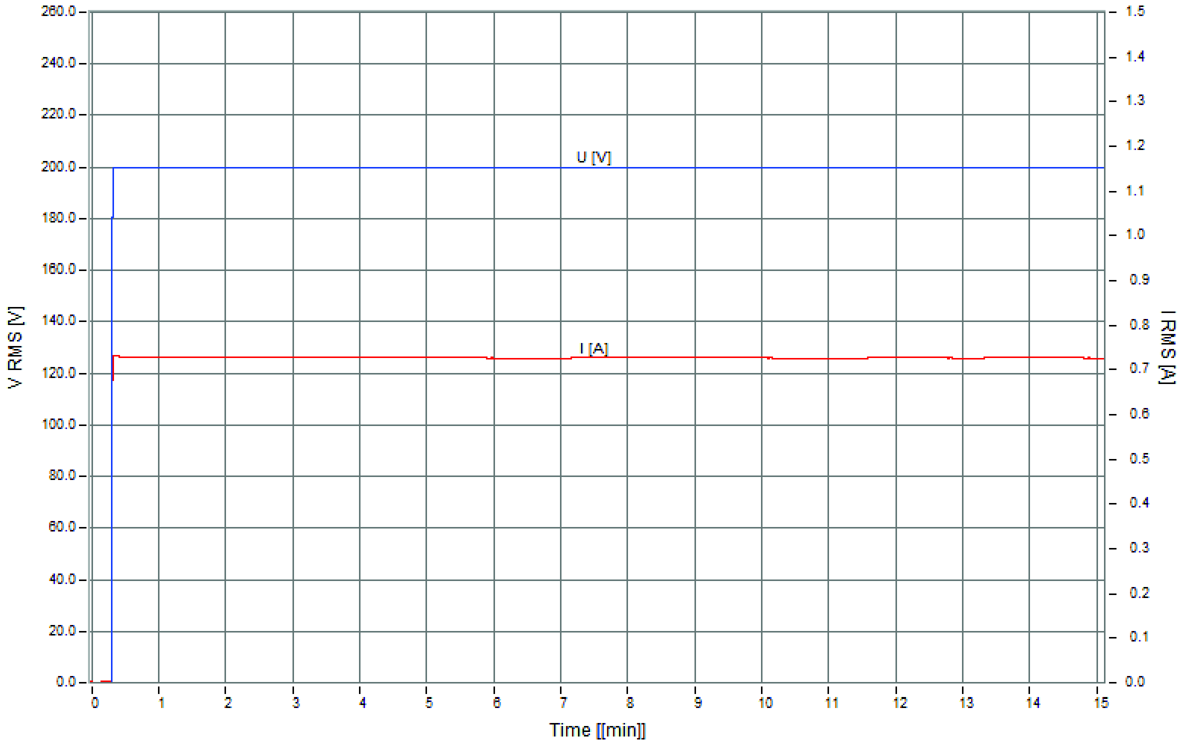


Figure 16. Root Mean Square of voltage and current - 200 V

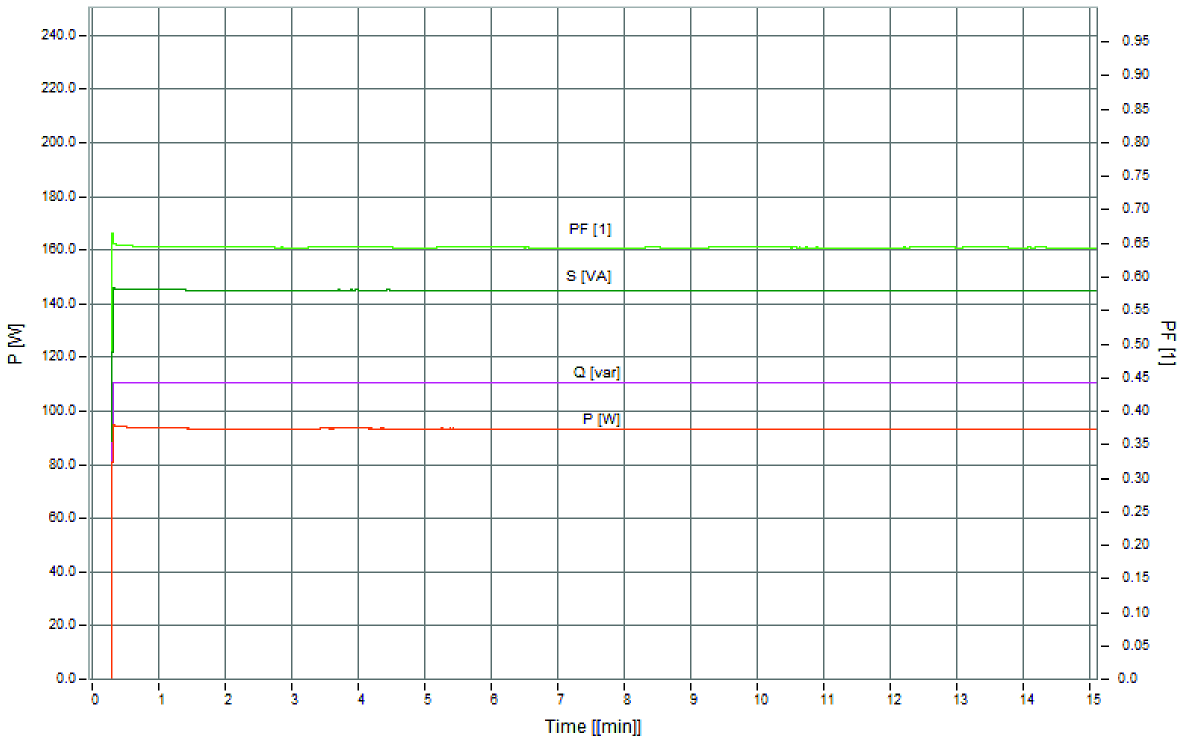


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 199.59	[V]	*****	0.00⁰
I L1 = 0.72	[A]	*****	49.83⁰

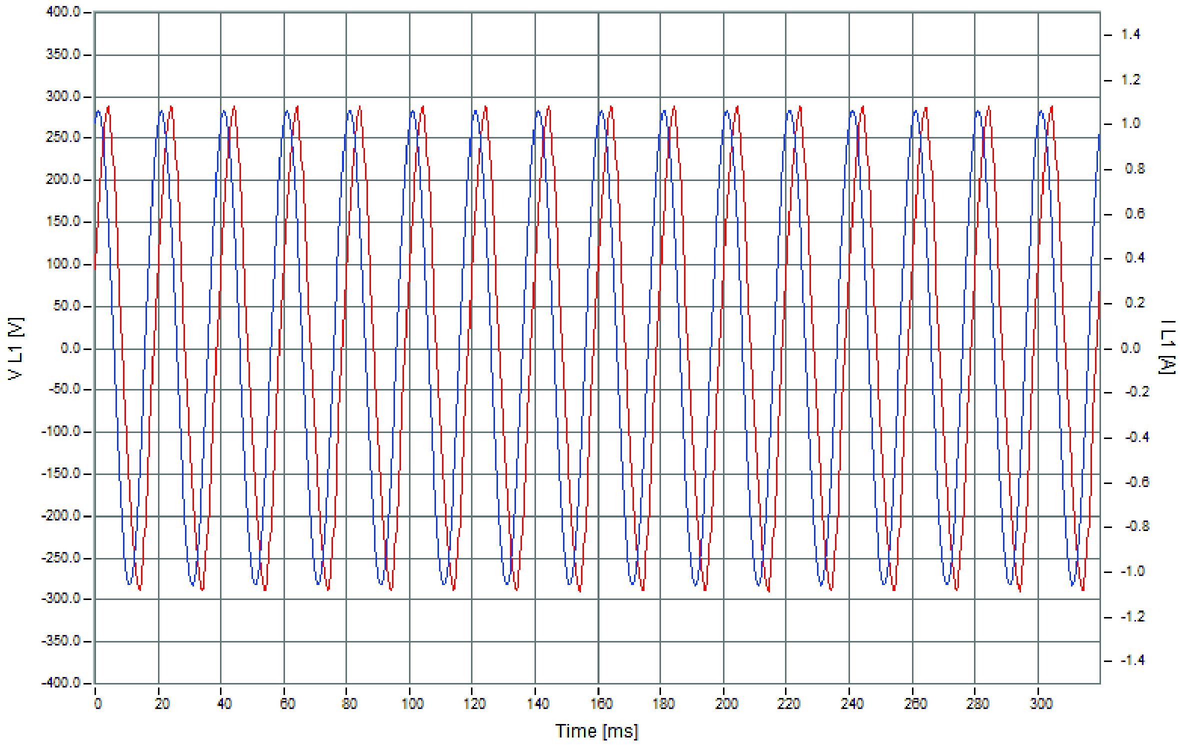


Figure 18. Current and voltage signal curve - 200 V

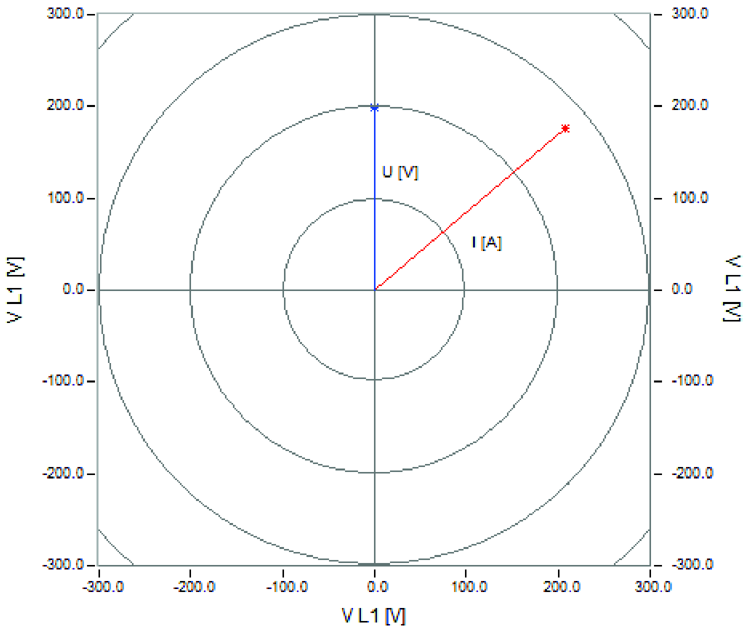


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

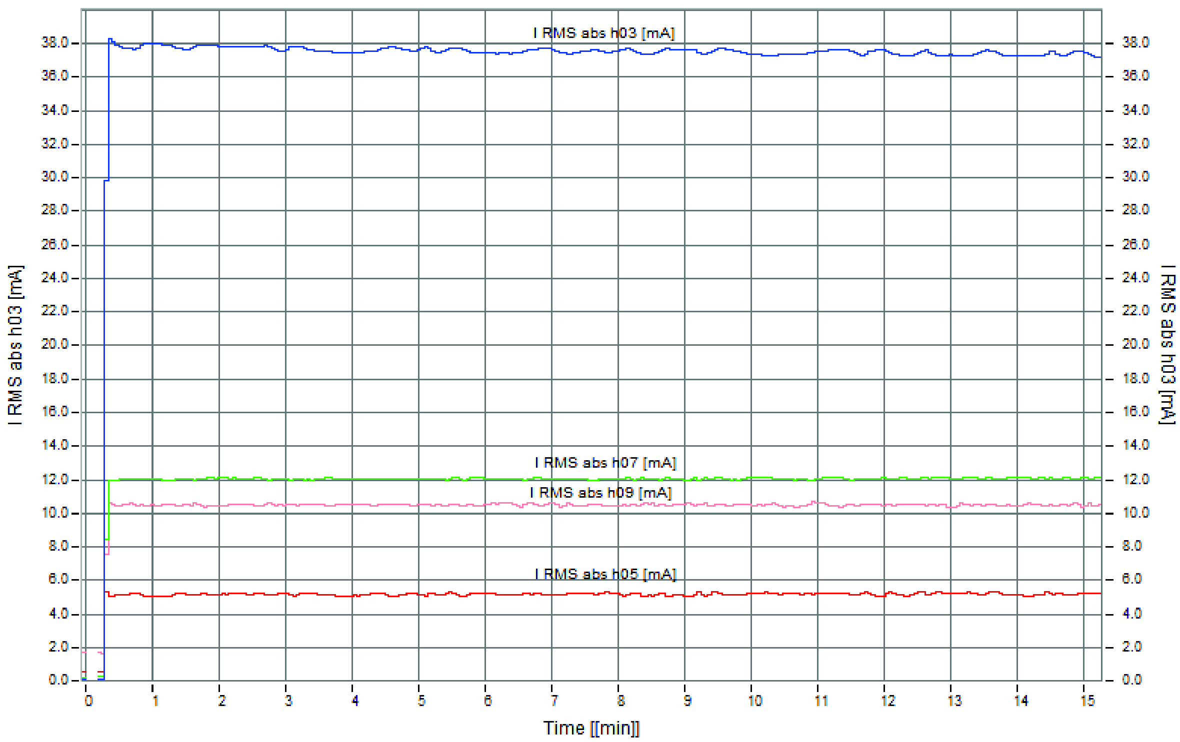


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

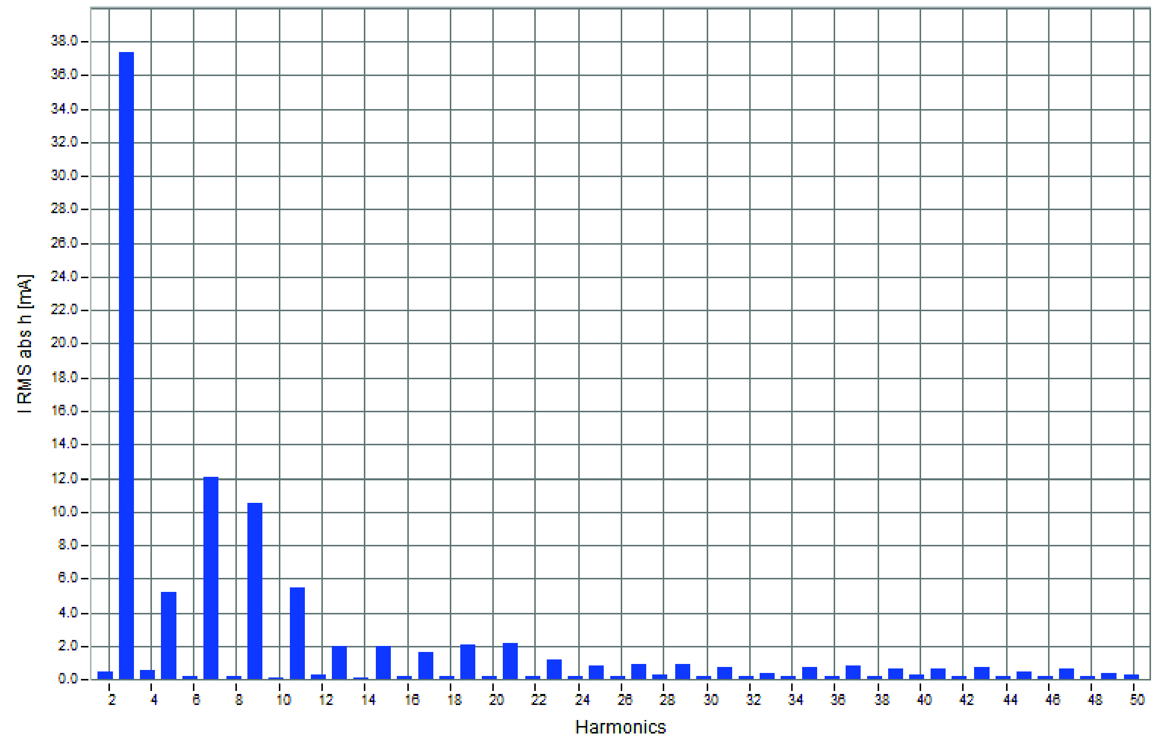


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 5.74\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 5.73\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:

Voltage: U = 209.64 V
Current: I = 0.74A
Active Power = 96.02 W
Reactive Power = 122.06 var
Apparent Power = 155.57 VA
Power Factor = 0.61

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

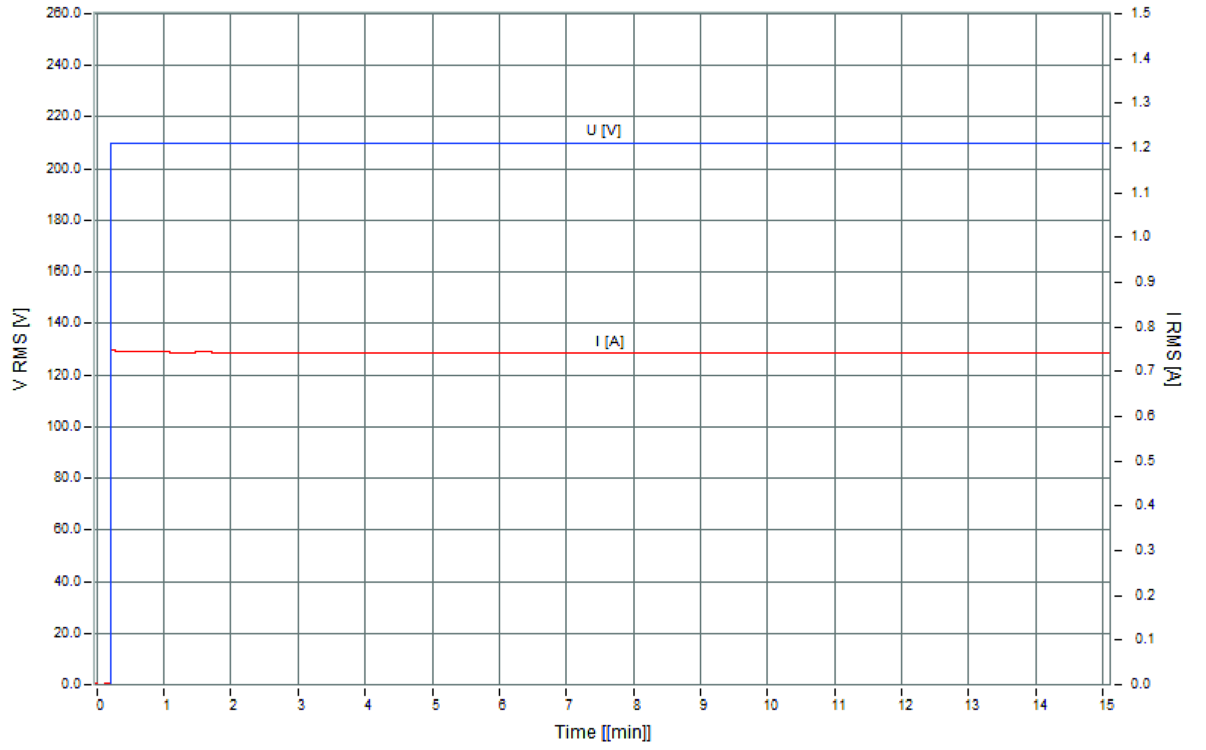


Figure 22. Root Mean Square of voltage and current - 210 V

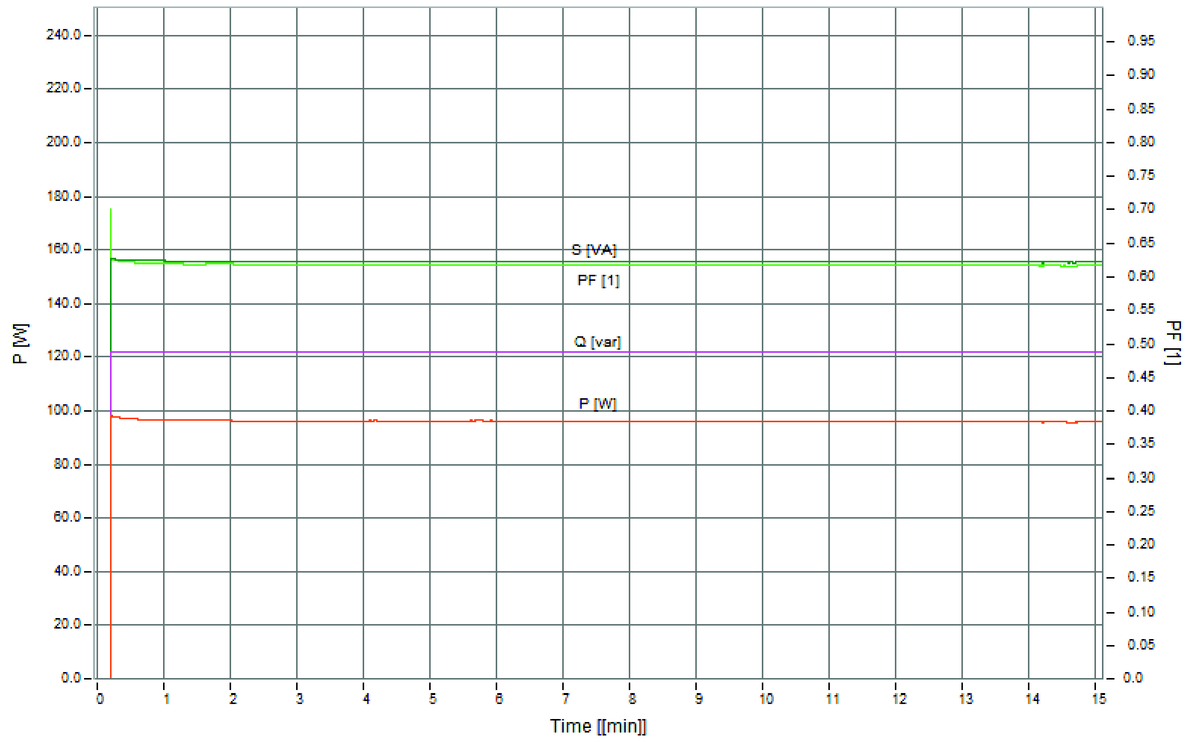


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 209.65	[V]	*****	0.00⁰
I L1 = 0.74	[A]	*****	51.74⁰

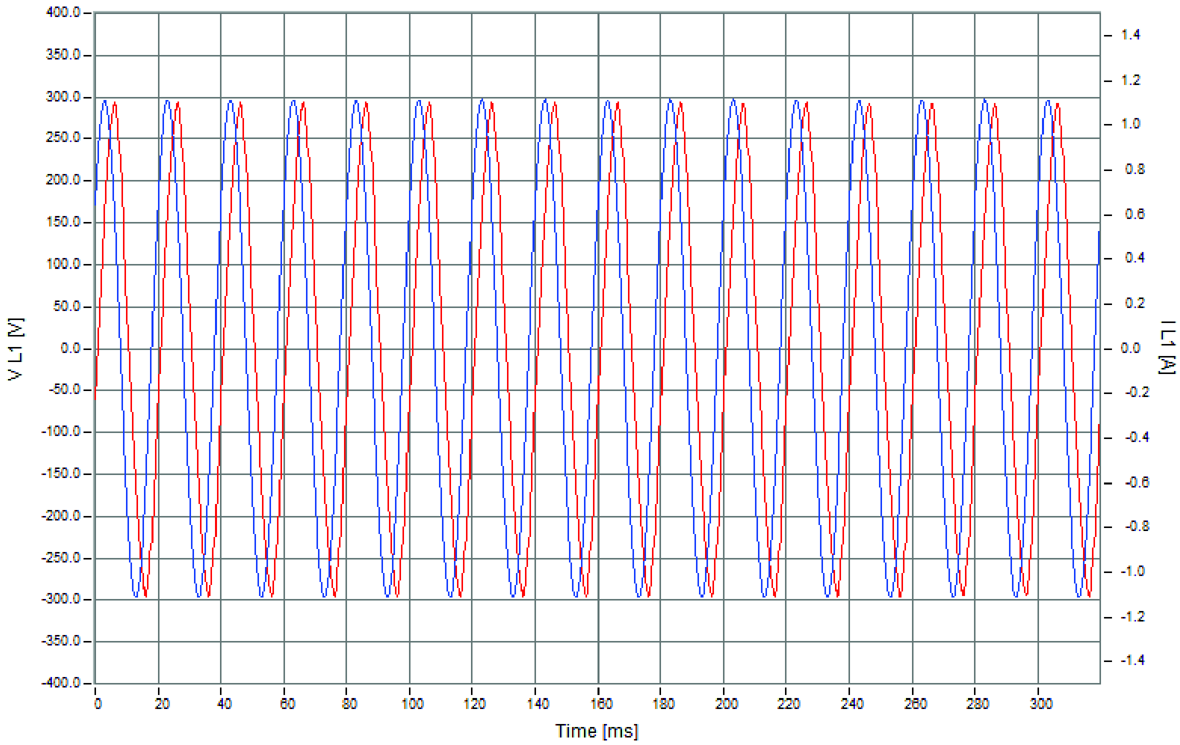


Figure 24. Current and voltage signal curve - 210 V

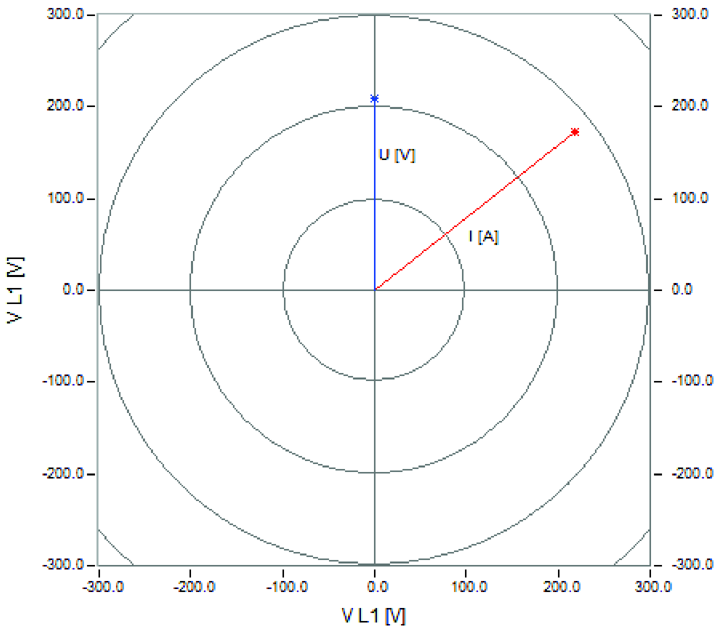


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

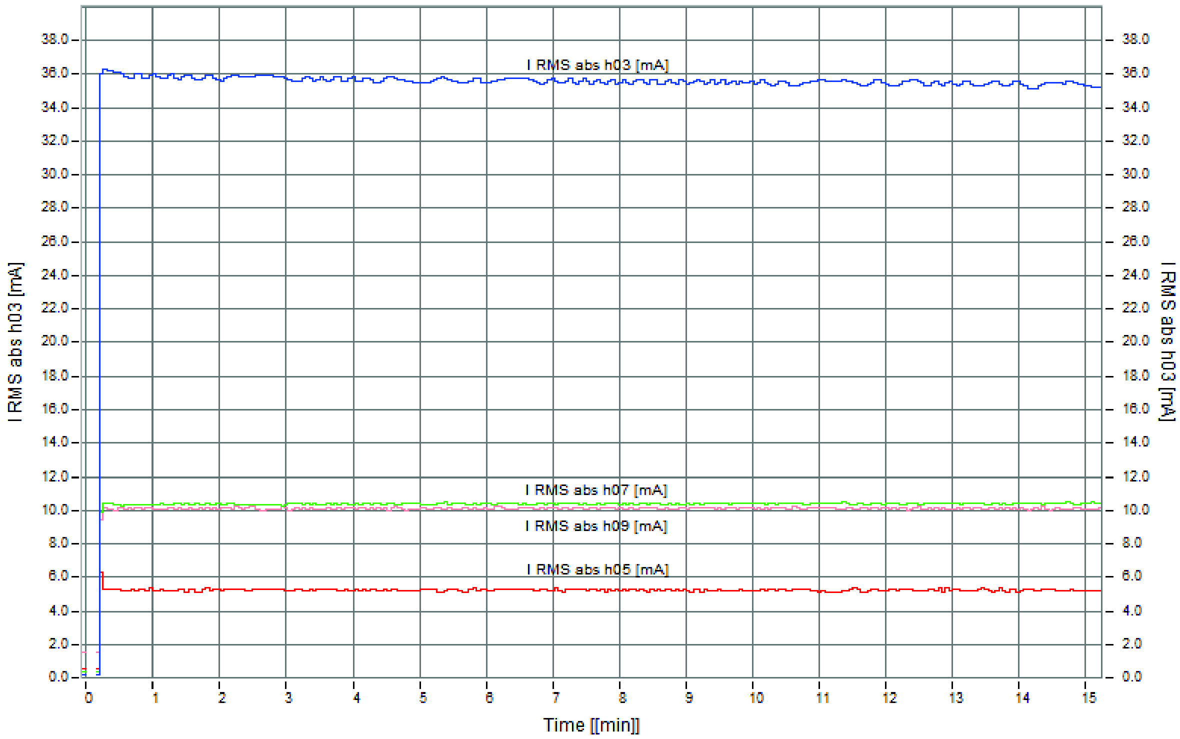


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

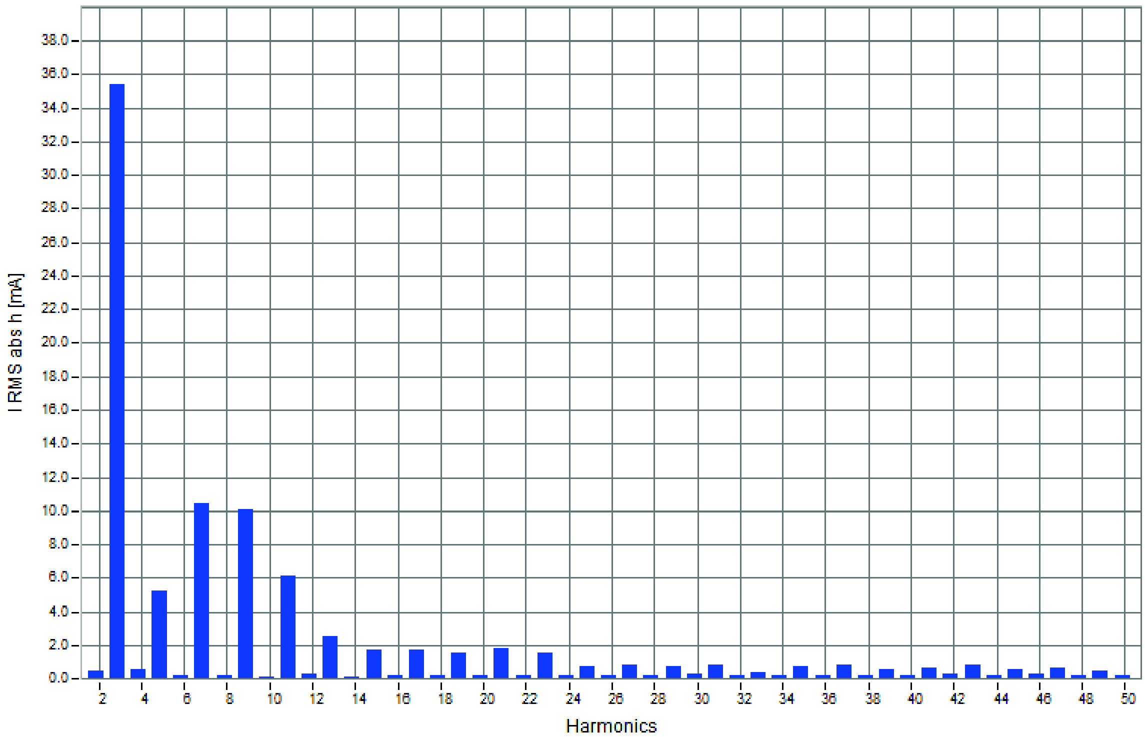


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 5.32\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 5.31\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 219.70 V

Current: I = 0.76 A

Active Power = 99.34 W

Reactive Power = 133.96 var

Apparent Power = 166.99 VA

Power Factor = 0.59

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

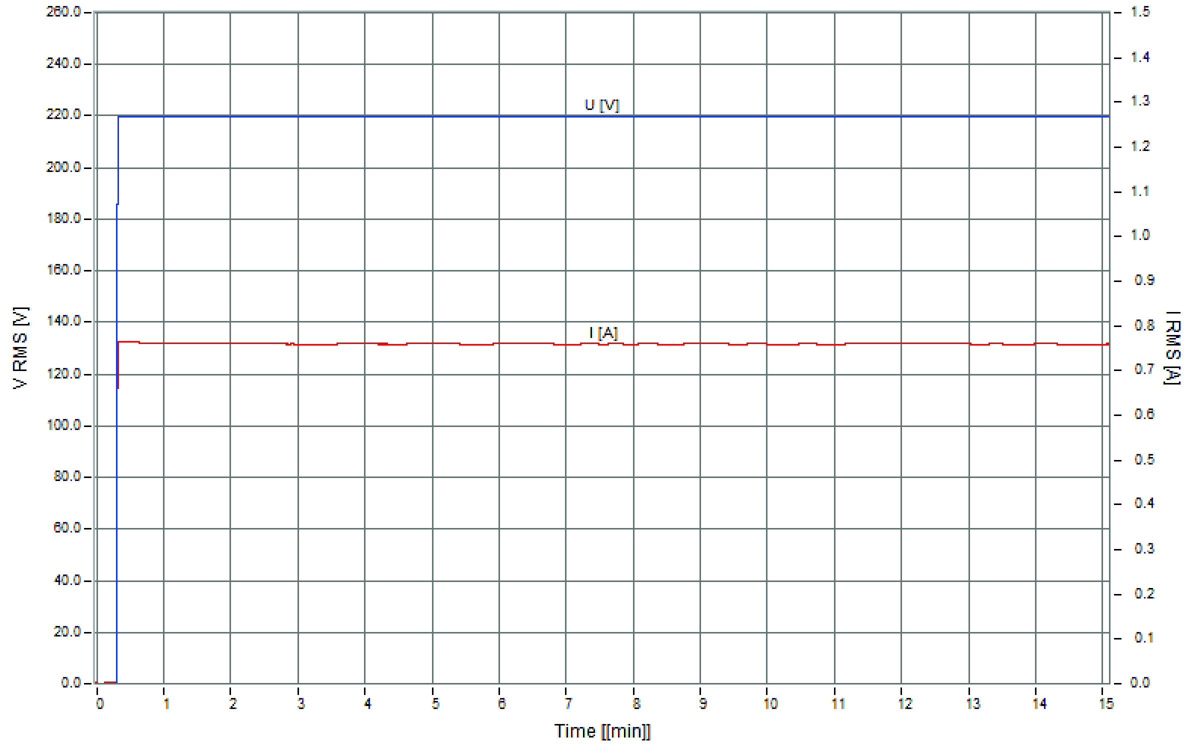


Figure 28. Root Mean Square of voltage and current - 220 V

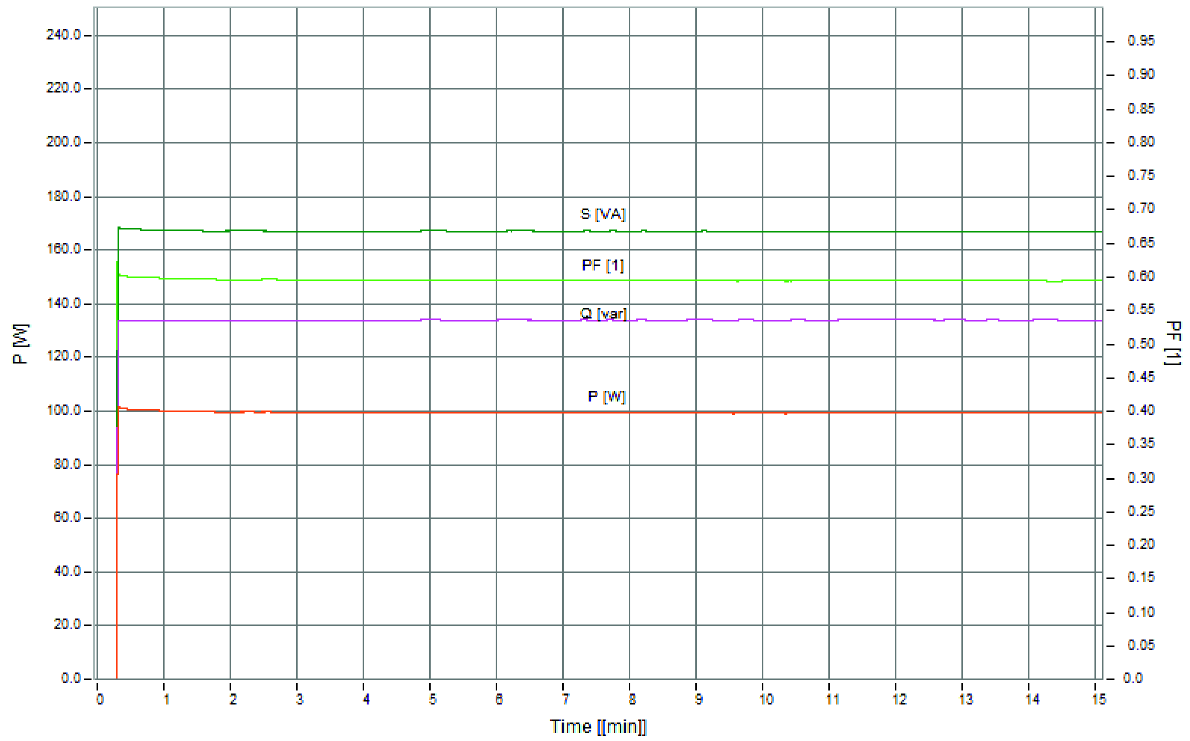


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 219.71	[V]	*****	0.00⁰
I L1 = 0.75	[A]	*****	53.35⁰

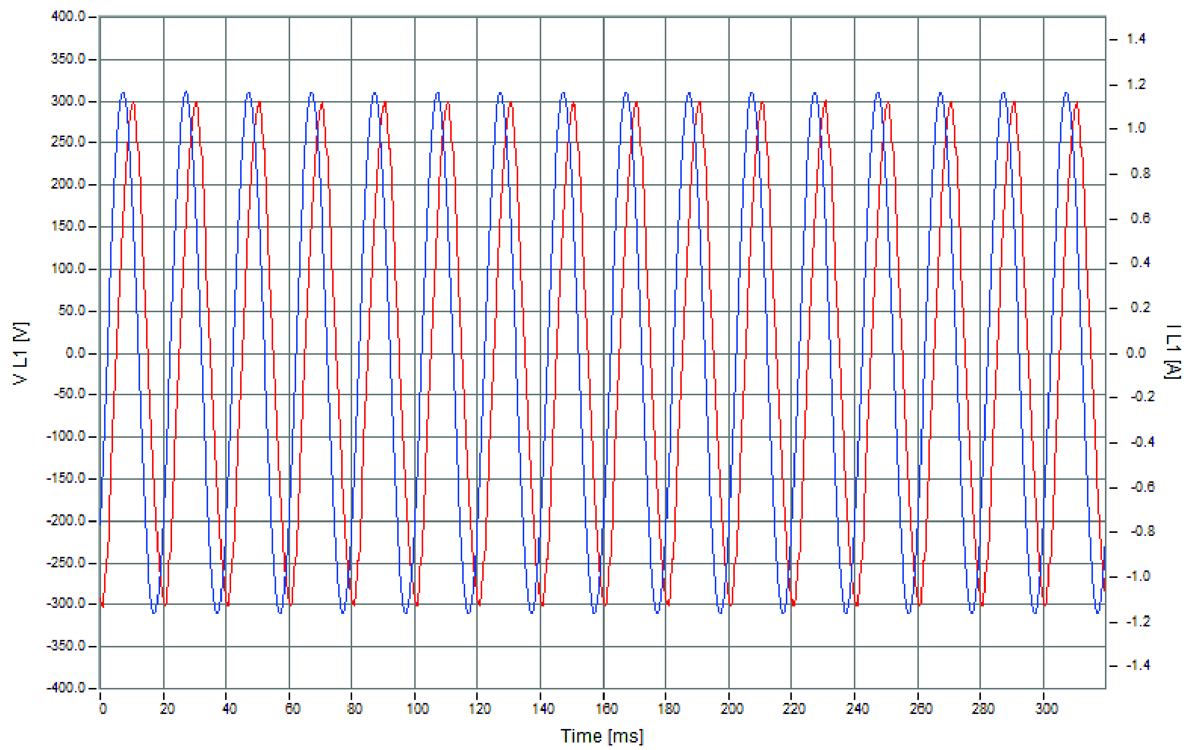


Figure 30. Current and voltage signal curve - 220 V

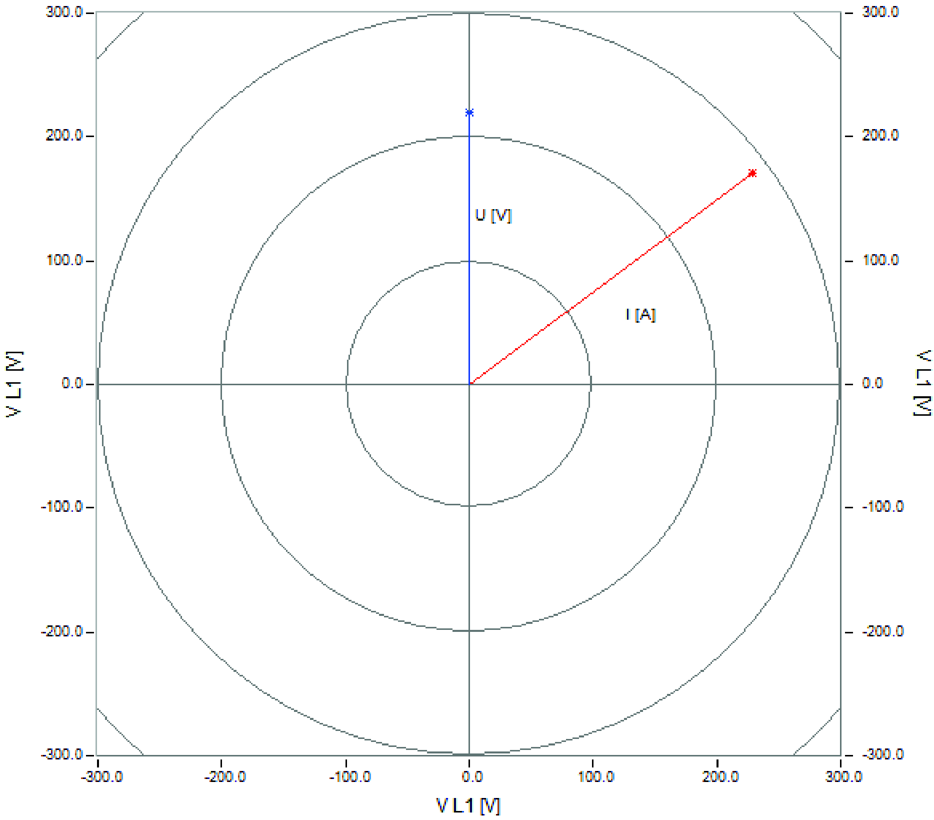


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

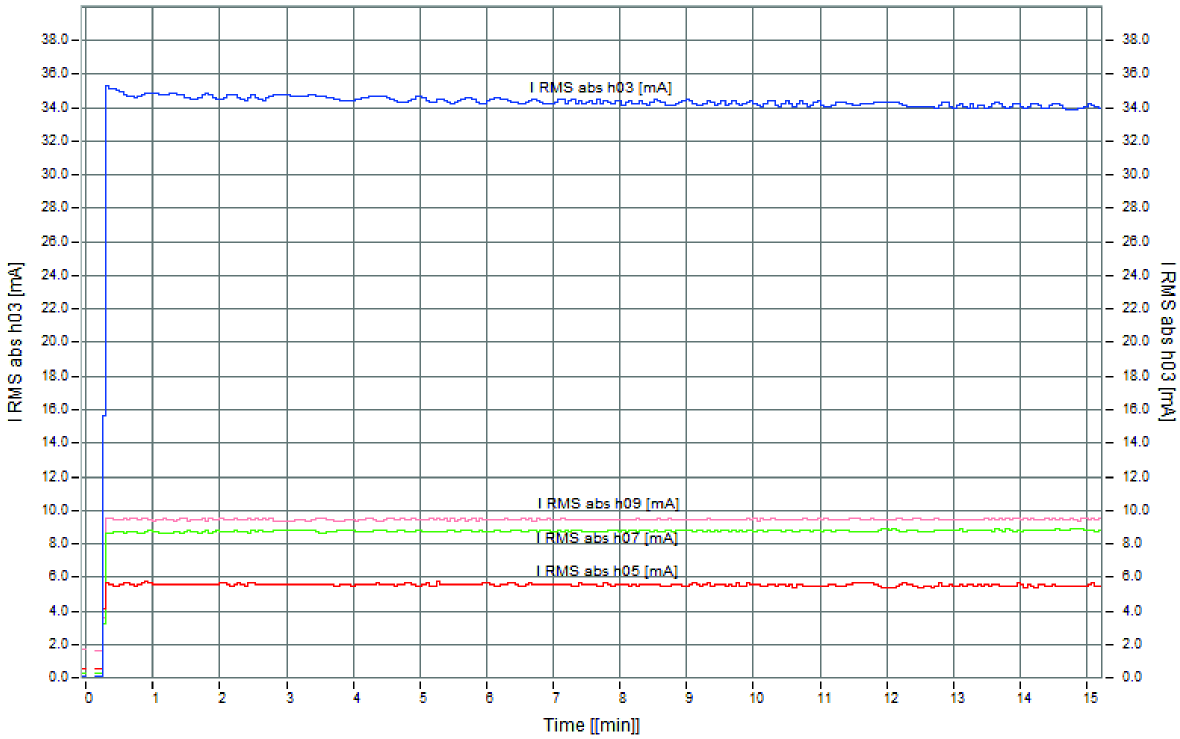


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

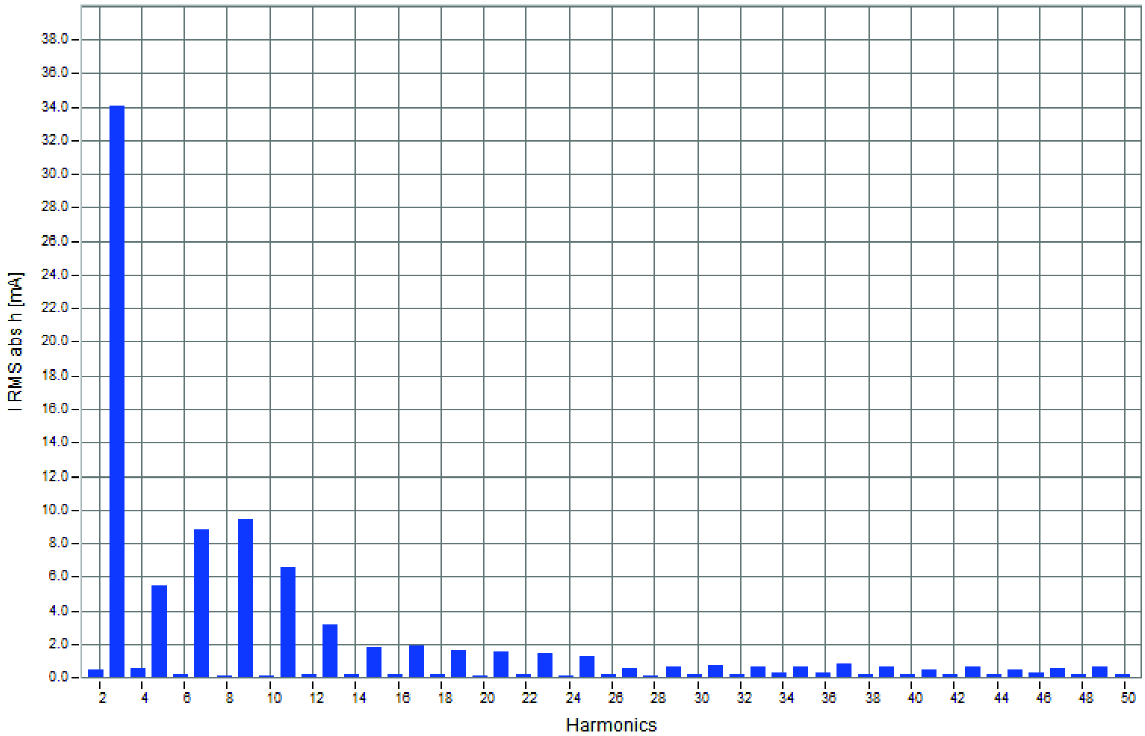


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.99\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.98\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 239.84 V
Current: I = 0.79 A
Active Power = 105.91 W
Reactive Power = 159.12 var
Apparent Power = 191.34 VA
Power Factor = 0.5

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

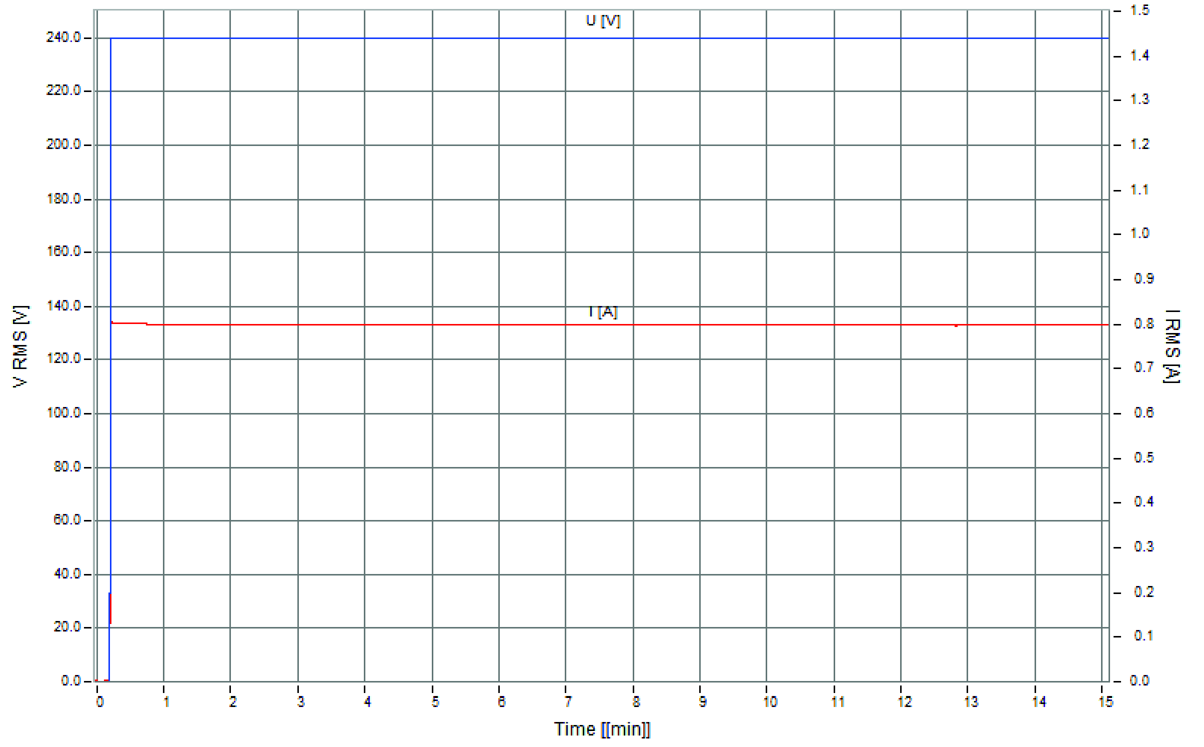


Figure 34. Root Mean Square of voltage and current - 240 V

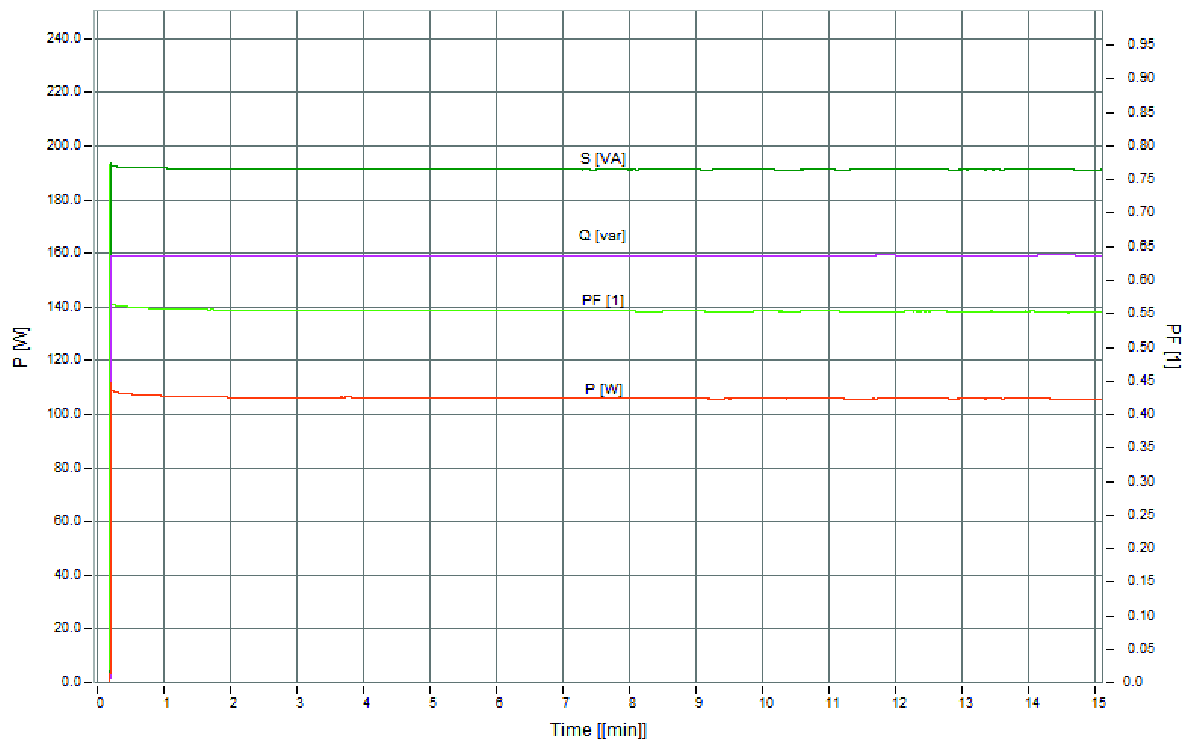


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 23.85	[V]	*****	0.00^0
I L1 = 0.79	[A]	*****	76.29^0

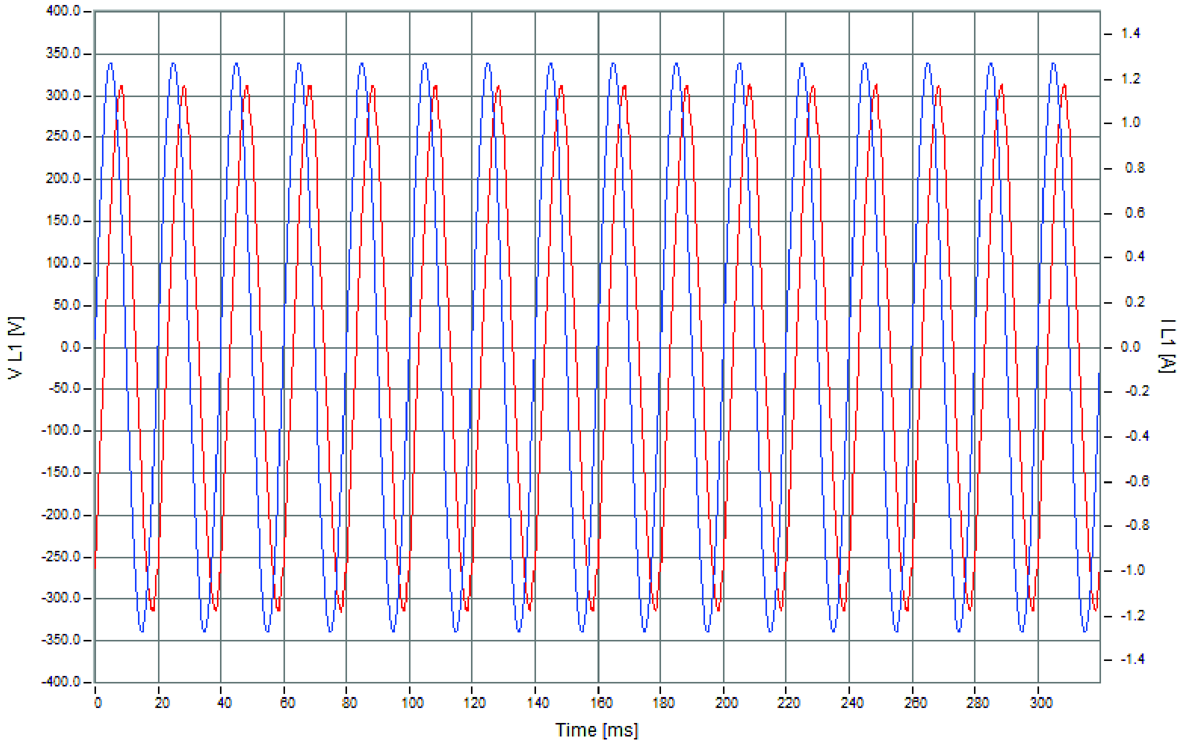


Figure 36. Current and voltage signal curve - 240 V

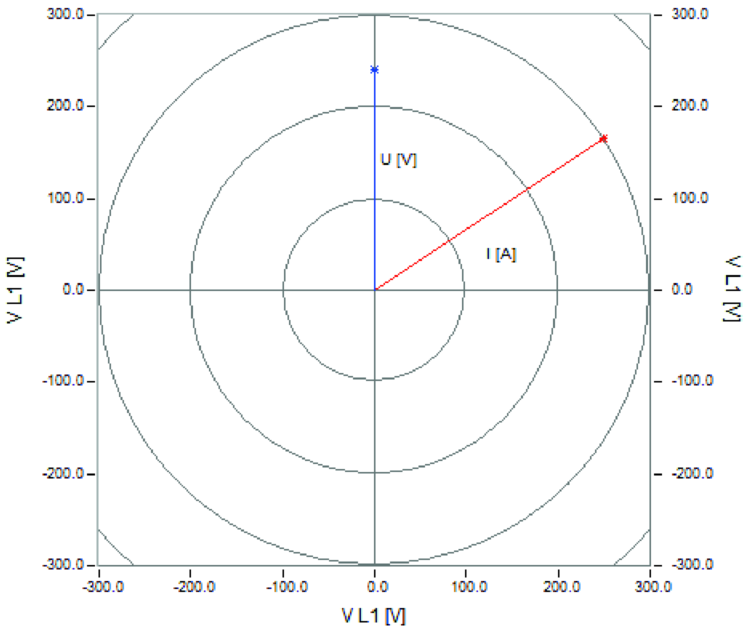


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

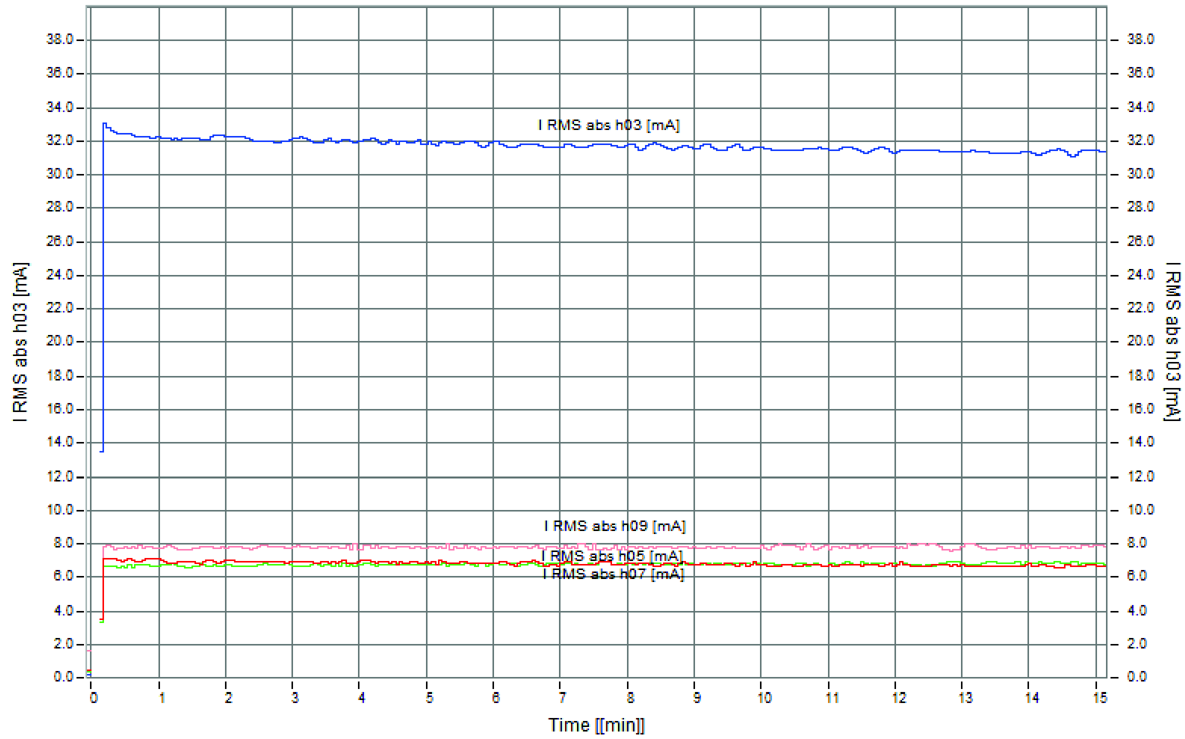


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

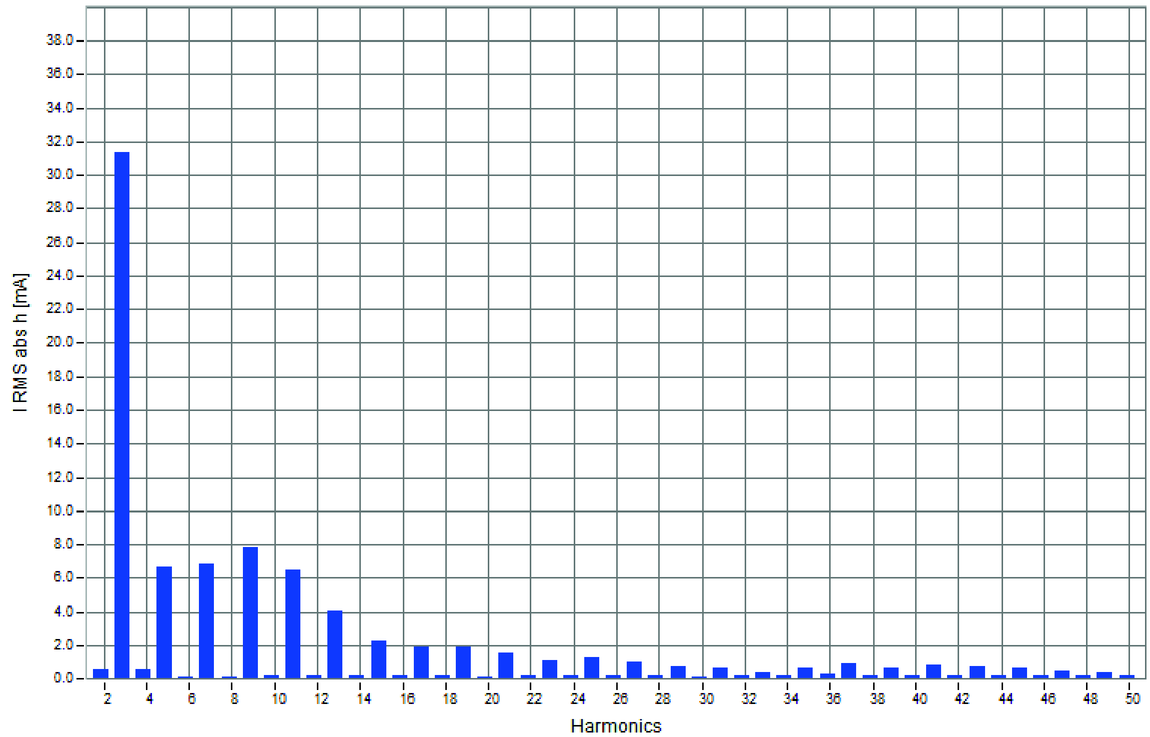


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.38\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.37\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 249.92 V
Current: I = 0.81 A
Active Power = 109.79 W
Reactive Power = 172.38 var
Apparent Power = 204.56 VA
Power Factor = 0.53

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

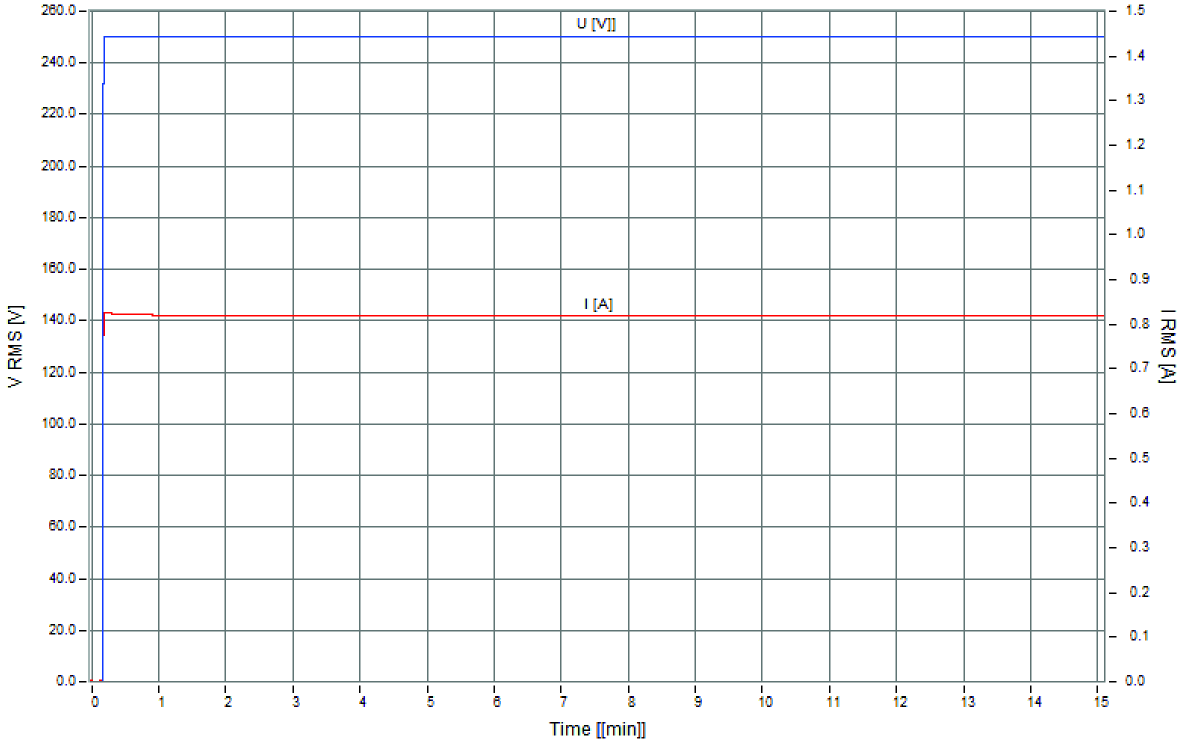


Figure 40. Root Mean Square of voltage and current - 250 V

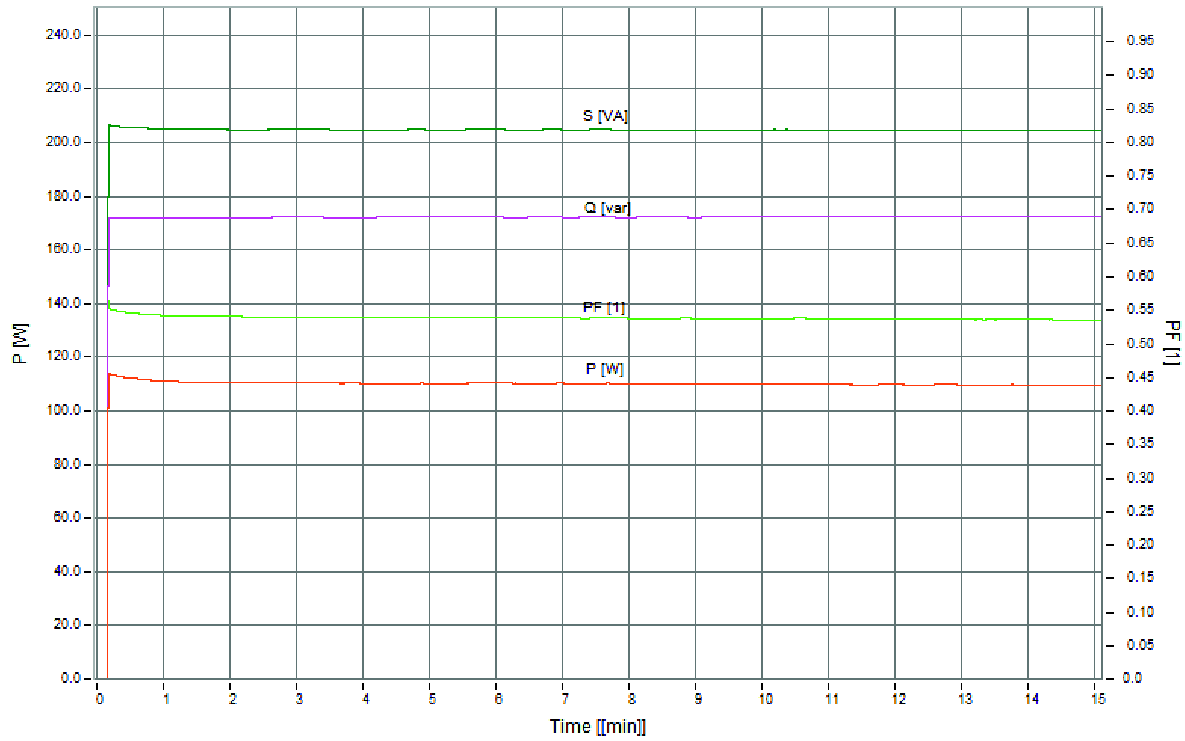


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 249.94	[V]	*****	0,00⁰
I L1 = 0.81	[A]	*****	57.48⁰

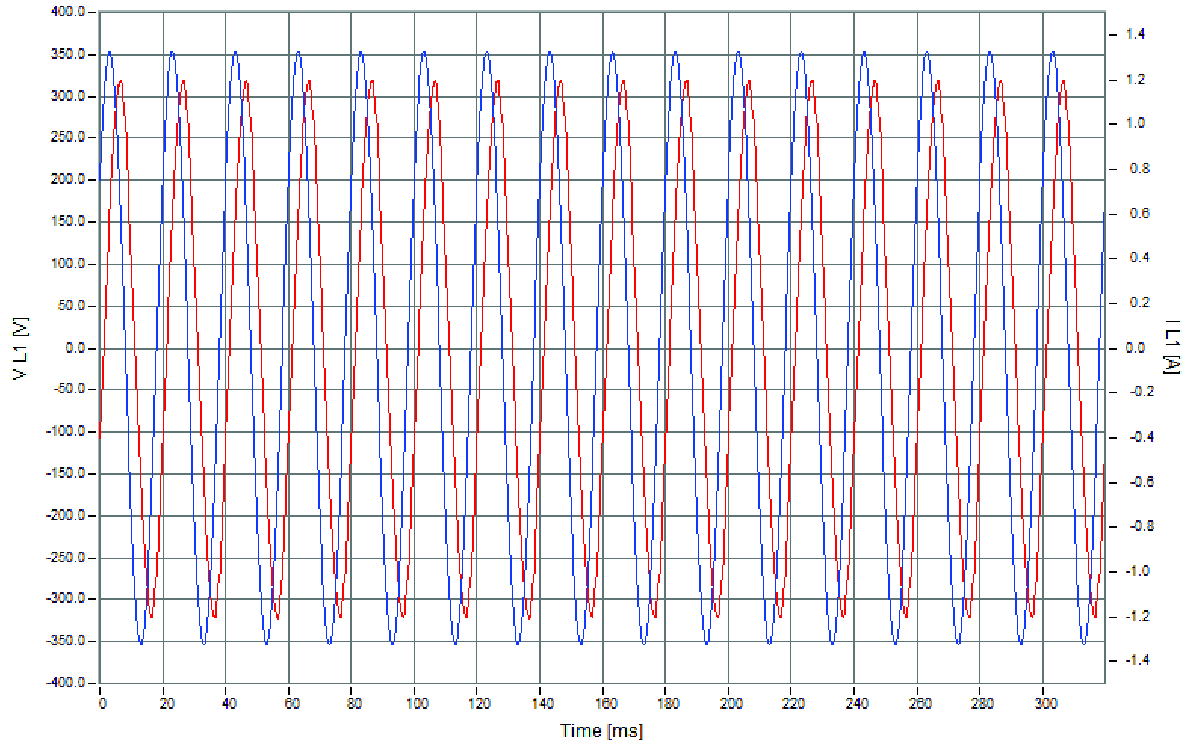


Figure 42. Current and voltage signal curve - 250 V

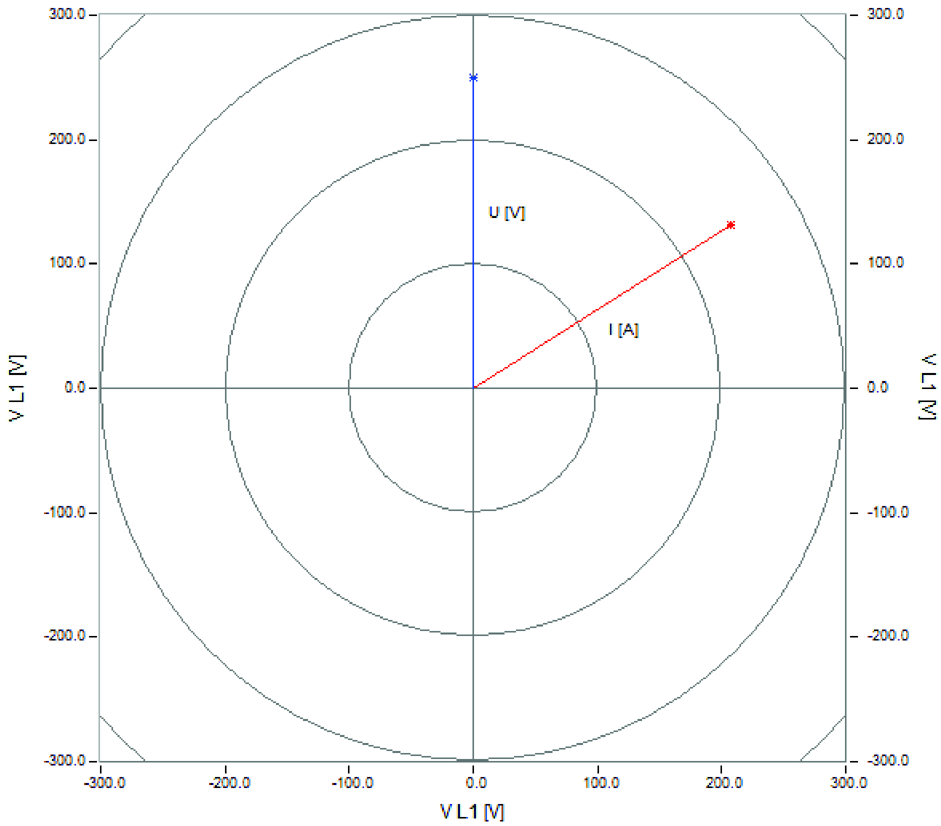


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

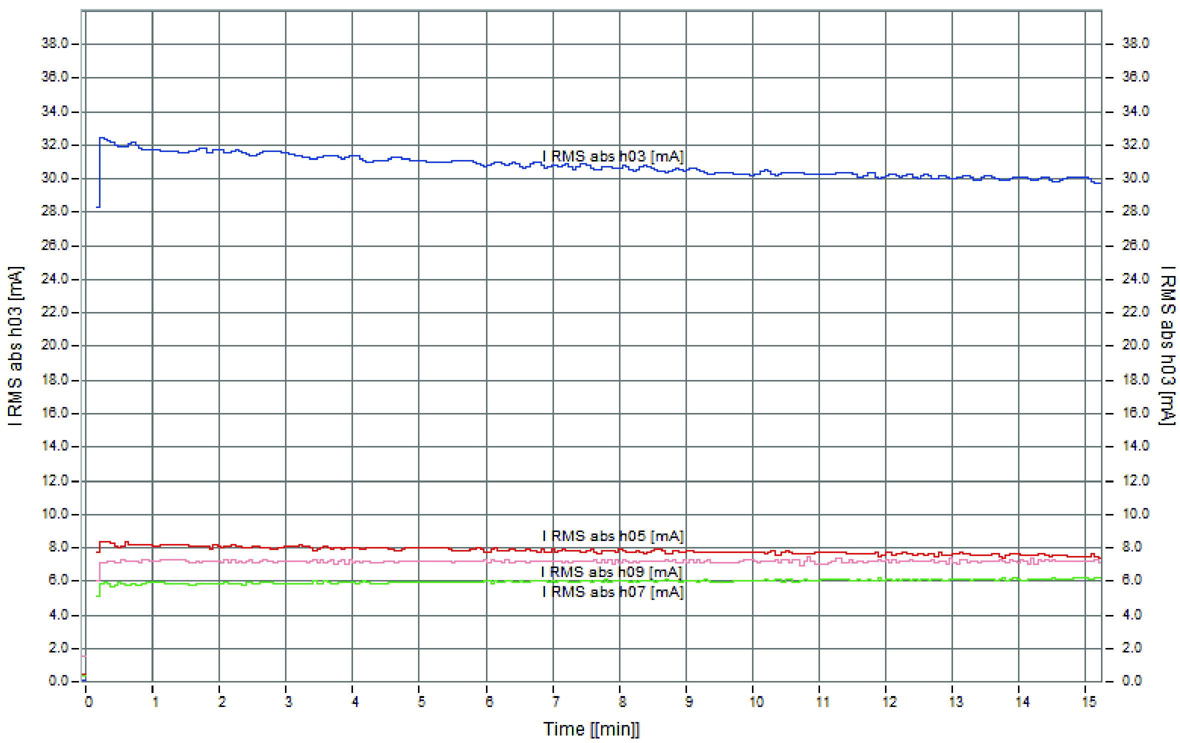


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

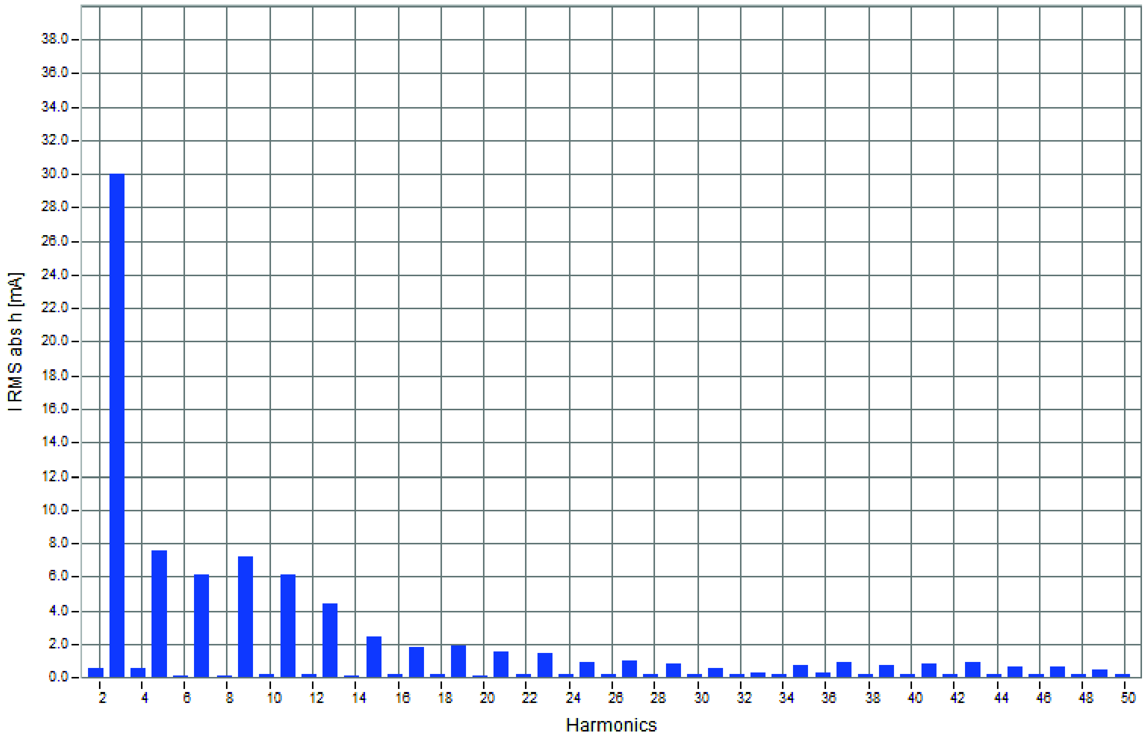


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 4.11\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 4.10\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 6.09%, for the minimum voltage, 0.82 p.u.. The minimum THD, 4.11%, is measured for the maximum voltage 1.09 p.u.. Further increase of the voltage causes a slight decrease of the THD.

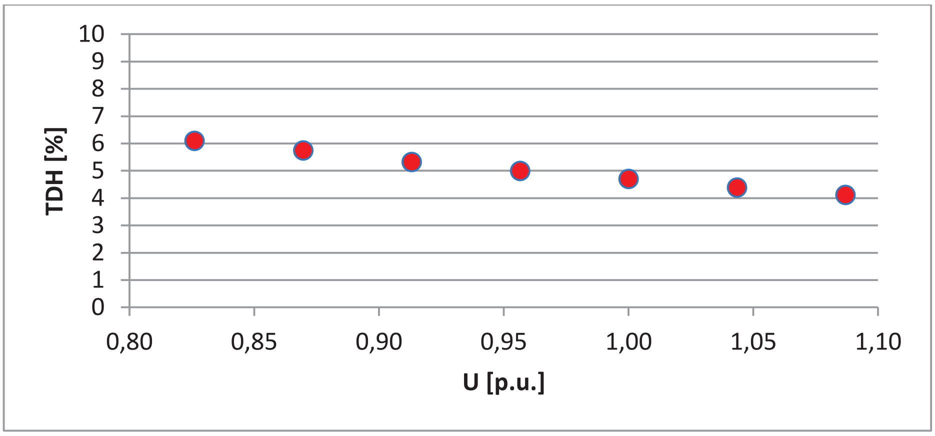


Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature

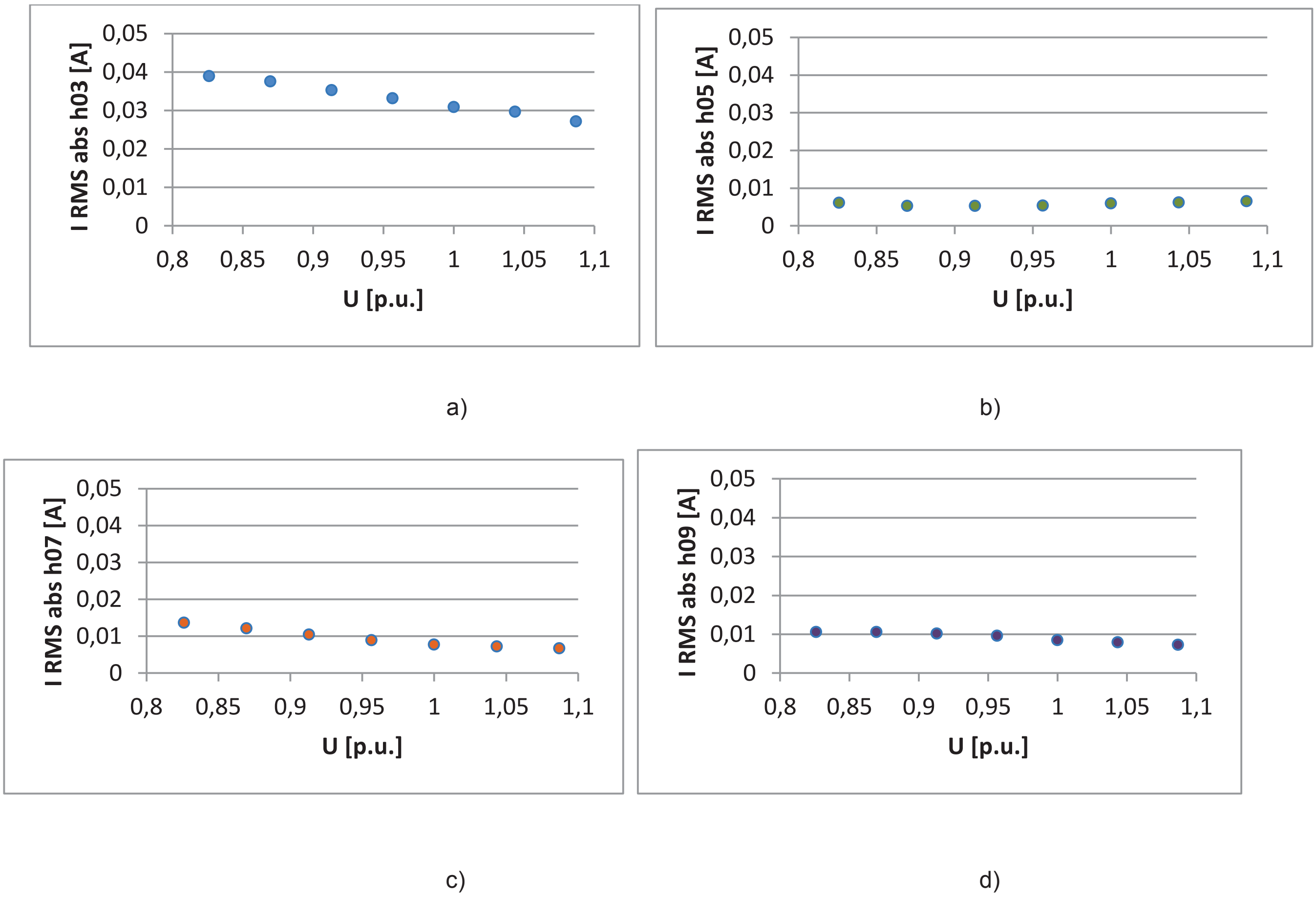


Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) , c) and d) show the 3d, 7th and 9th harmonic, which decreases with the voltage increase. Figures 47. b) shows the 5th harmonic respectively, which has parabolic behaviour .

Technische Universität Wien
Institut für Energiesysteme und Elektrische Antriebe
Gußhausstraße 25/370-1
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MEASUREMENT PROTOCOL 8

SPL-60
2Xmodule-60Xlight source

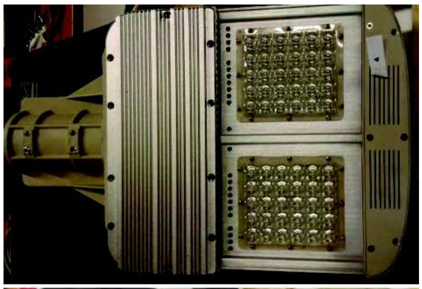
Vienna 02.February 2016

1. Content

2. List of figures

3. Light type

LED- 2XModouls
50 X light Source
Status: old



4. Technical data

SPL-60
Voltage: 100-240 V
Current: 0.9 A
Real power: 70 W
Frequency: 50-60 Hz

5. Measurement

5.1. Schema

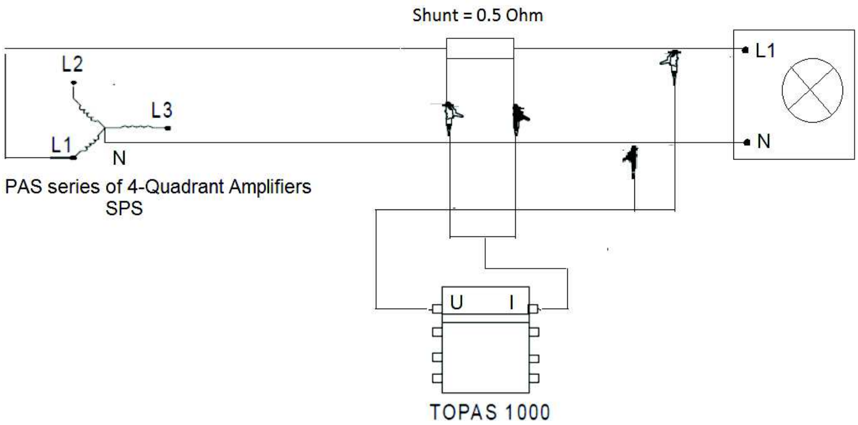


Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside
Voltage range: 190-250 V
Measurement interval: 15 min

Temperature: 23.1^{0}C
Shunt: 0.5 Ω

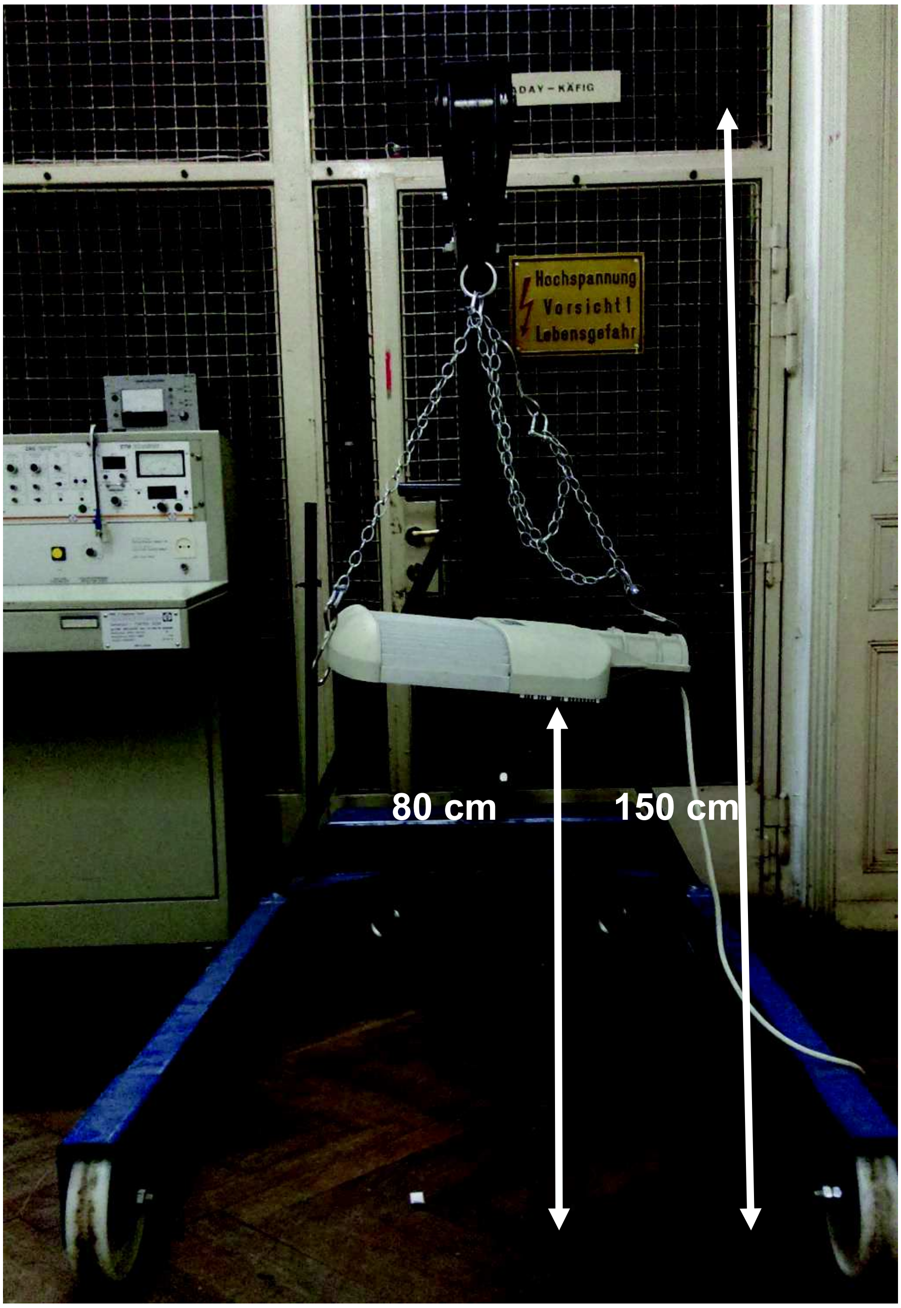


Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 229.93 V
Current: I = 0.74 A
Active Power = 84.62 W
Reactive Power = 148.41 var
Apparent Power = 170.90 VA
Power Factor = 0.49

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

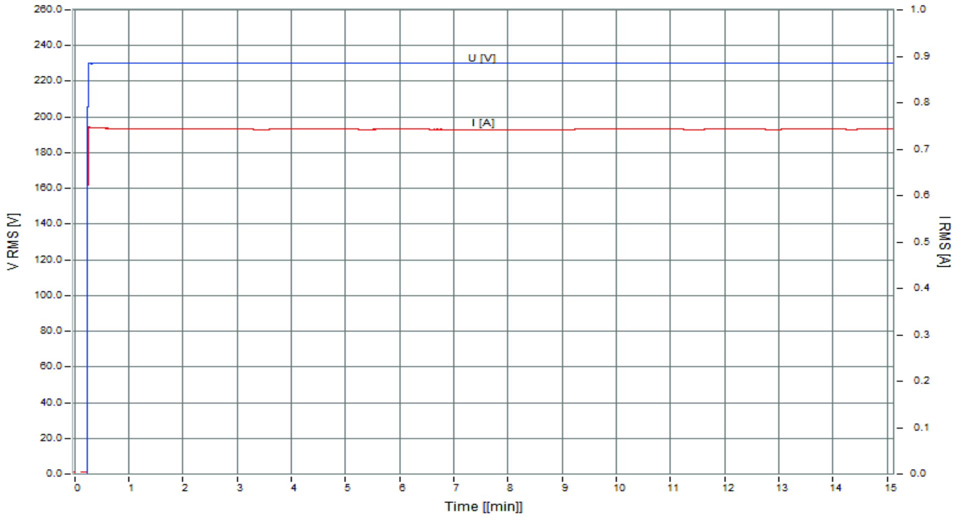


Figure 3. Root Mean Square of voltage and current - 230 V

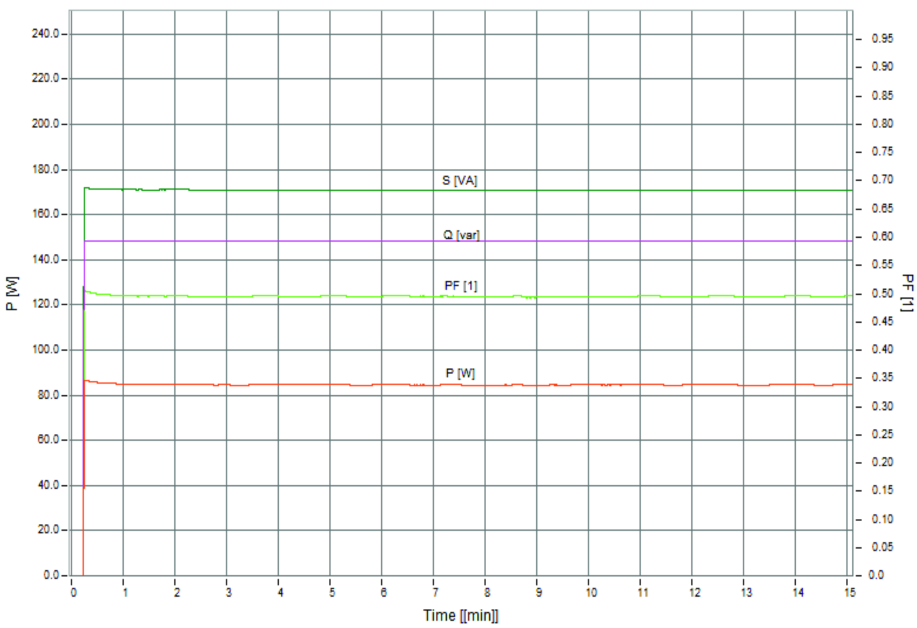


Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 229.93	[V]	*****	0.00⁰
I L1 = 0.74	[A]	*****	60.34⁰

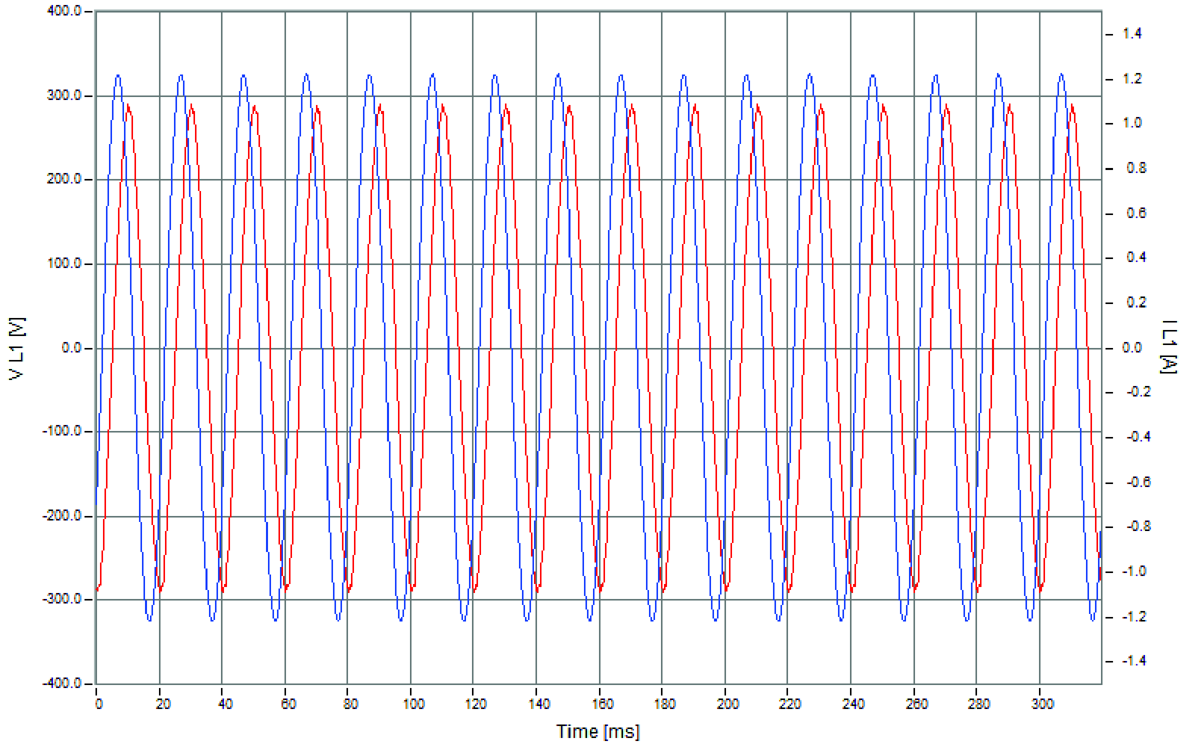


Figure 5. Current and voltage signal curve - 230 V

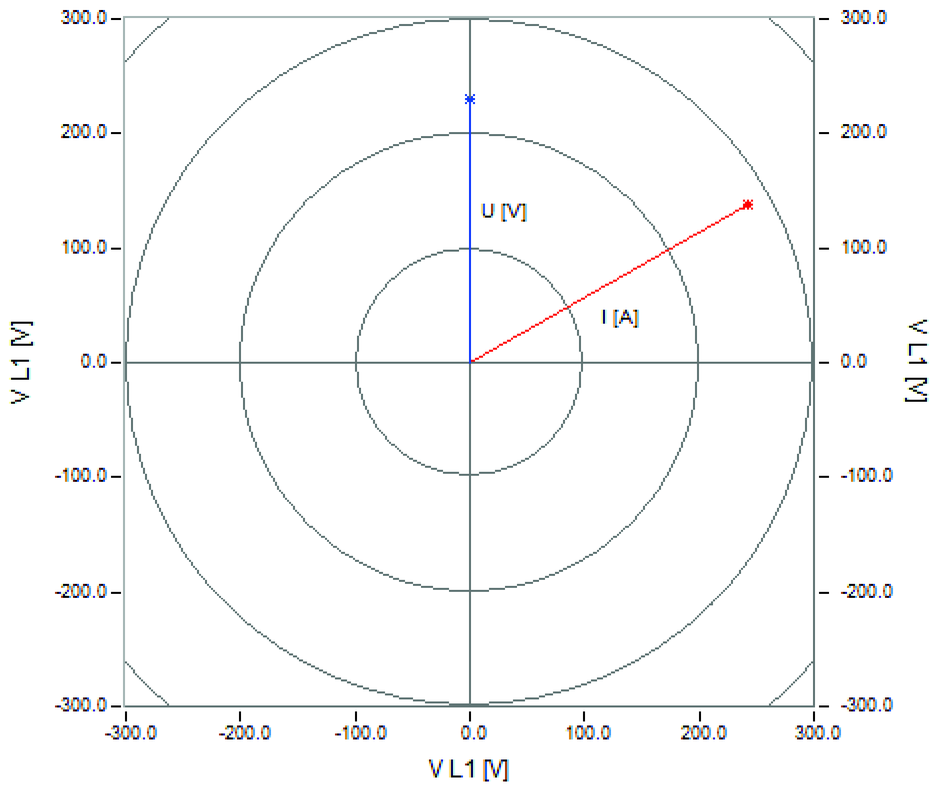


Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

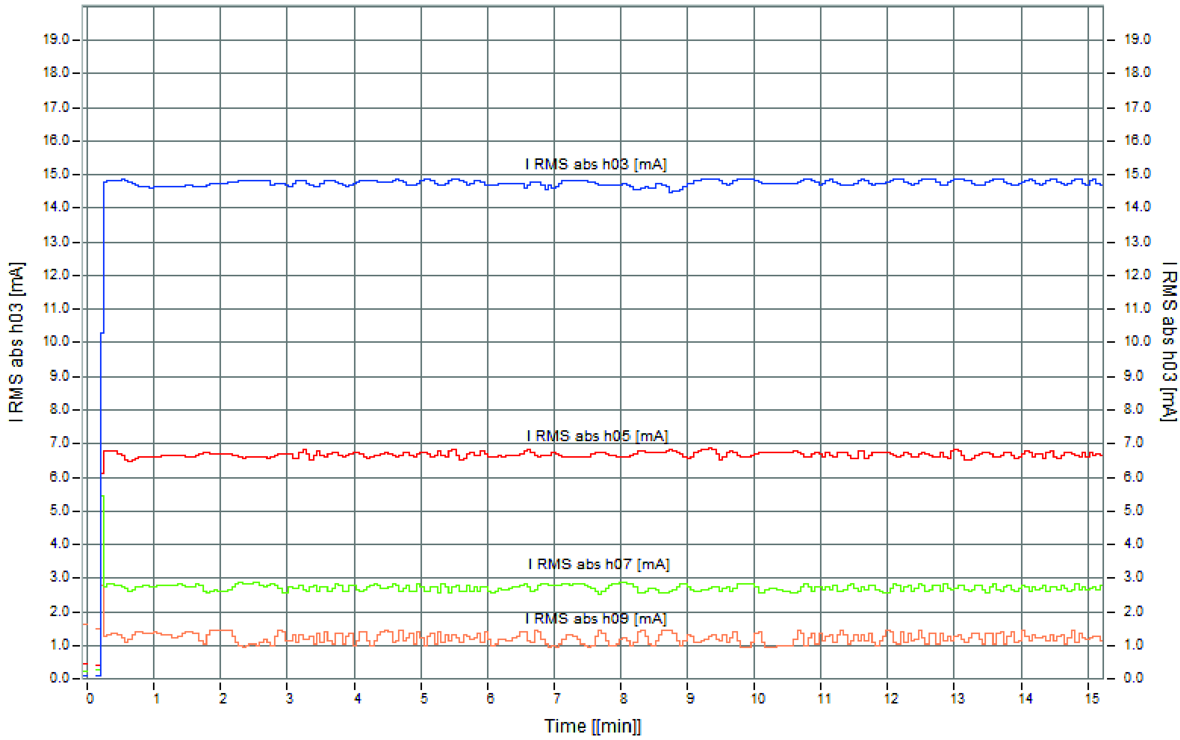


Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

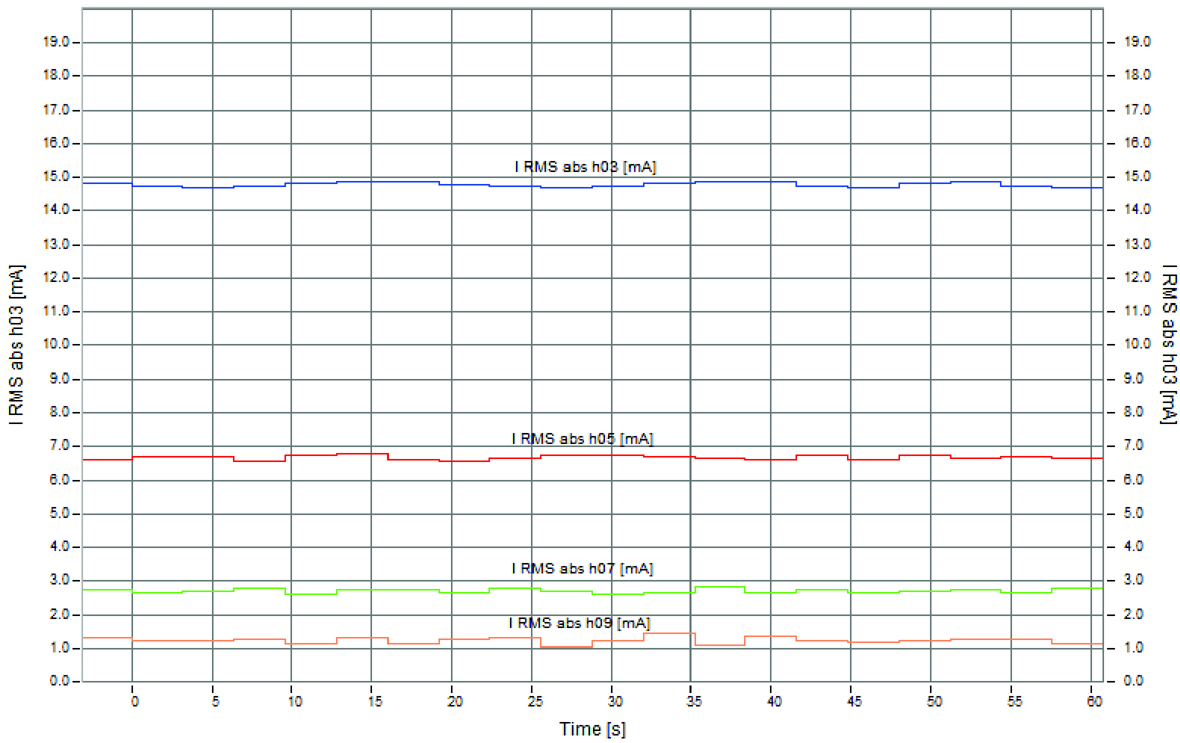


Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

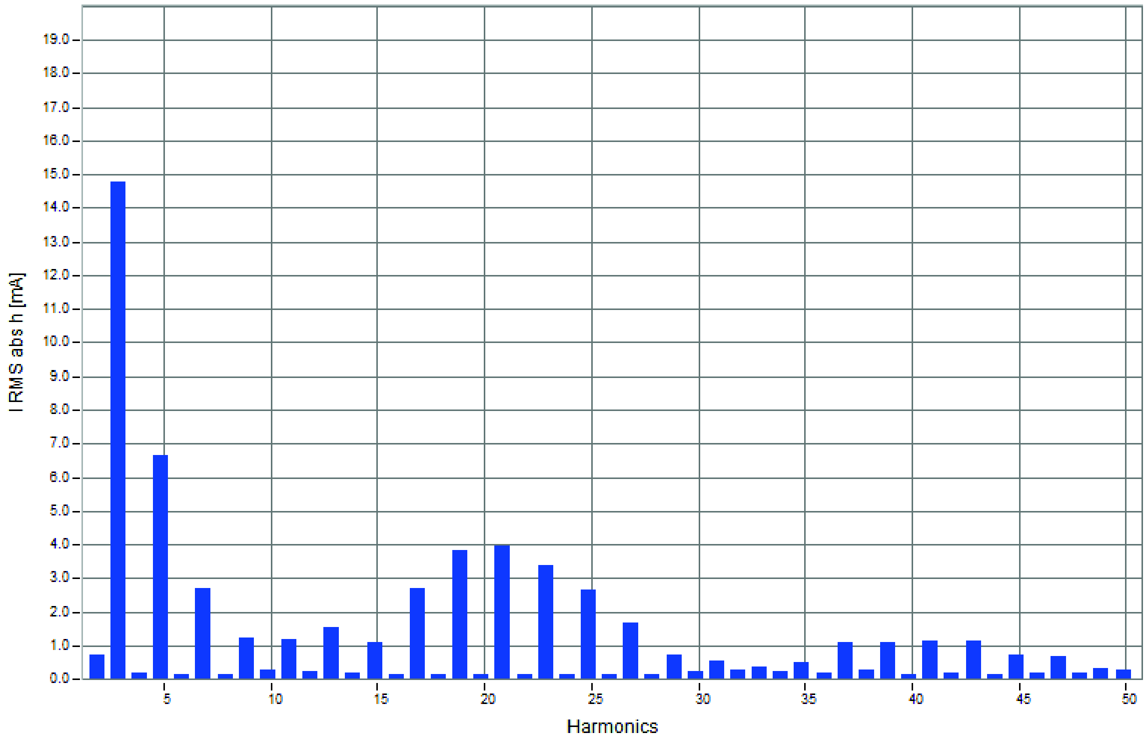


Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.49\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.49\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 189.73 V
Current: I = 0.65 A
Active Power = 73.29 W
Reactive Power = 99.88 var
Apparent Power = 123.95 VA
Power Factor = 0.59

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

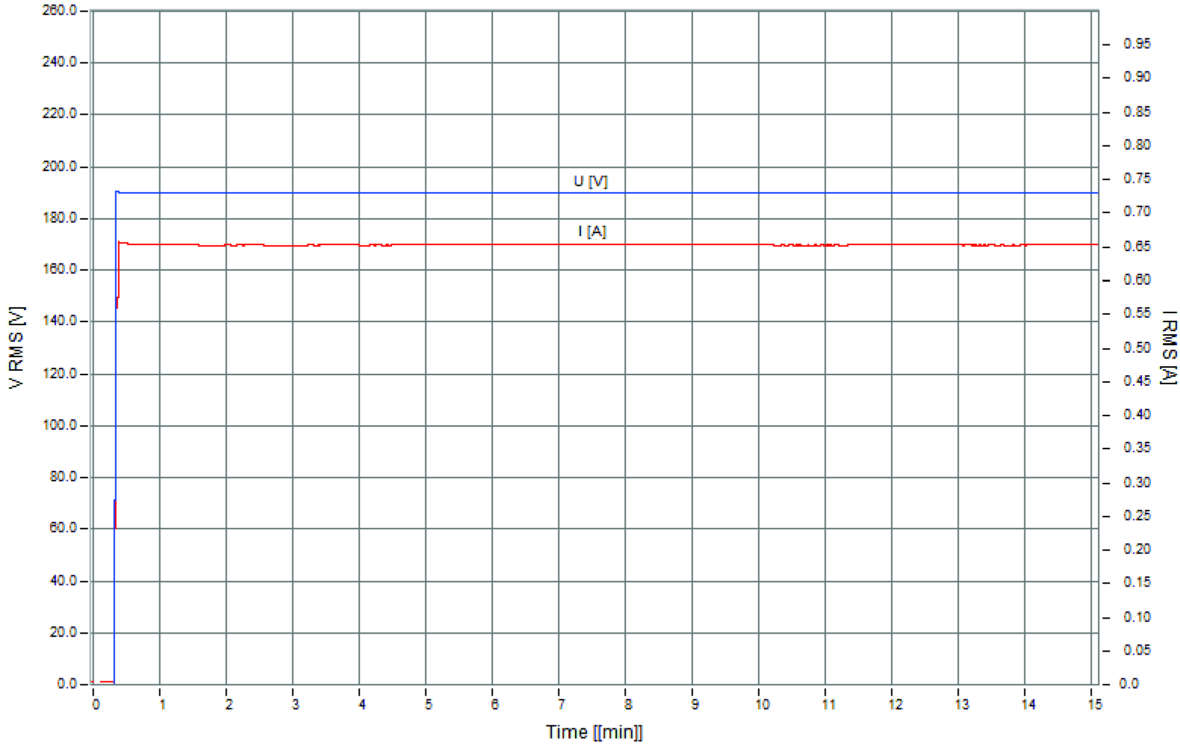


Figure 10. Root Mean Square of voltage and current - 190 V

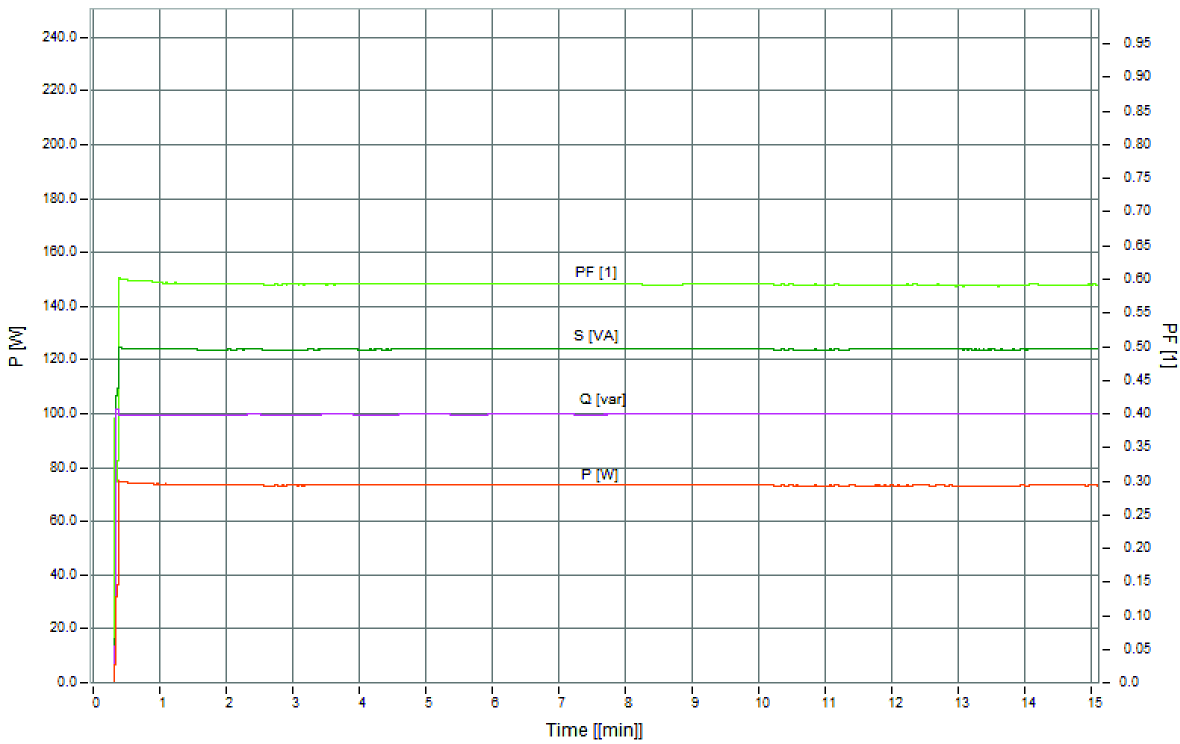


Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 189.74	[V]	*****	0.00⁰
I L1 = 0.65	[A]	*****	53.33⁰

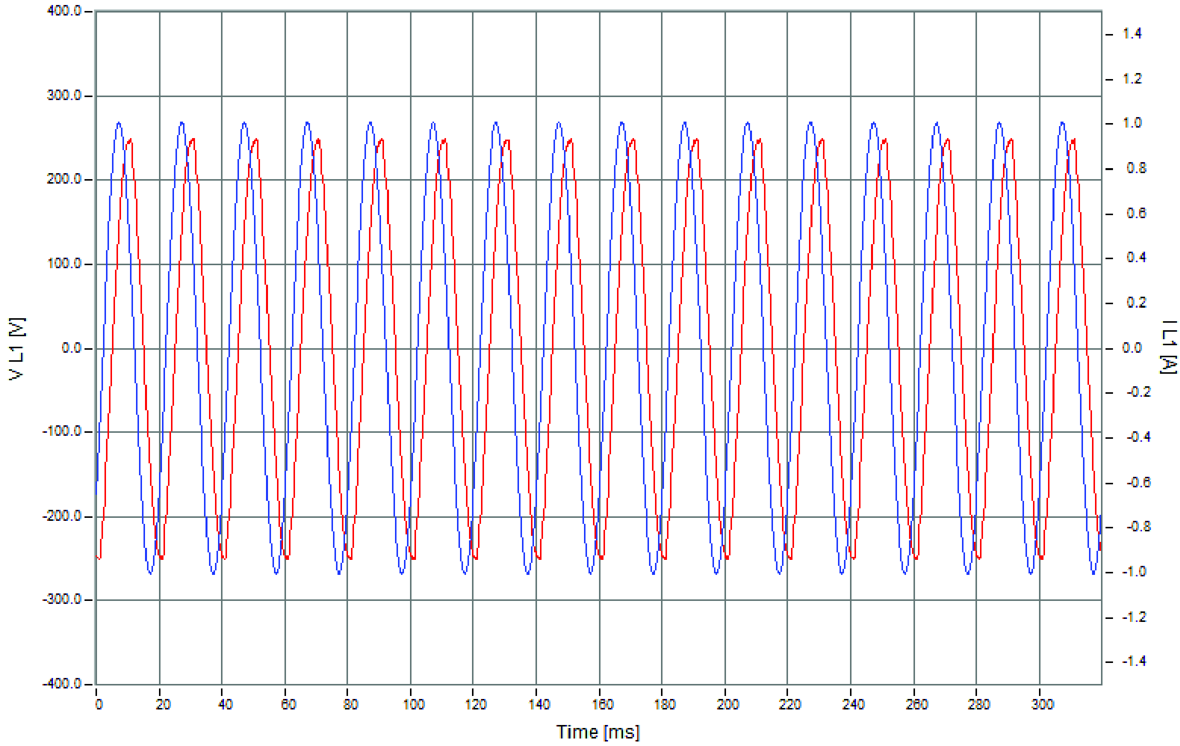


Figure 12. Current and voltage signal curve - 190 V

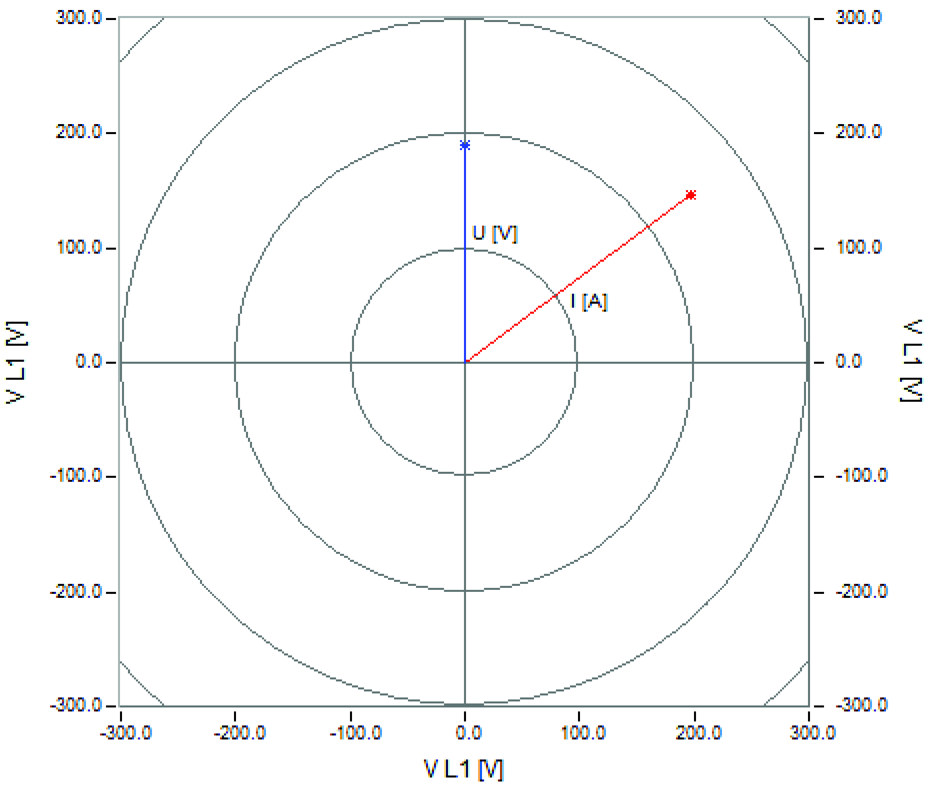


Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

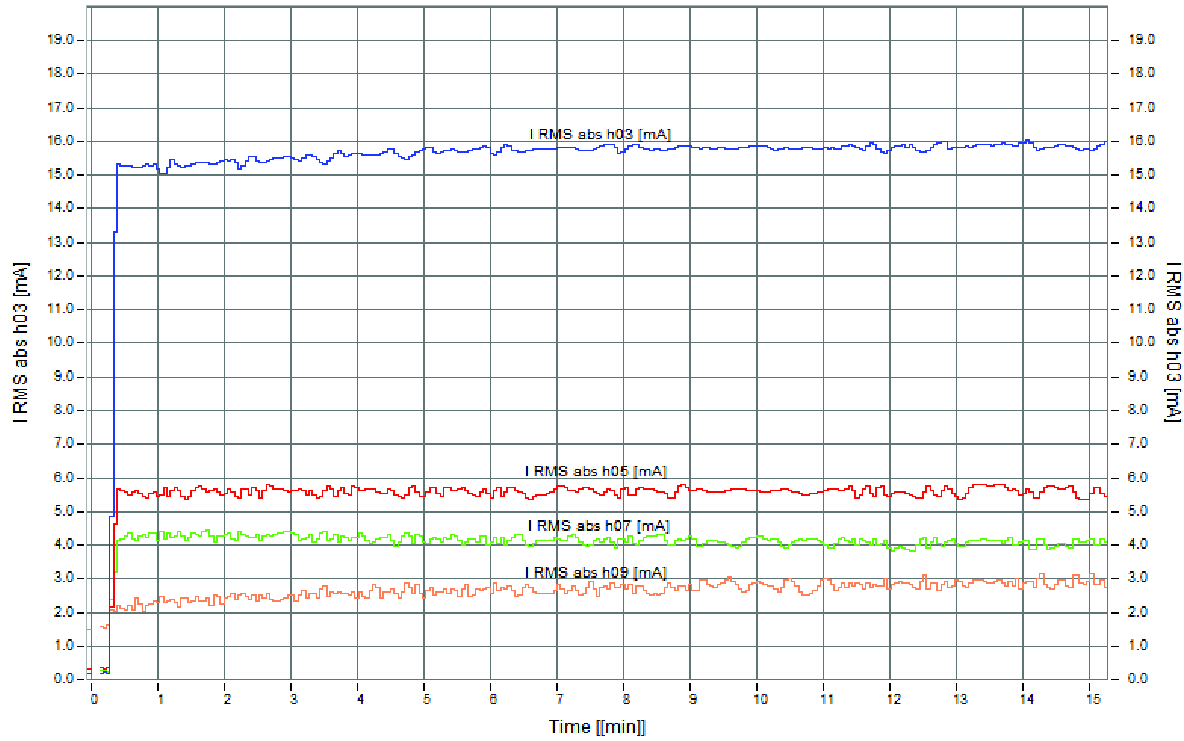


Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

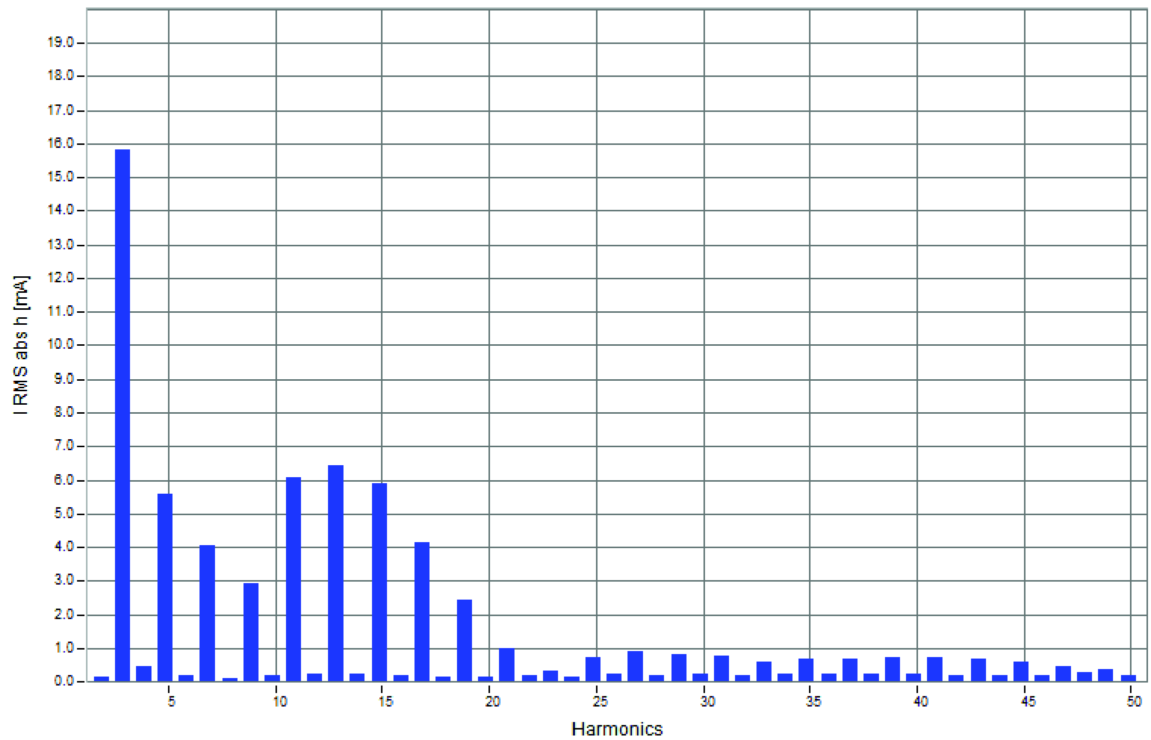


Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 3.24\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 3.24\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 199.78 V
Current: I = 0.67 A
Active Power = 75.58 W
Reactive Power = 111.50 var
Apparent Power = 134.76 VA
Power Factor = 0.56

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

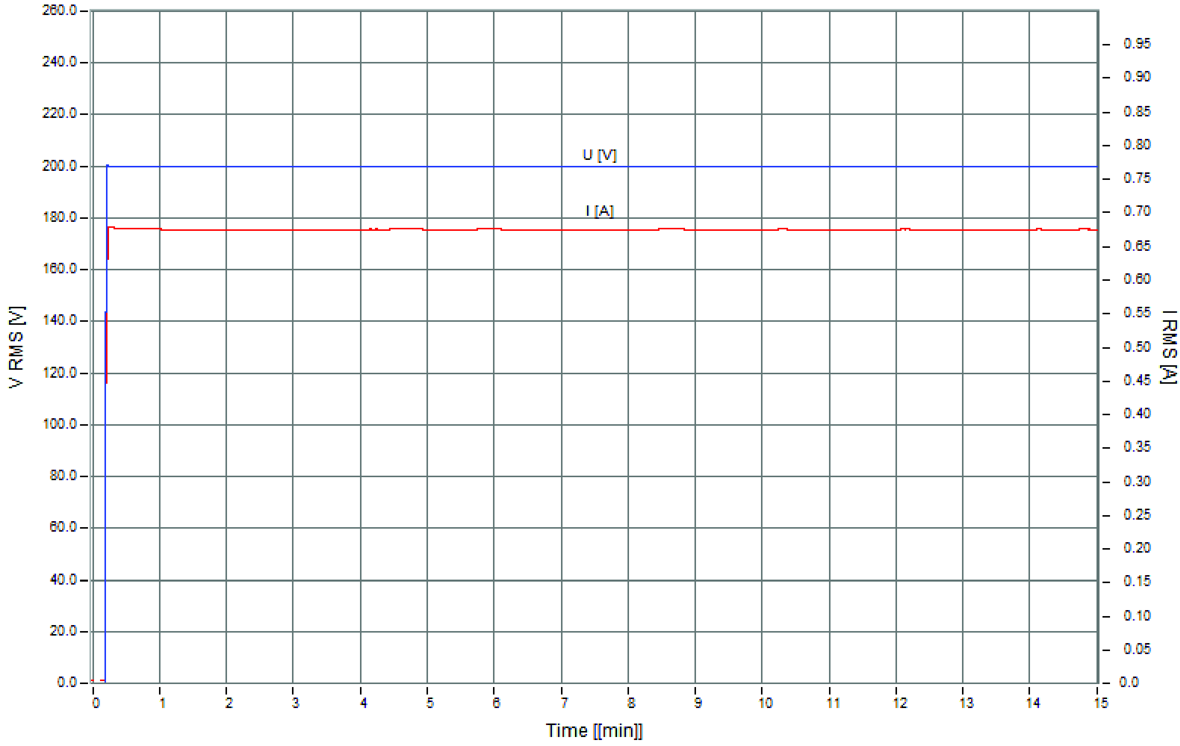


Figure 16. Root Mean Square of voltage and current - 200 V

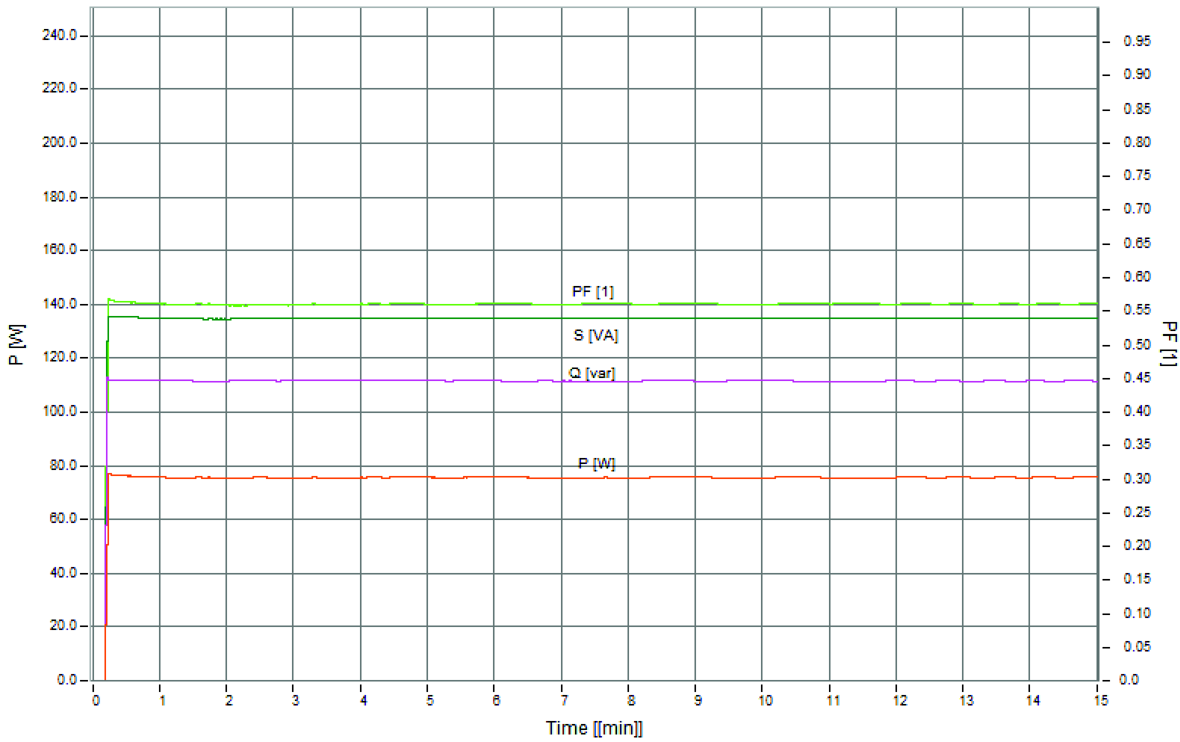


Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 199.79	[V]	*****	0.00^0
I L1 = 0.67	[A]	*****	55.91^0

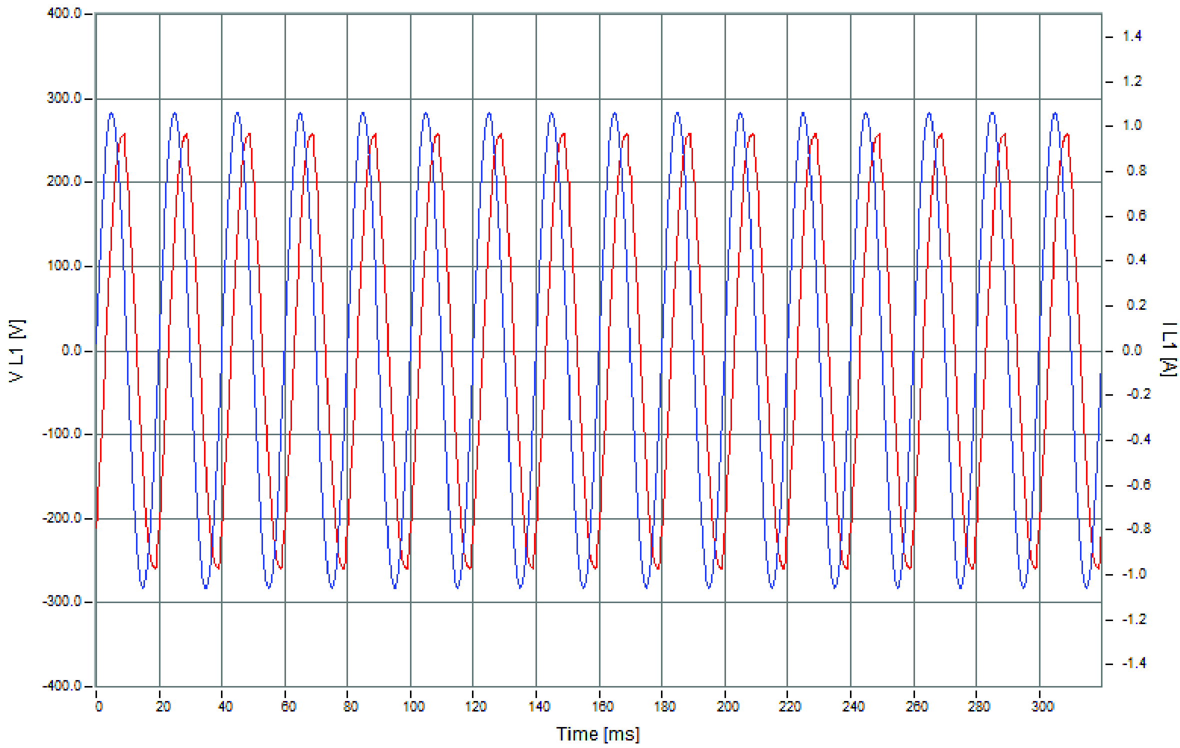


Figure 18. Current and voltage signal curve - 200 V

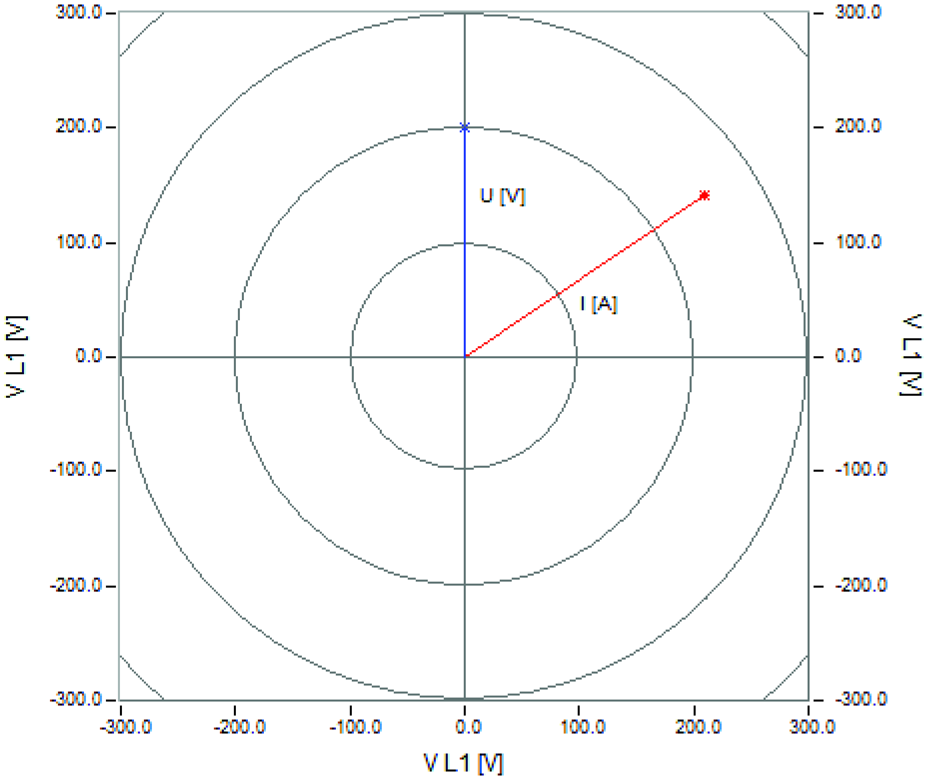


Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

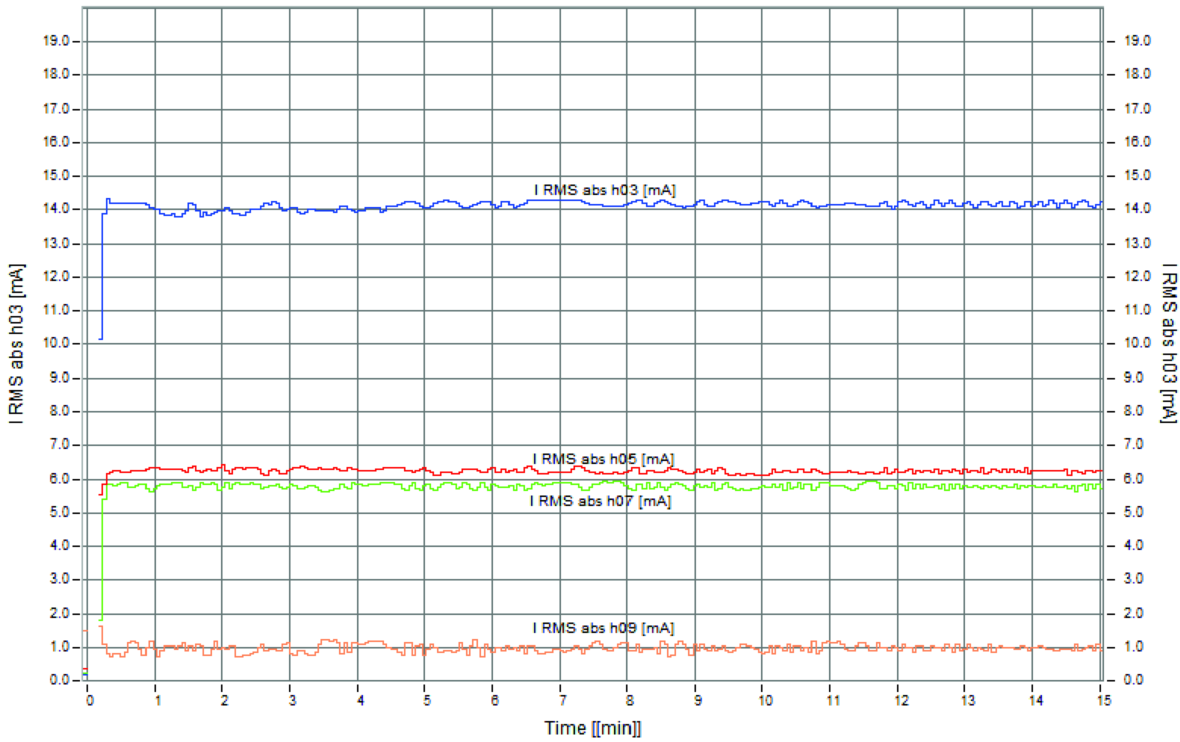


Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

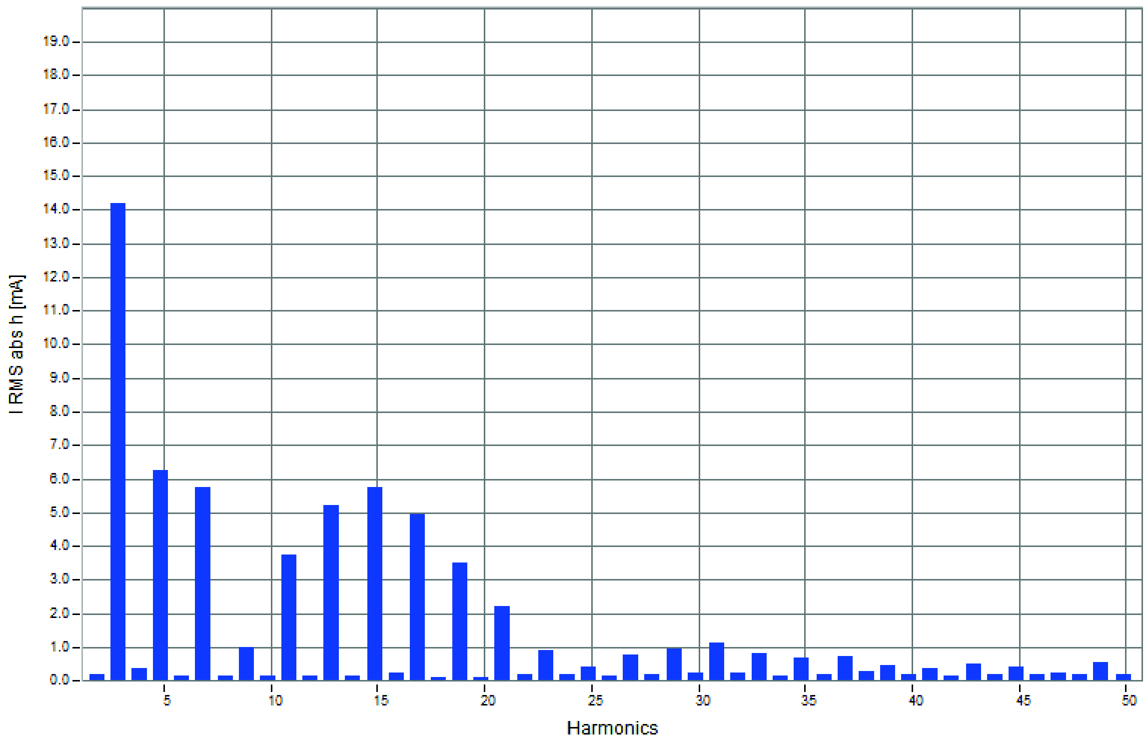


Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.95\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.95\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:
Voltage: U = 209.83 V
Current: I = 0.69 A
Active Power = 78.52 W
Reactive Power = 123.13 var
Apparent Power = 146.09 VA
Power Factor = 0.53

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

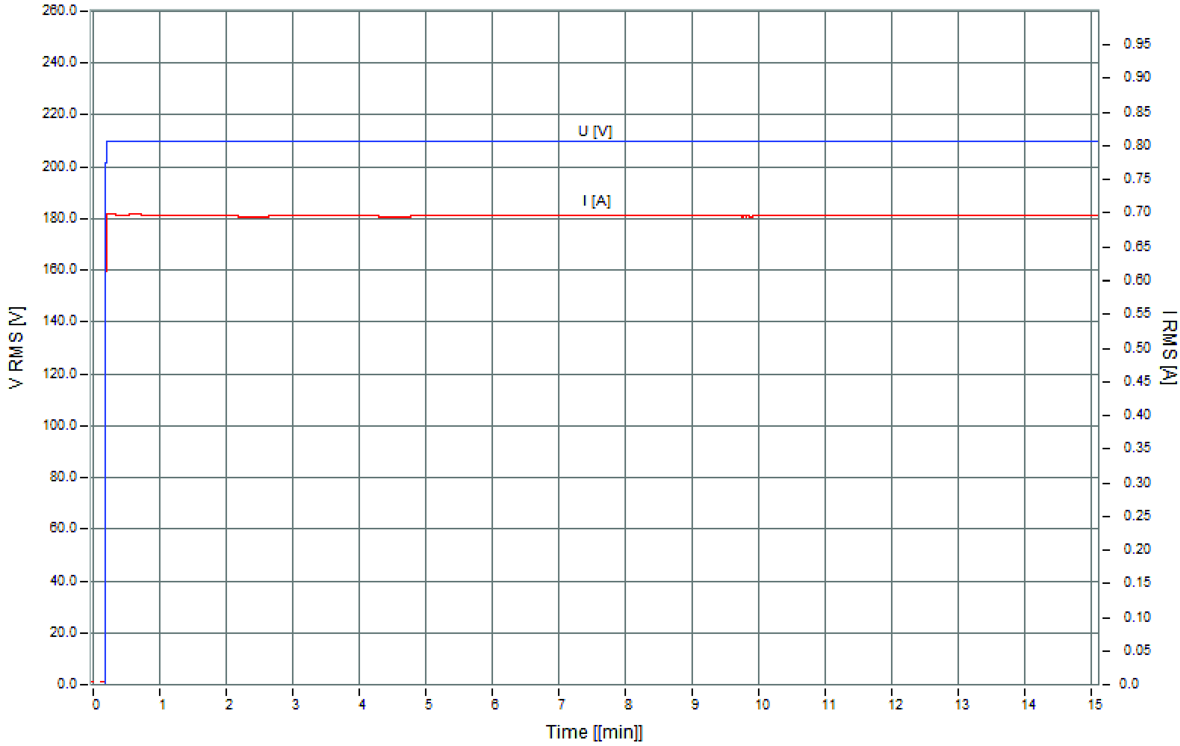


Figure 22. Root Mean Square of voltage and current - 210 V

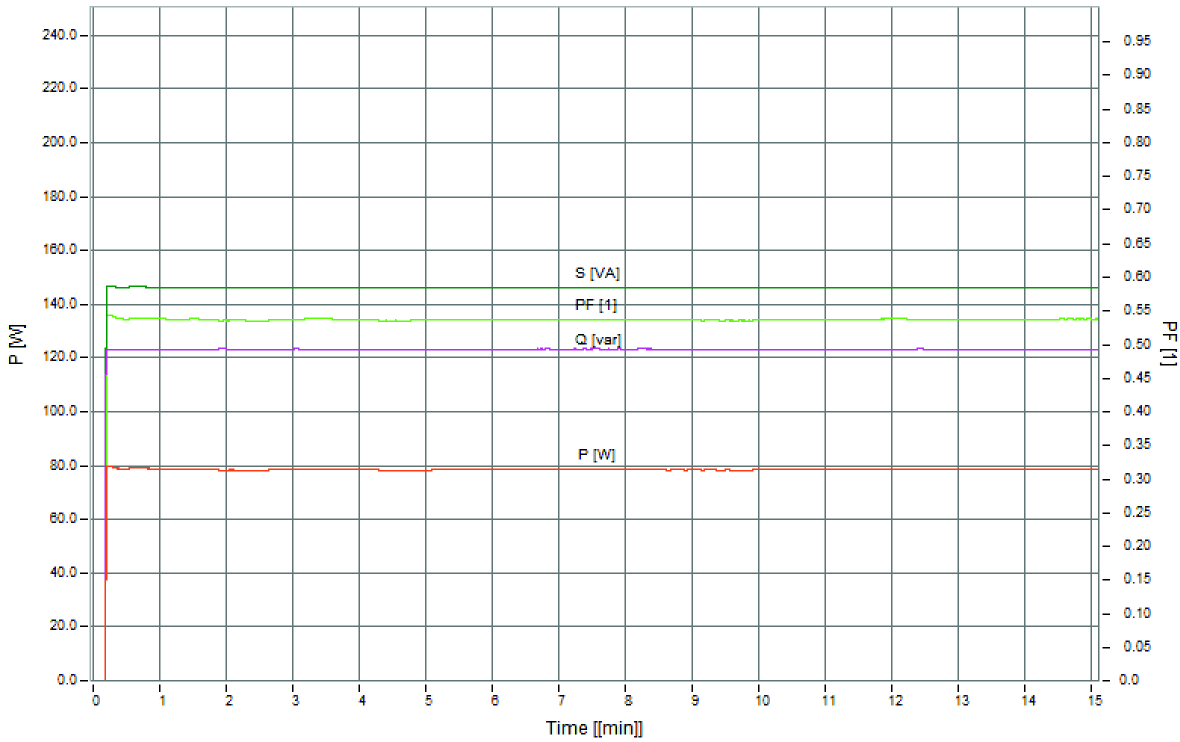


Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 209.84	[V]	*****	0.00⁰
I L1 = 0.69	[A]	*****	57.46⁰

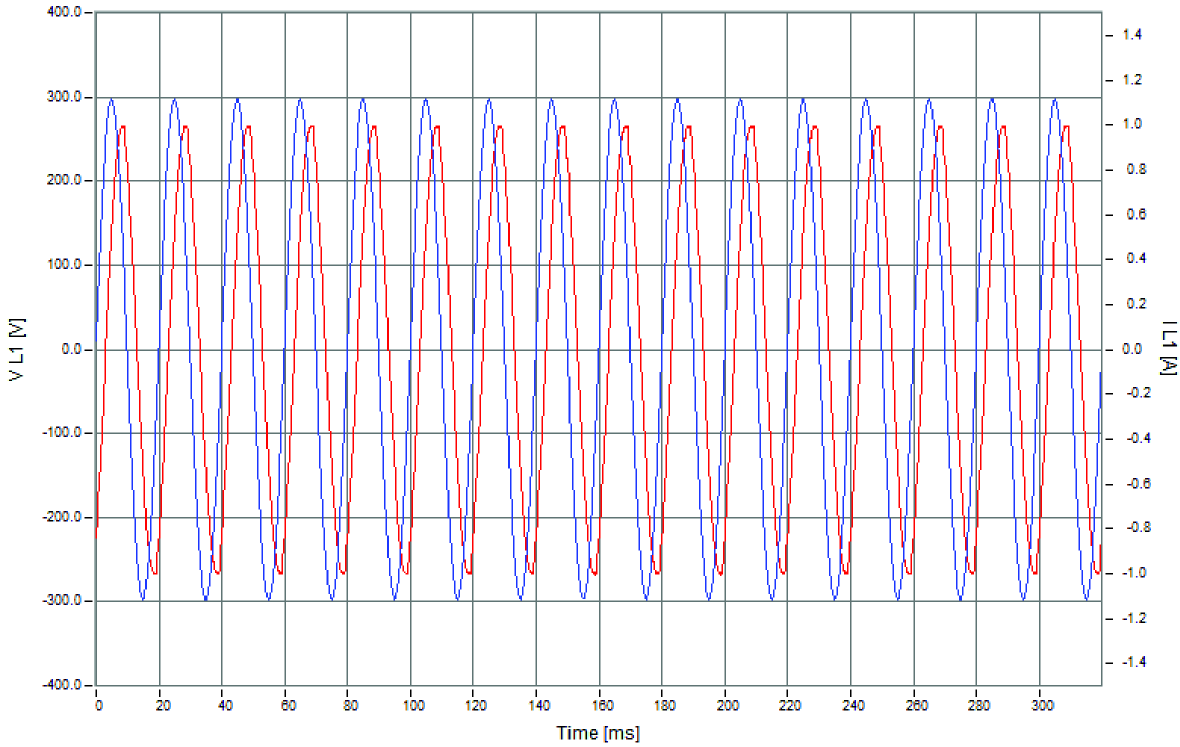


Figure 24. Current and voltage signal curve - 210 V

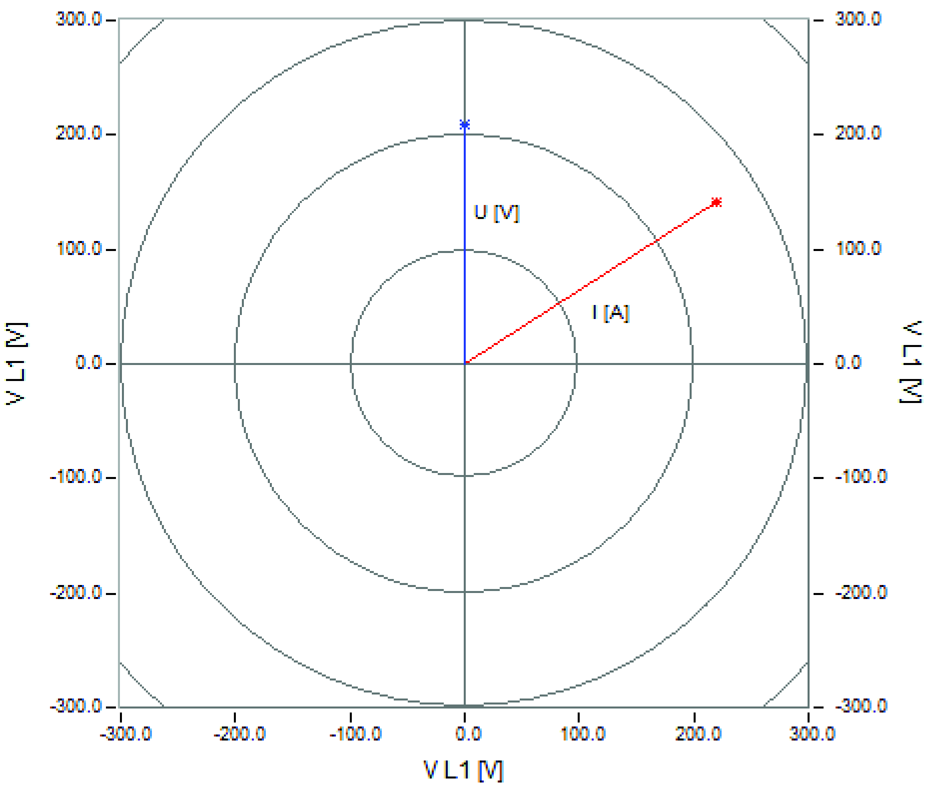


Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

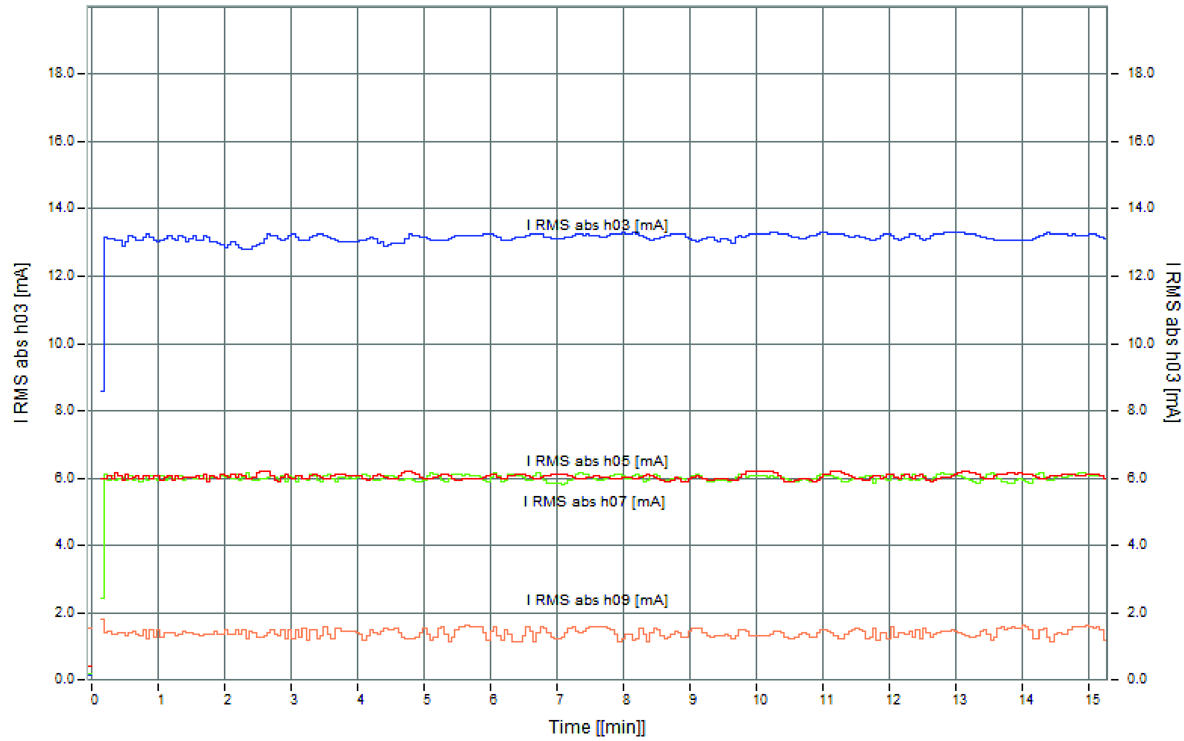


Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

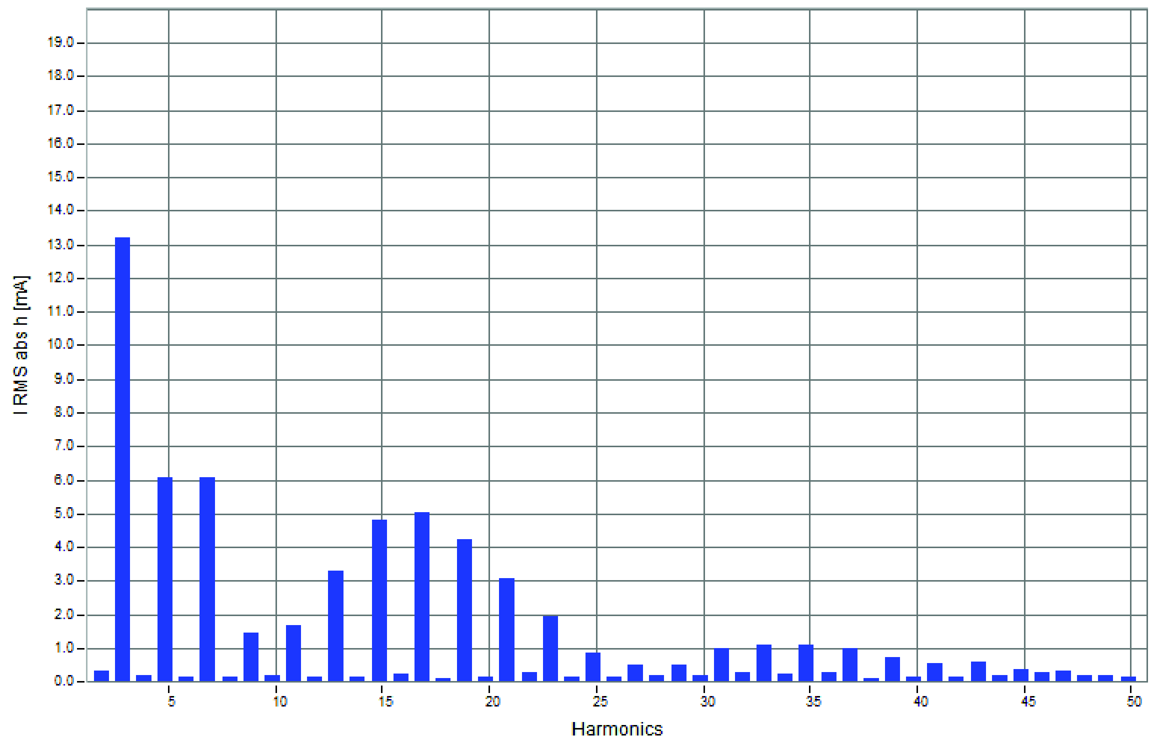


Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.69\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.69\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 219.90 V

Current: I = 0.71 A

Active Power = 81.55 W

Reactive Power = 135.60 var

Apparent Power = 158.29 VA

Power Factor = 0.51

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

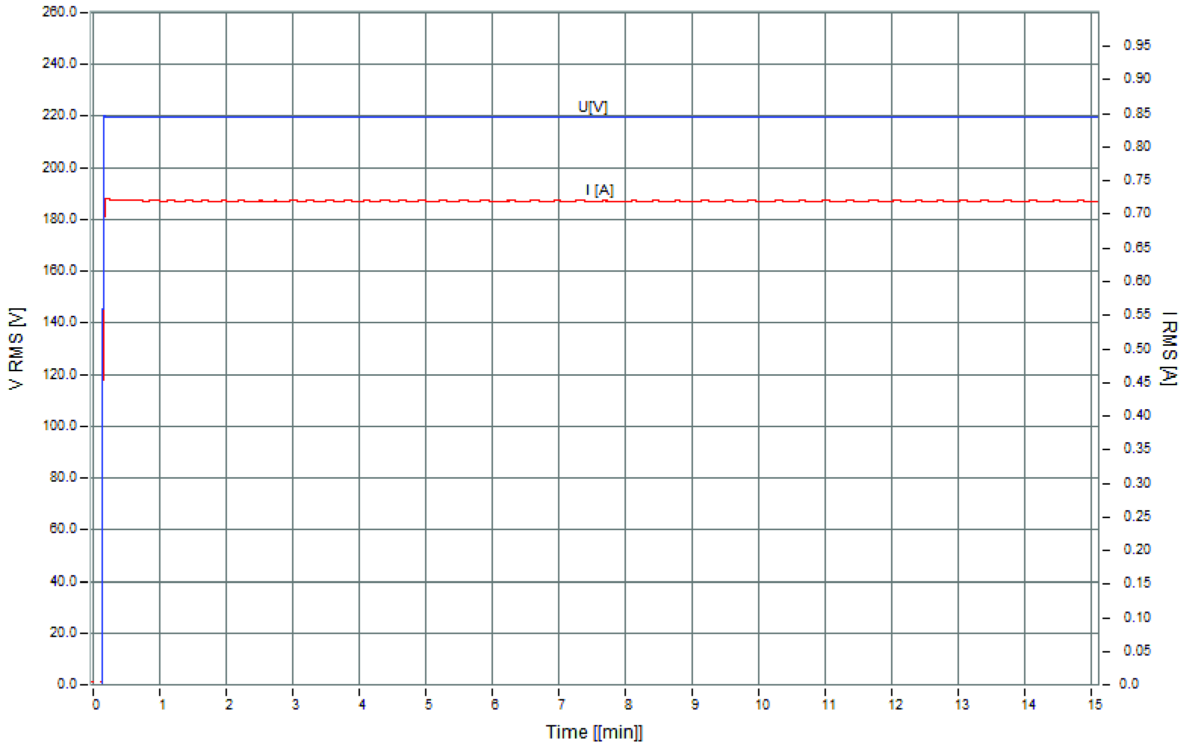


Figure 28. Root Mean Square of voltage and current - 220 V

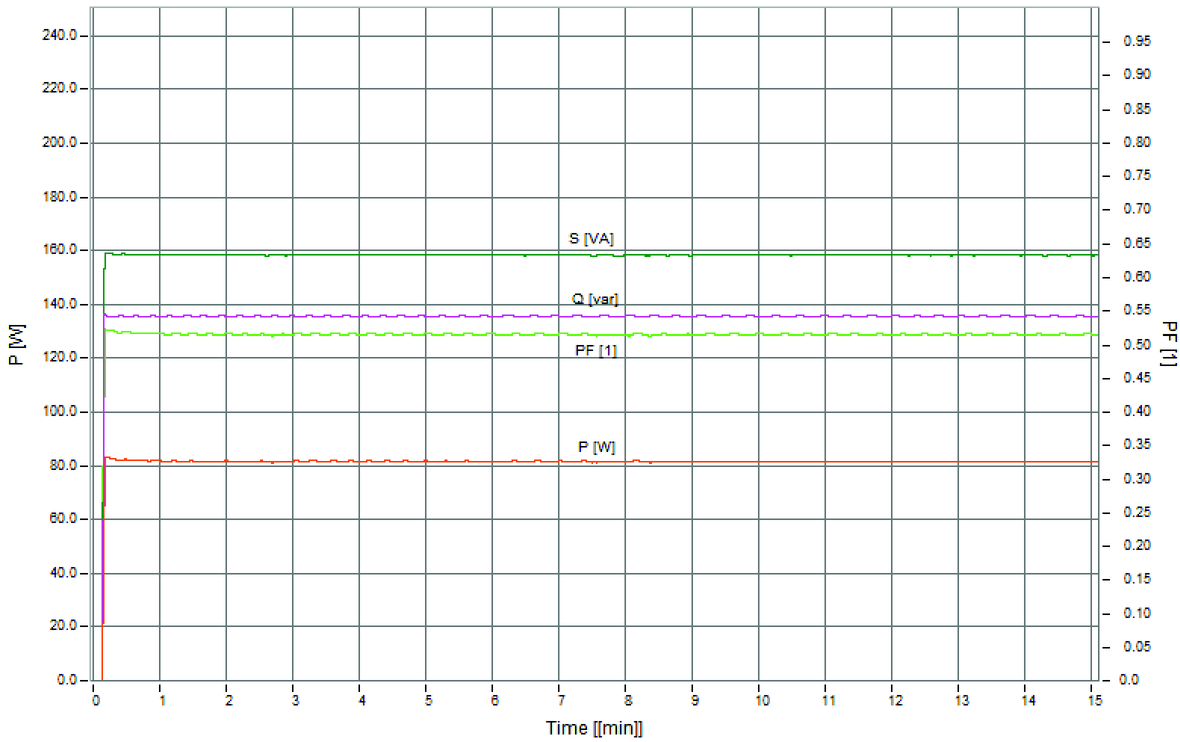


Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 220.34	[V]	*****	0.00⁰
I L1 = 0.71	[A]	*****	59.08⁰

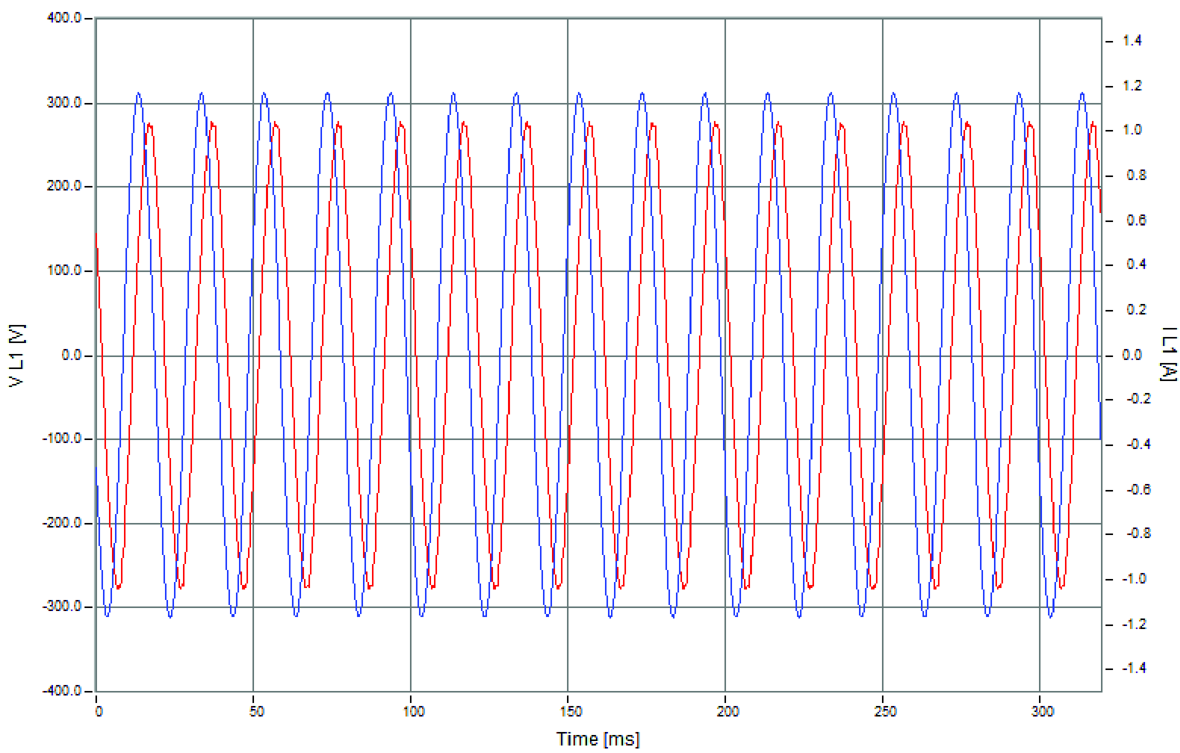


Figure 30. Current and voltage signal curve - 220 V

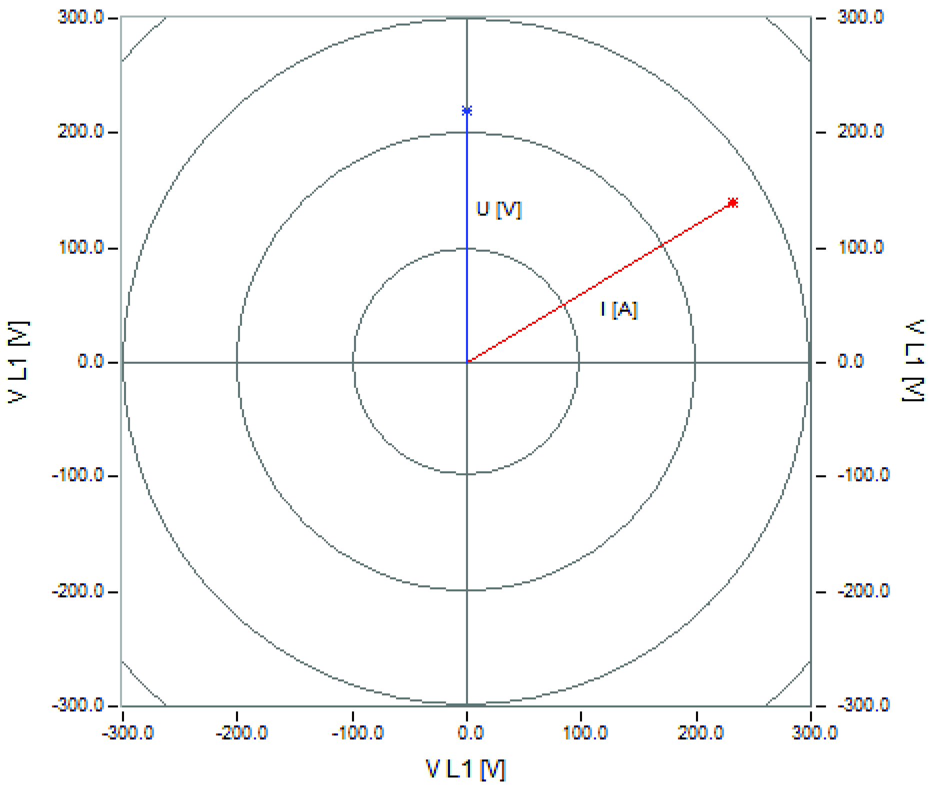


Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

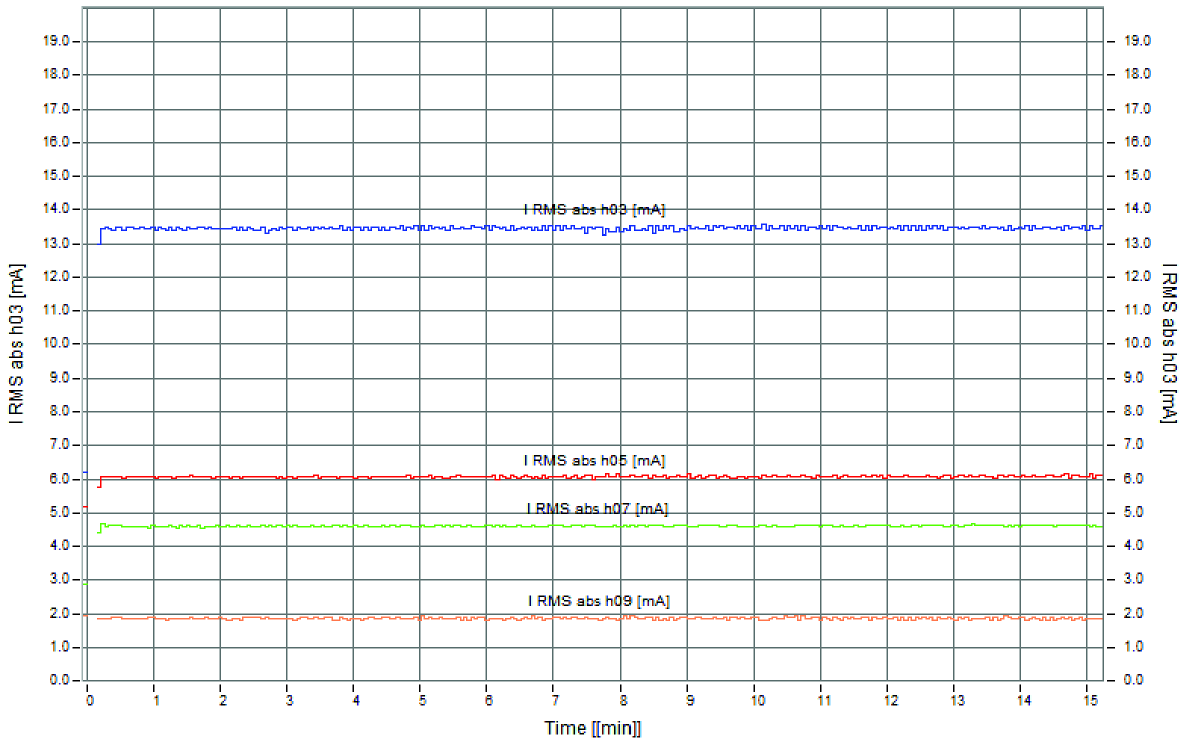


Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

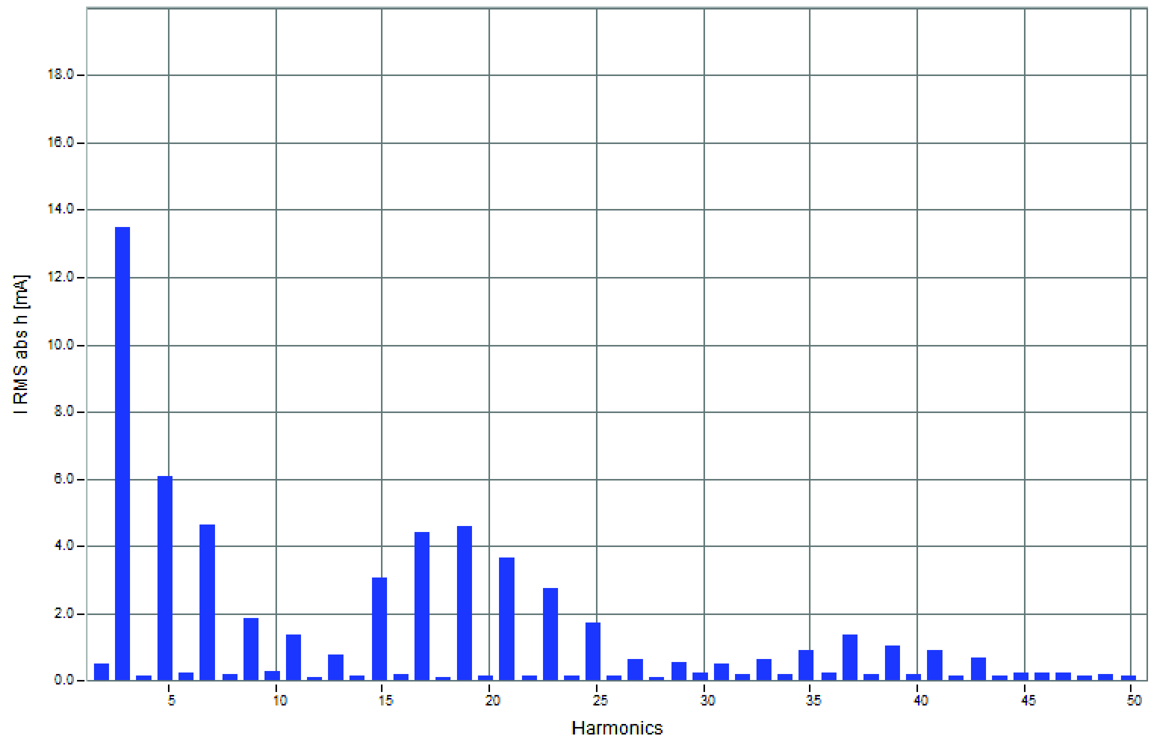


Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.51\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.50\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:

Voltage: U = 240.00 V
Current: I = 0.76 A
Active Power = 87.86 W
Reactive Power = 161.52 var
Apparent Power = 183.93 VA
Power Factor = 0.47

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

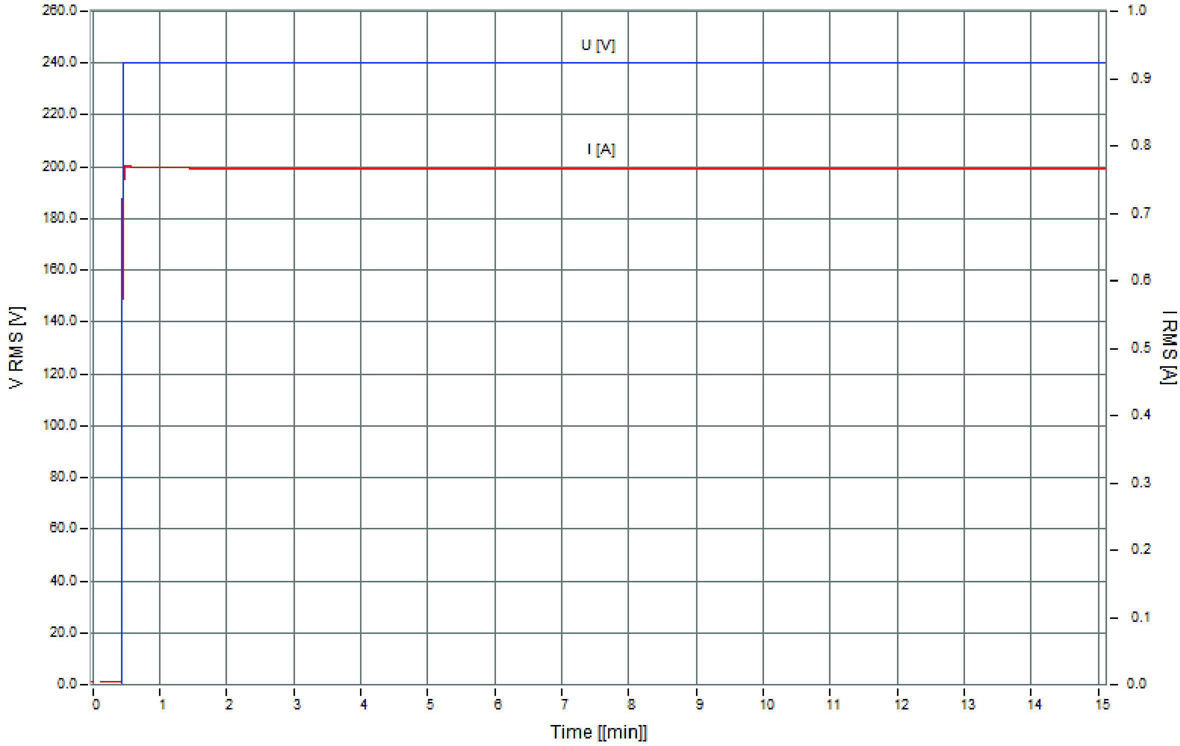


Figure 34. Root Mean Square of voltage and current - 240 V

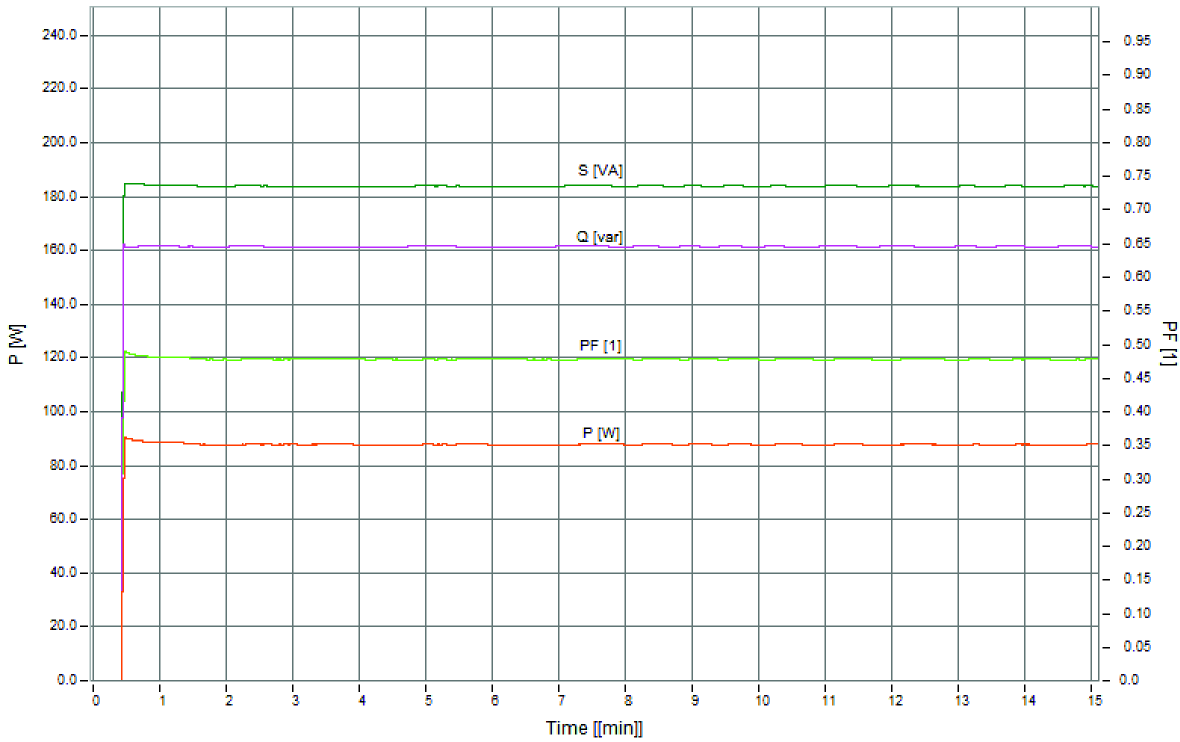


Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 240.47	[V]	*****	0.00^0
I L1 = 0.76	[A]	*****	61.44^0

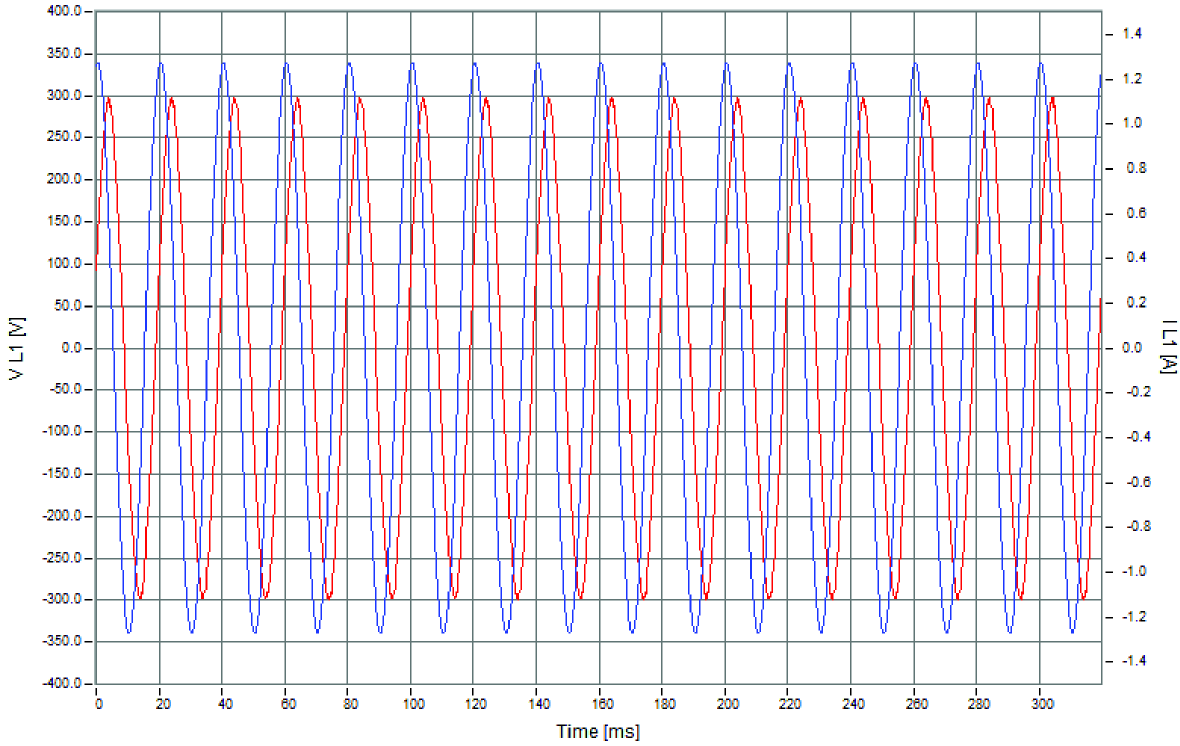


Figure 36. Current and voltage signal curve - 240 V

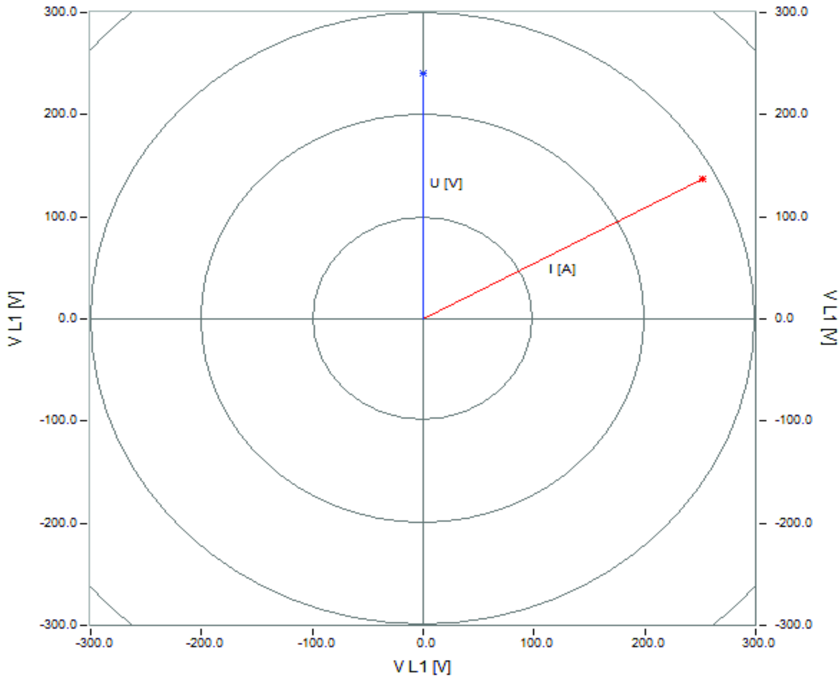


Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

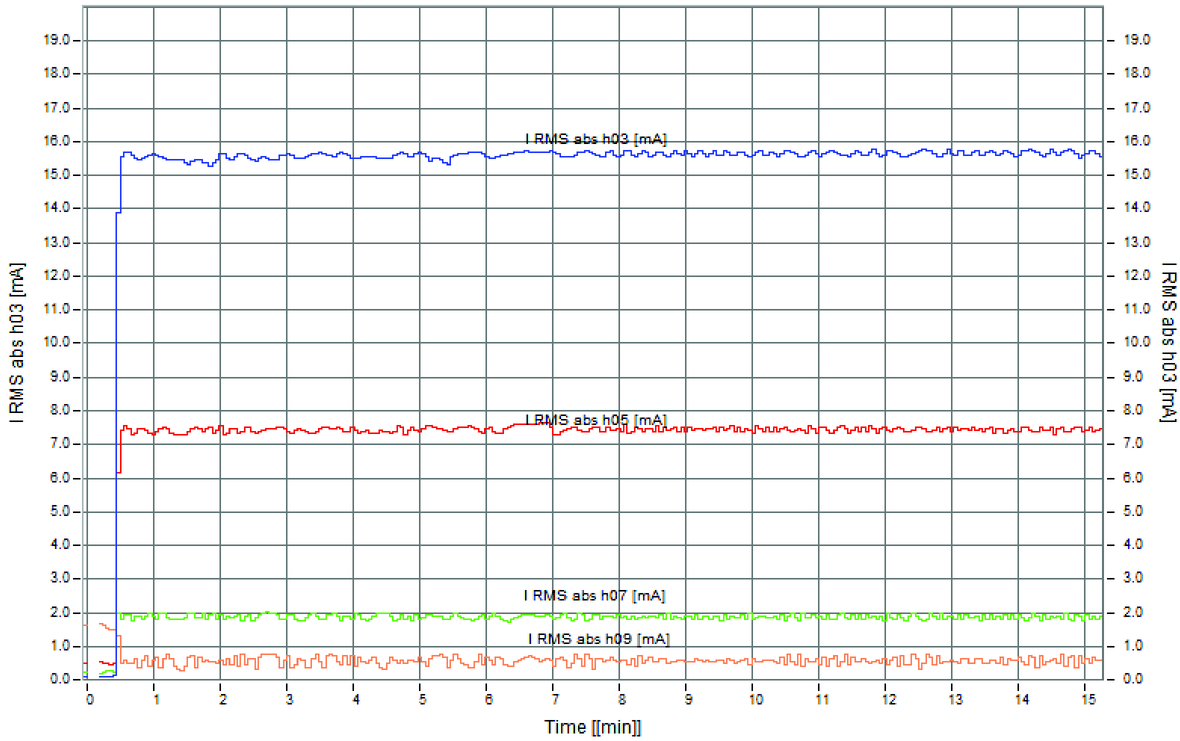


Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

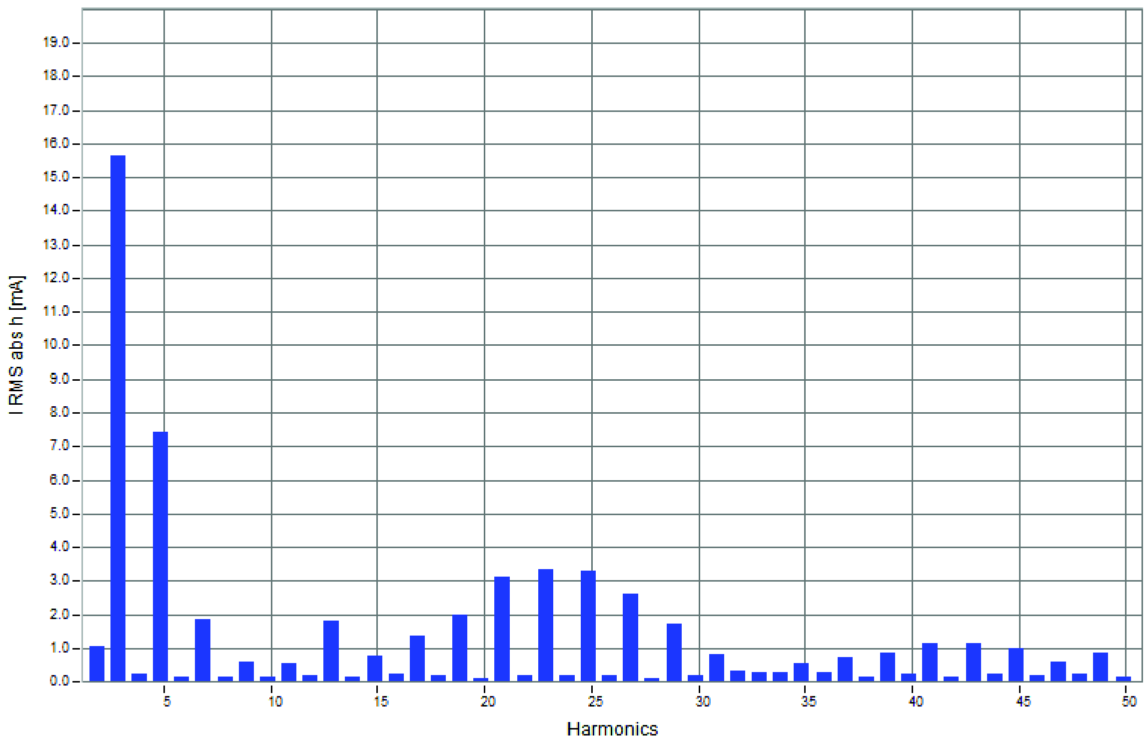


Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.48\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.48\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:
Voltage: U = 250.02 V
Current: I = 0.79 A
Active Power = 91.22 W
Reactive Power = 175.17 var
Apparent Power = 197.57 VA
Power Factor = 0.46

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

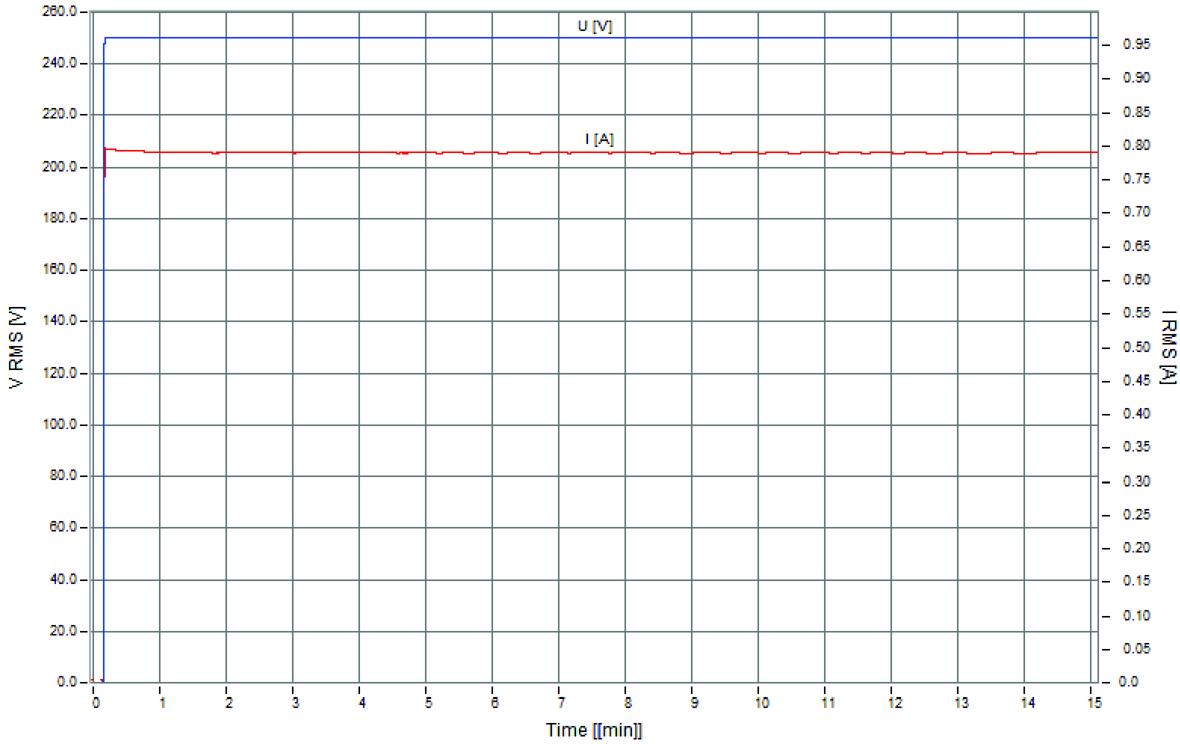


Figure 40. Root Mean Square of voltage and current - 250 V

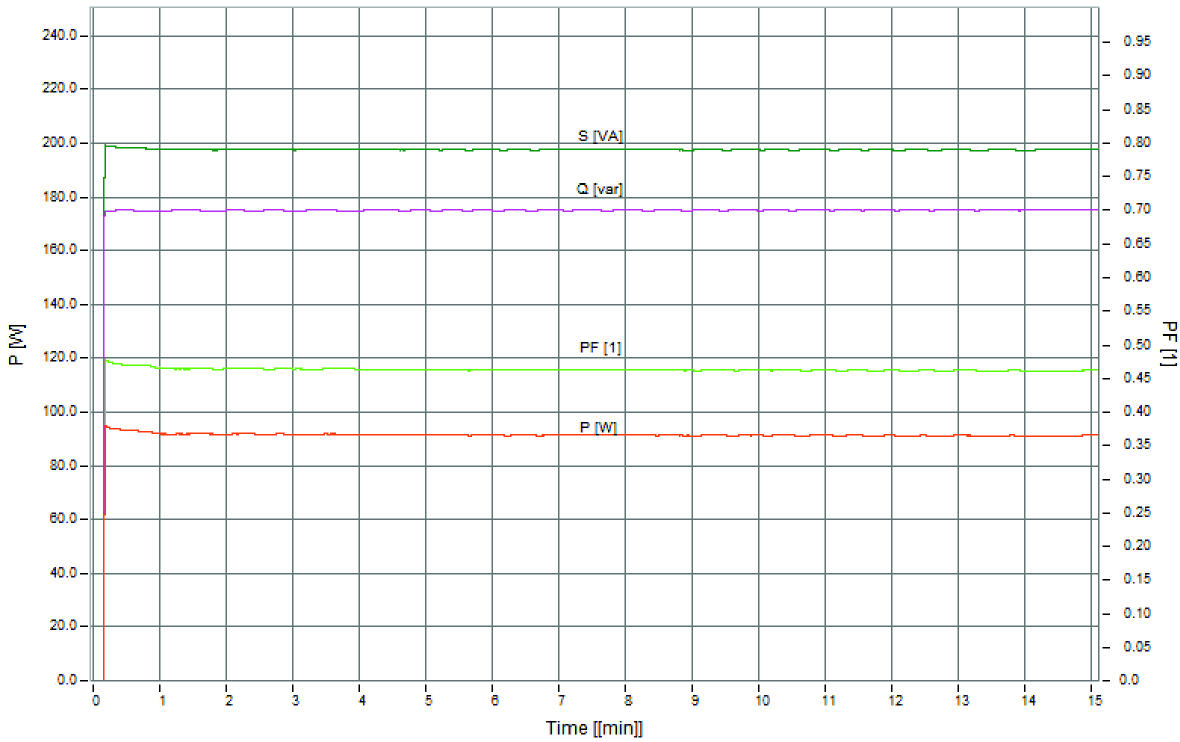


Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 250.62	[V]	*****	$0{,}00^0$
I L1 = 0.79	[A]	*****	62.35^0

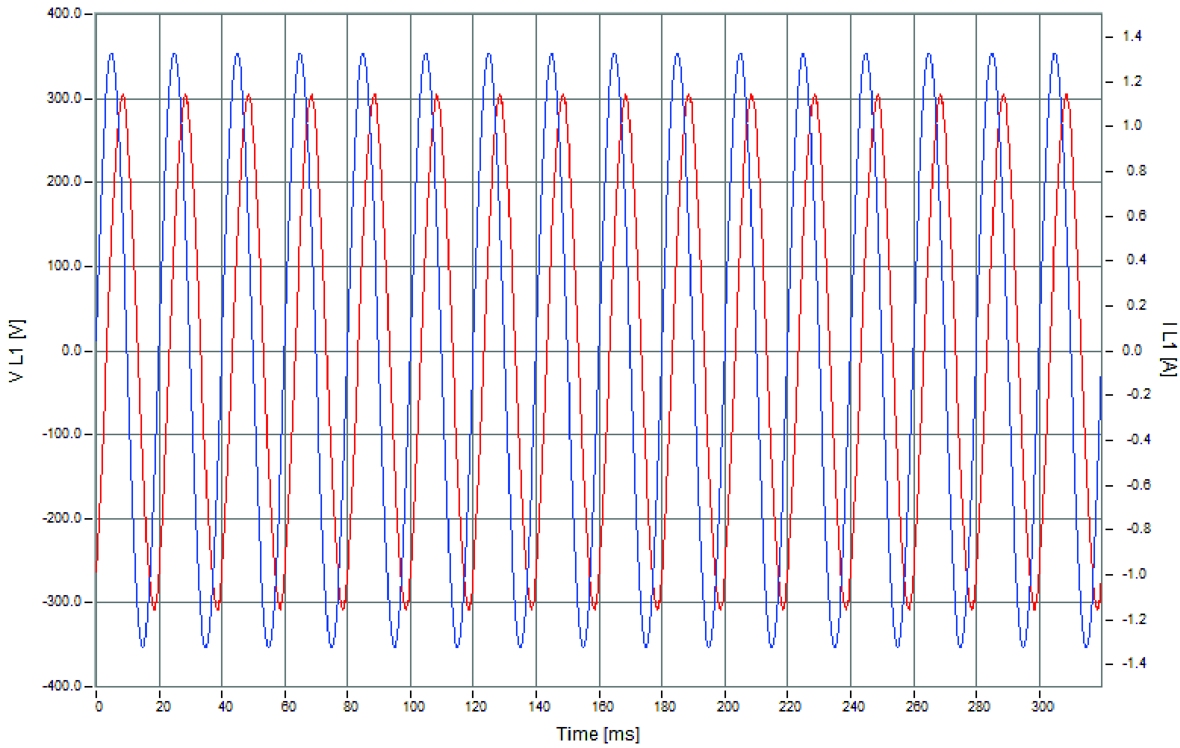


Figure 42. Current and voltage signal curve - 250 V

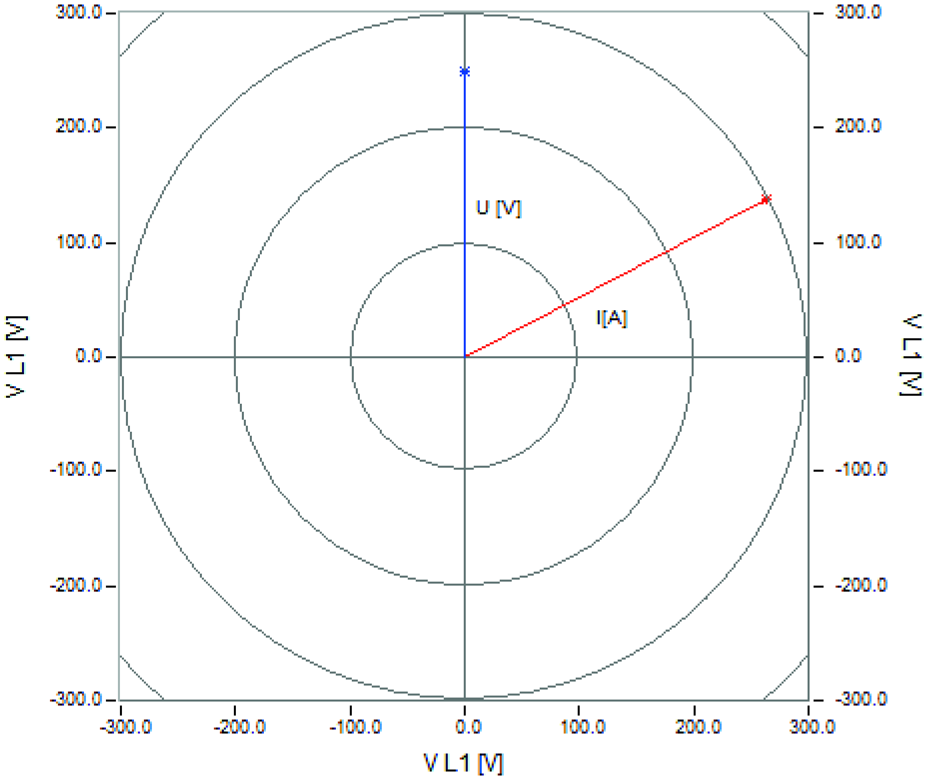


Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

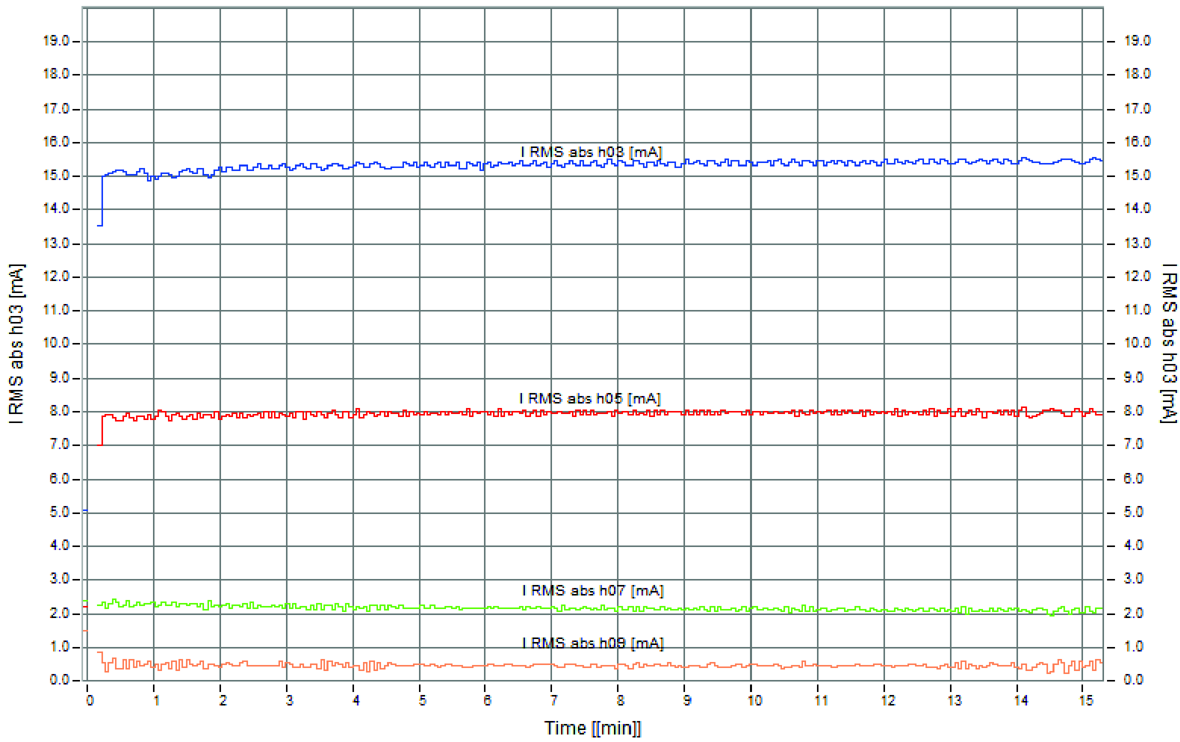


Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

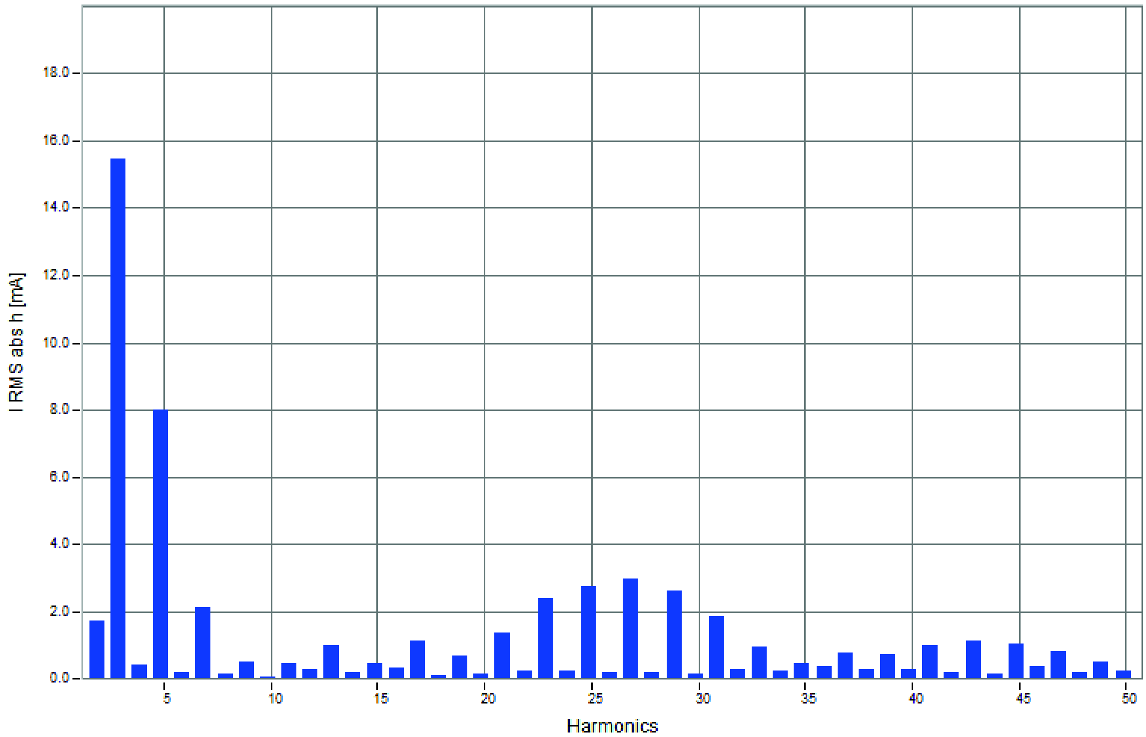


Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 2.38\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 2.38\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 3.24%, for the minimum voltage, 0.82 p.u.. The minimum THD, 2.38%, is measured for the maximum voltage 1.09 p.u.. Further increase of the voltage causes a slight decrease of the THD.

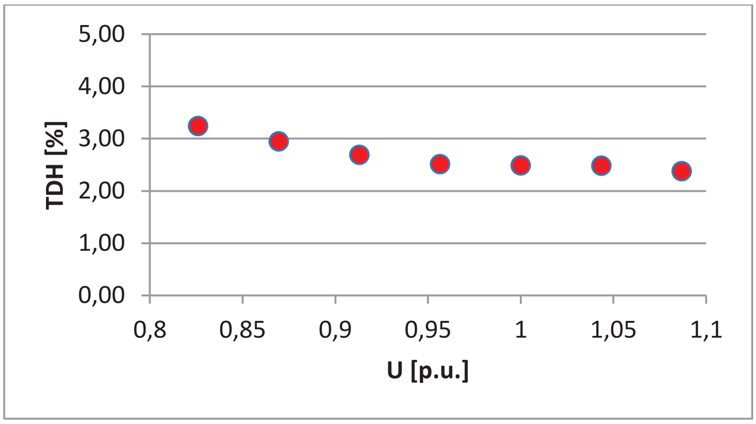
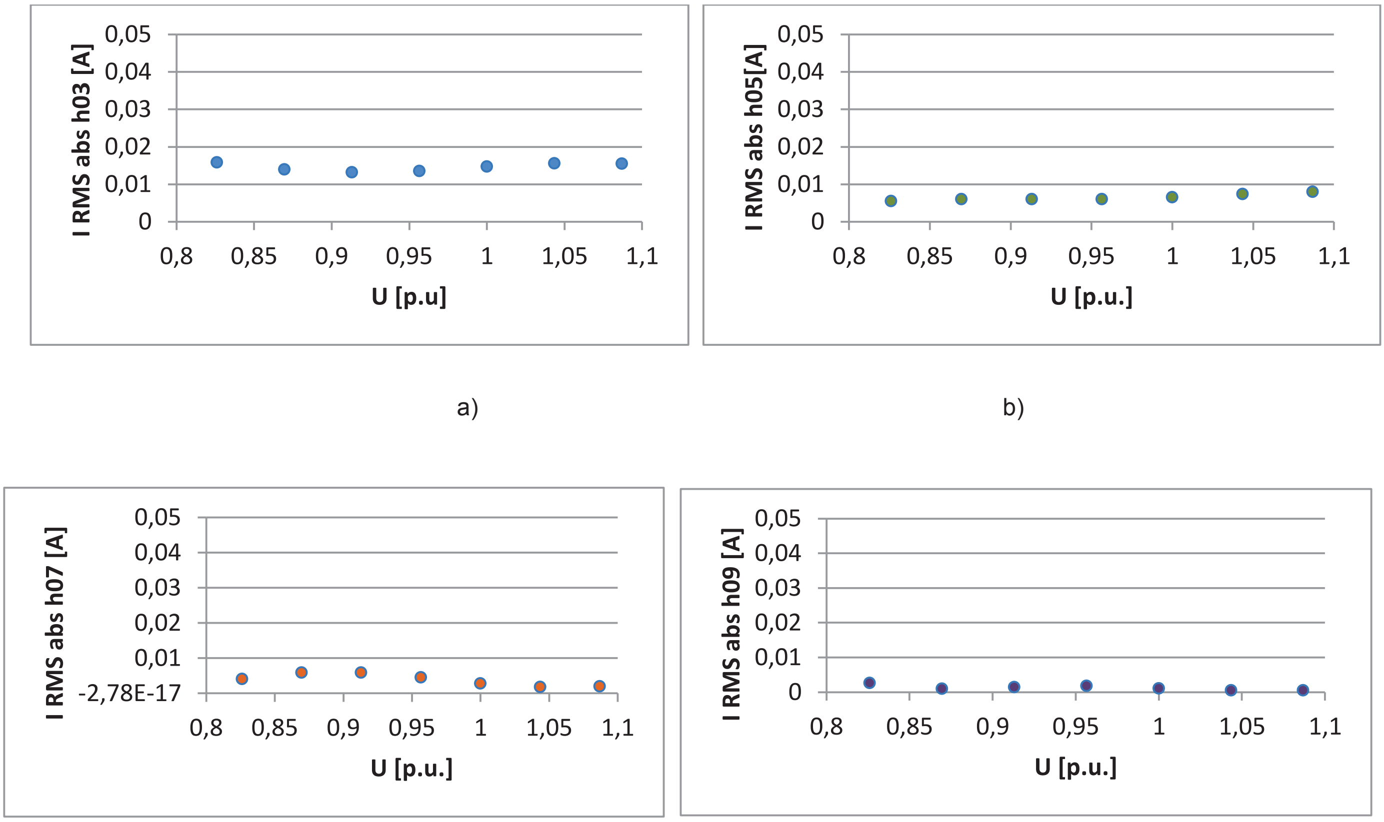


Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature



a) b)

c) d)

Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which has parabolic behaviour with minimum 0.013 on the voltage 0.95 . Figures 47. b) shows the 5th harmonic respectively, which have exponential rising behaviour . In this case the harmonic values are increasing with the voltage increases. Figure 47. c) shows 7th harmonic which has parabolic behaviour with maximum on the voltage 0.95.Figure 47,d) shows 9th harmonic which decreases marginally with the voltage increase.

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MEASUREMENT PROTOCOL 9

LED BRS419
1Xmodule-24Xlight source
Electronic ballast

Vienna 15.February 2016

1. Content

2. List of figures

3. Light type

LEDs
24 X light Source
Status: new

4. Technical data

Mile Wide LED Mini BRS419 ECO43-2S/740 | WSO GR
Voltage: 220-240 V
Real power : 17 W
Frequency : 50-60 Hz

Electronic ballast: **PHILIPS**
Voltage: 40 W
Current: 0.7 A

5. Measurement

5.1. Schema

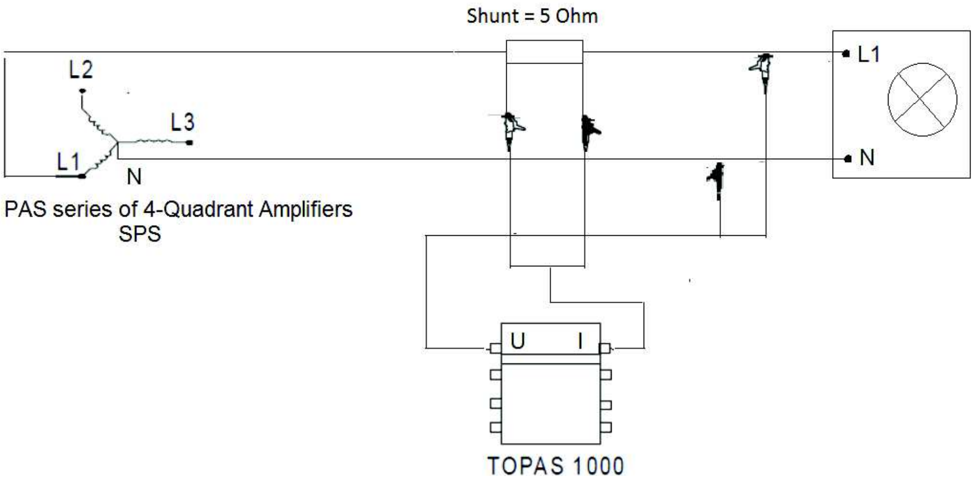

Figure 1. Measurement schema

5.2. Instrument

PAS series of 4-Quadrant amplifiers (SPS): low harmonic distortion even under non linear condition - very low internal resistance.

Power Quality Analyser TOPAS 1000: load behaviour and harmonics.

5.3. Process

Place: Inside
Temperature: 23.0°C
Voltage range: 190-250 V
Shunt: 5 Ω
Measurement interval: 15 min

Figure 2. Measurement place

6. Measurement results

6.1. Nominal condition (voltage 1 p.u. ; 230 V)

Average value from last five minutes of measurement
Voltage: U = 230.39 V
Current: I = 0.082 A
Active Power = 15.35 W
Reactive Power = 11.09 var
Apparent Power = 19.03 VA
Power Factor = 0.8

6.1.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

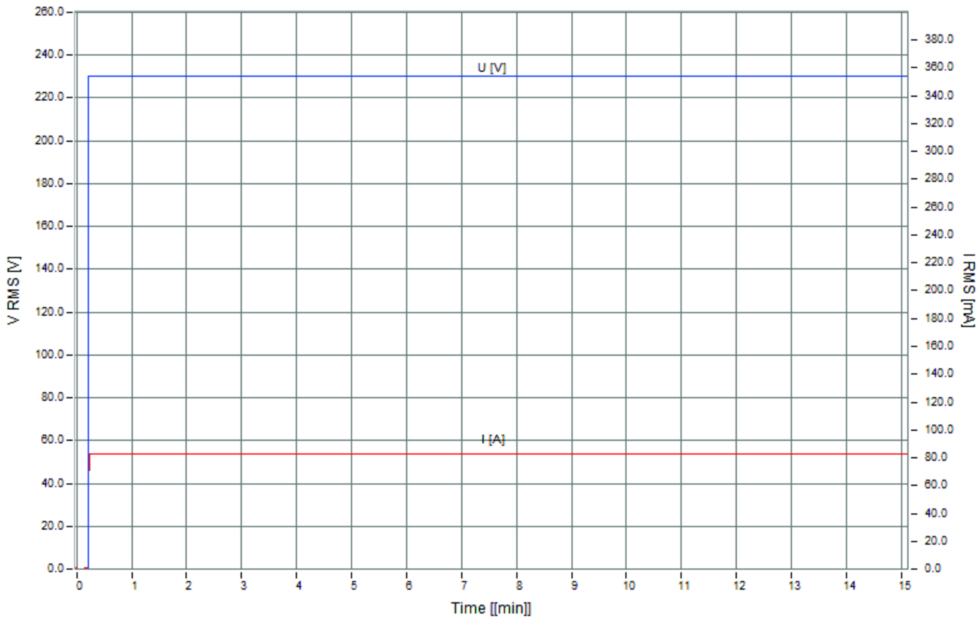

Figure 3. Root Mean Square of voltage and current - 230 V

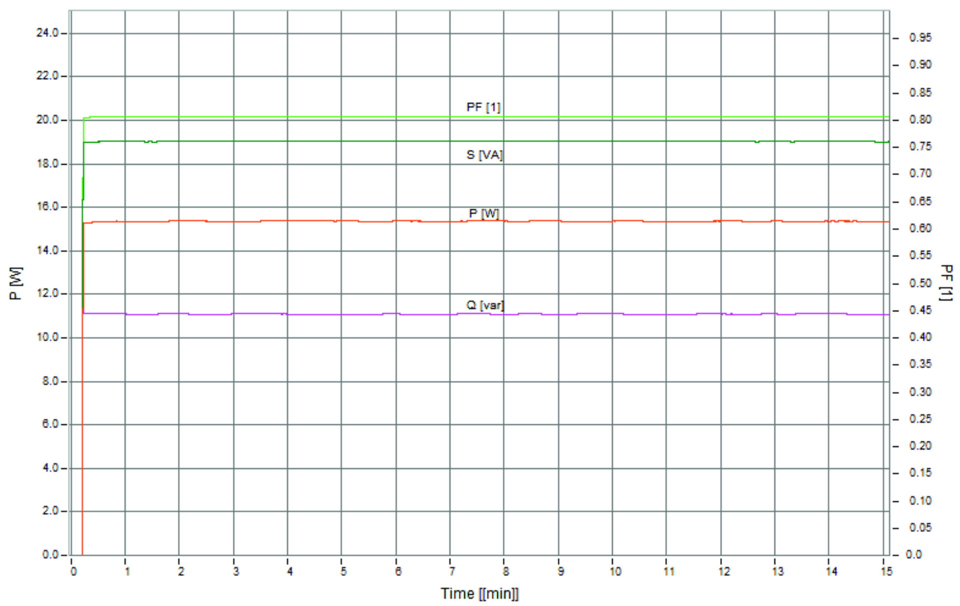

Figure 4. Root Mean Square of active Power, reactive power, apparent power and power factor - 230 V

6.1.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 230.39	[V]	*****	0.00^0
I L1 = 0.082	[A]	*****	35.78

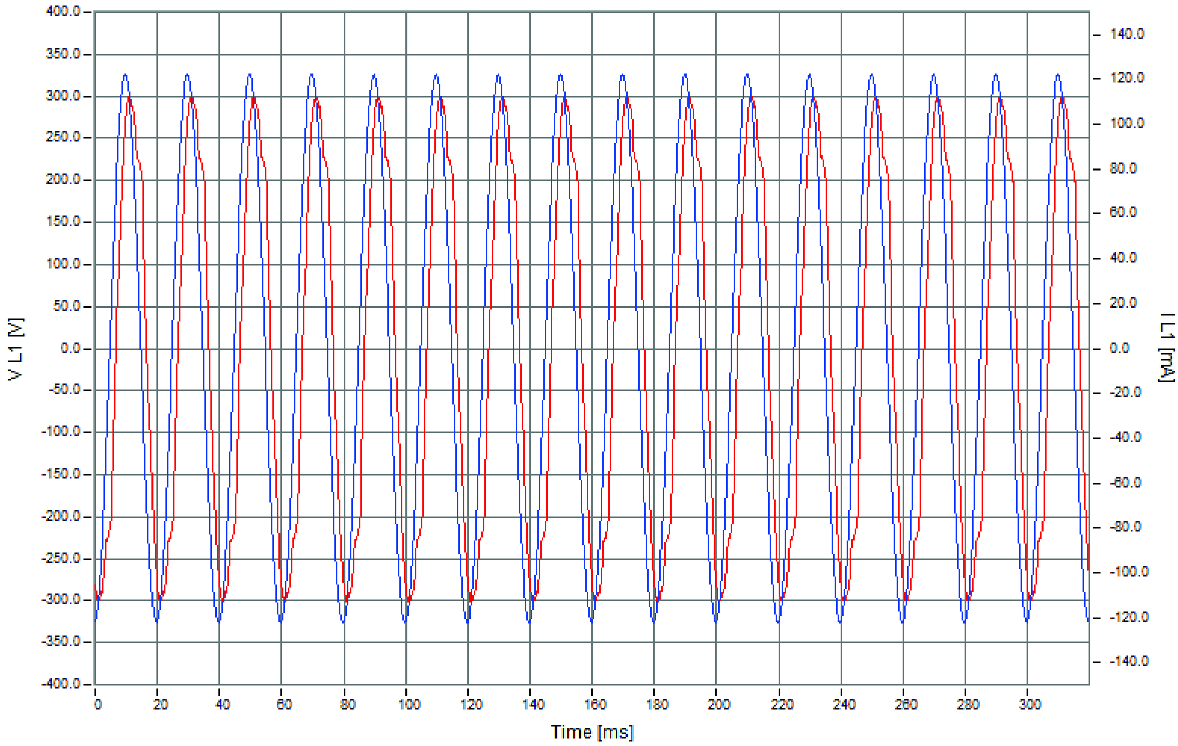

Figure 5. Current and voltage signal curve - 230 V

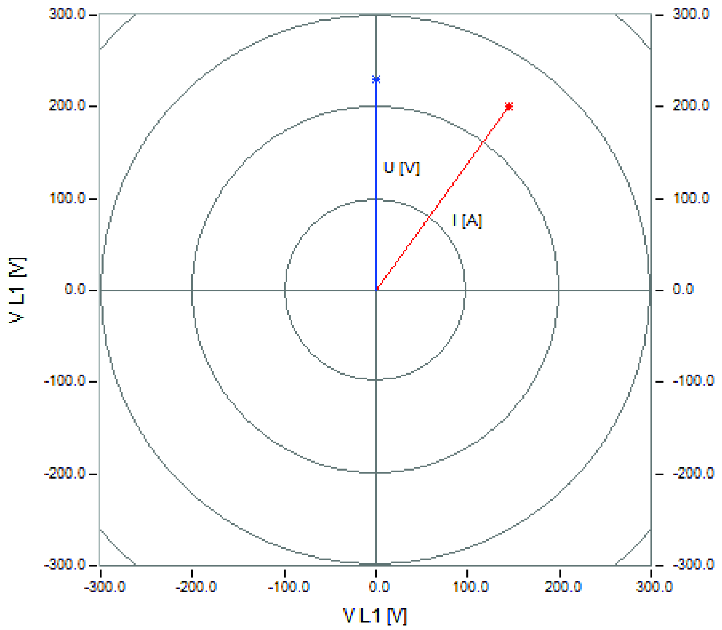

Figure 6. Voltage and current vectors- 230 V

6.1.3. Current harmonics

The evolution of current harmonics for 15 min. is shown in Figure 7 and it can be seen these values are stable in the last minute (Figure 8).

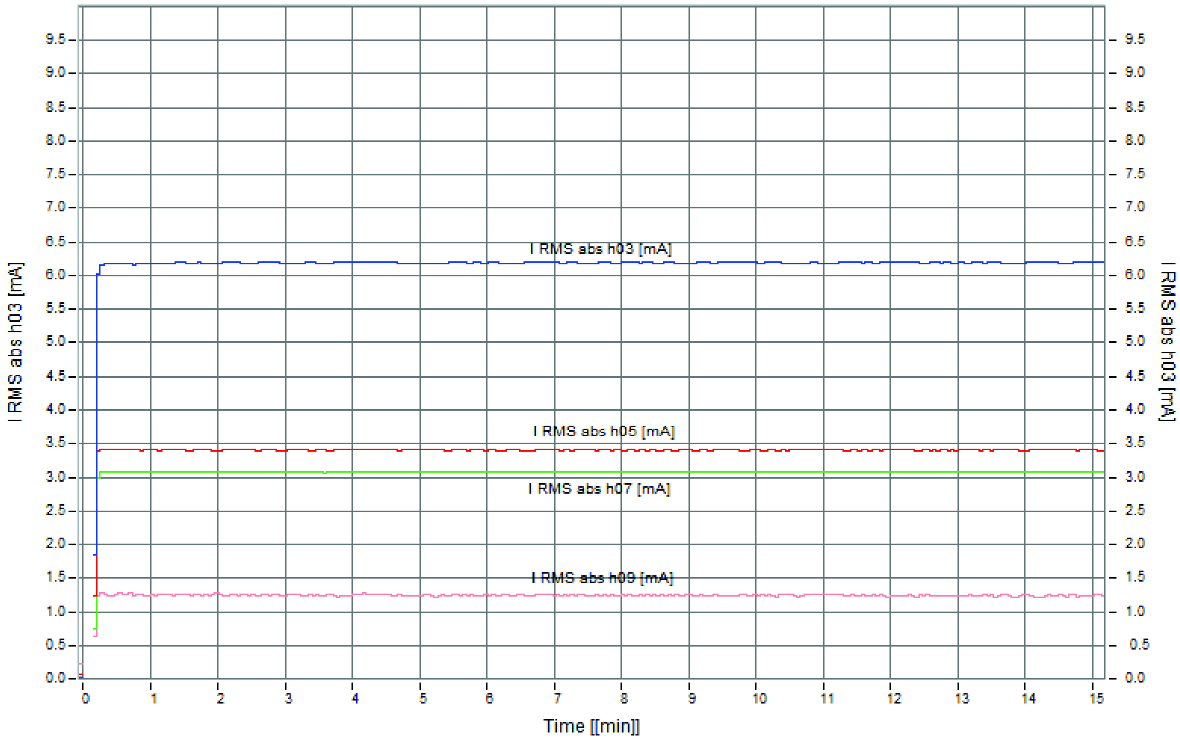

Figure 7. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 230 V

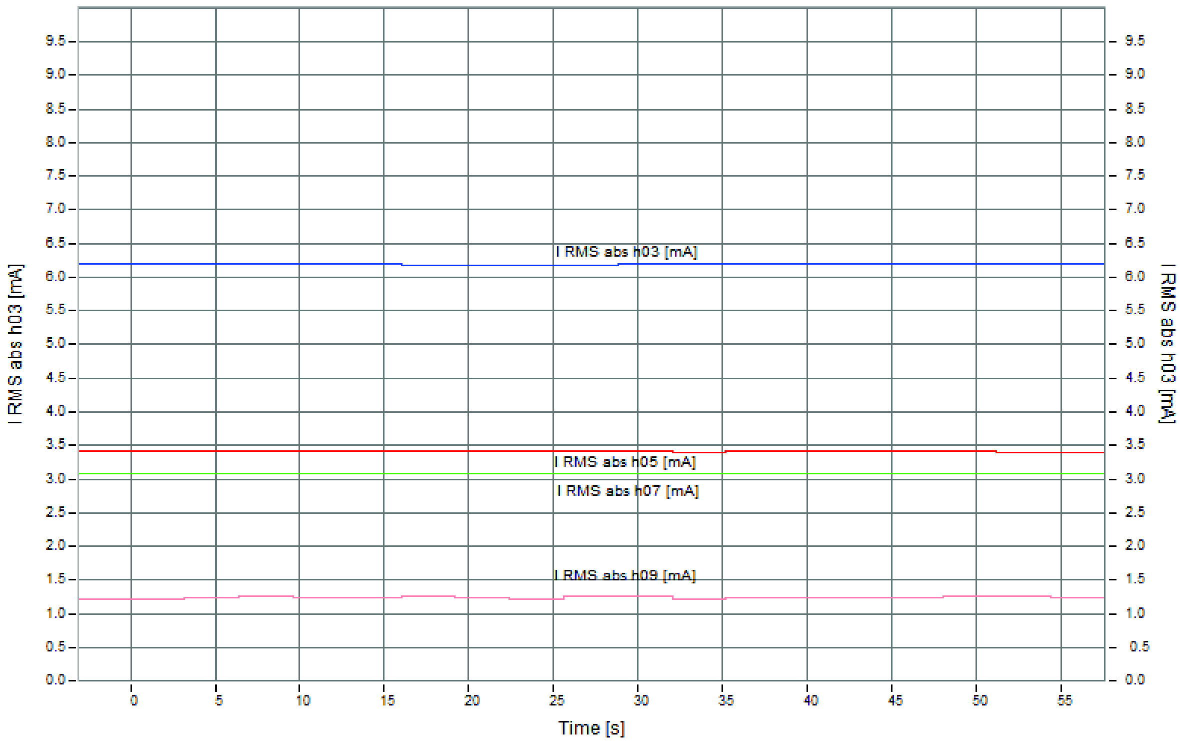

Figure 8. Evolution of 3rd, 5th, 7th and 9th harmonic current in the last minute - 230

Total harmonic distortion for the last minute of mueasurement is depicted in Figure 9.

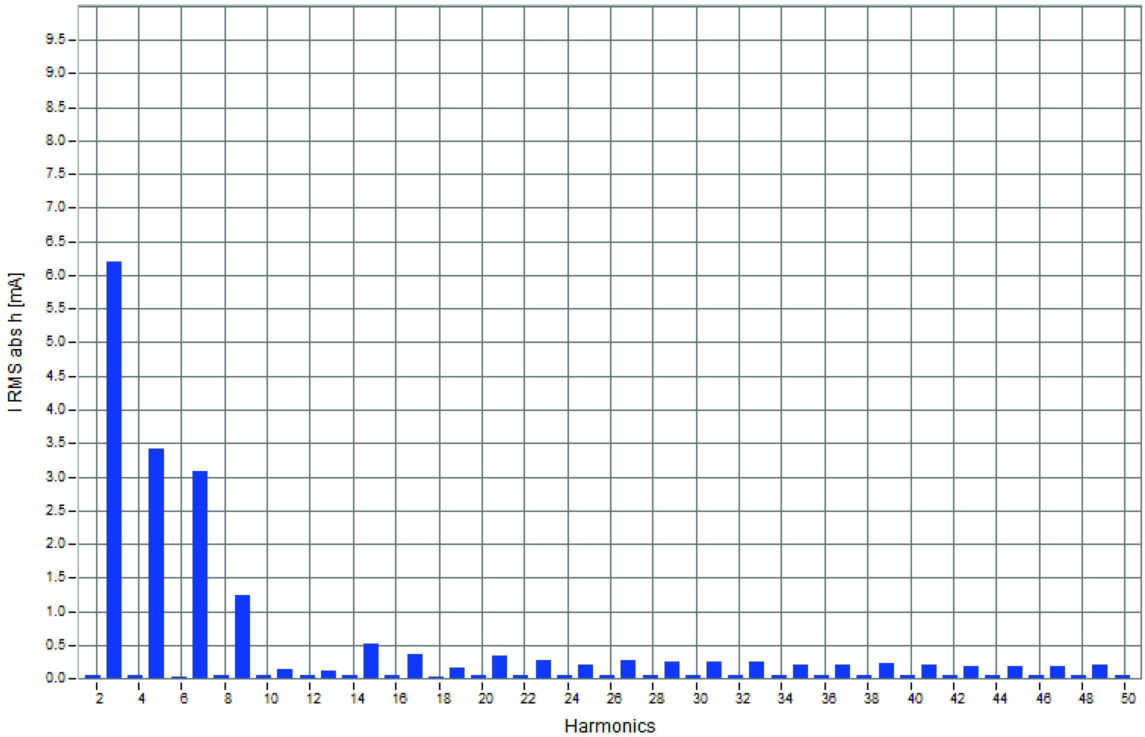

Figure 9. Root Mean Square absolute value of TDH in mA of the last minute - 230 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.60\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_N^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.55\ \%$$

6.2. Voltage lower than nominal (0.82 p.u. ; 190 V)

Average value from last five minutes of measurement:
Voltage: U = 190.30 V
Current: I = 0.081 A
Active Power = 13.60 W
Reactive Power = 7.40 var
Apparent Power = 15.56 VA
Power Factor = 0.87

6.2.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

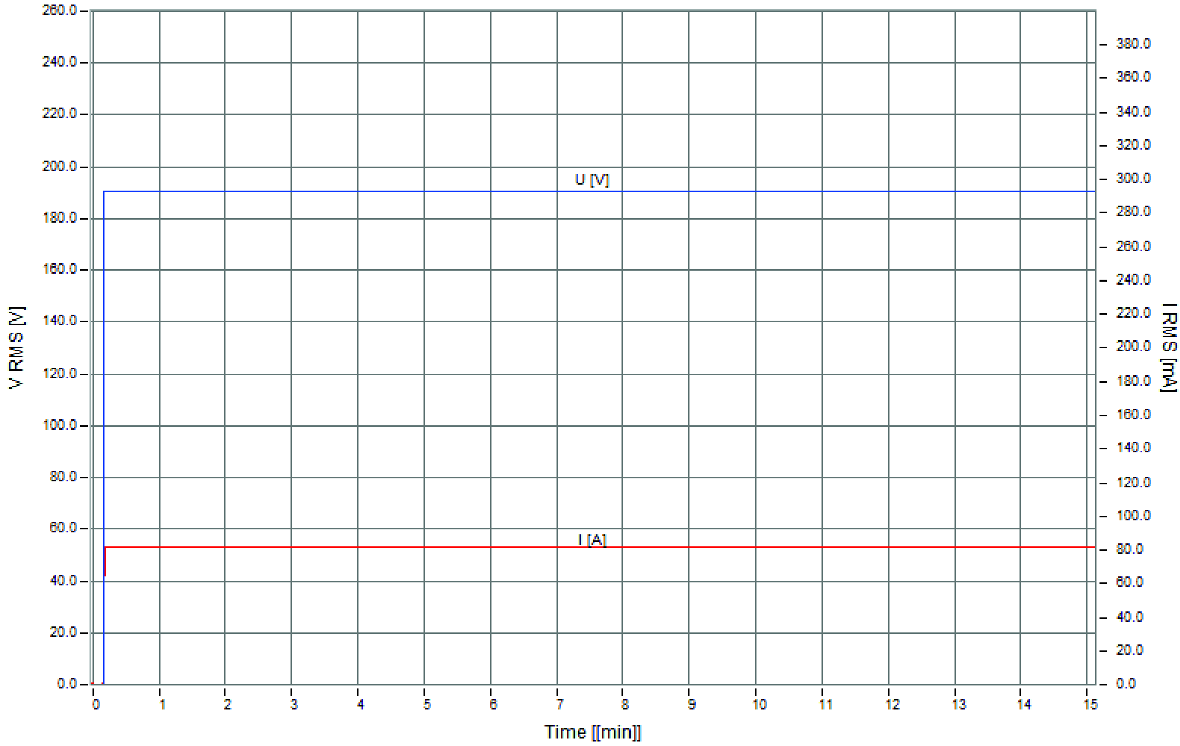

Figure 10. Root Mean Square of voltage and current - 190 V

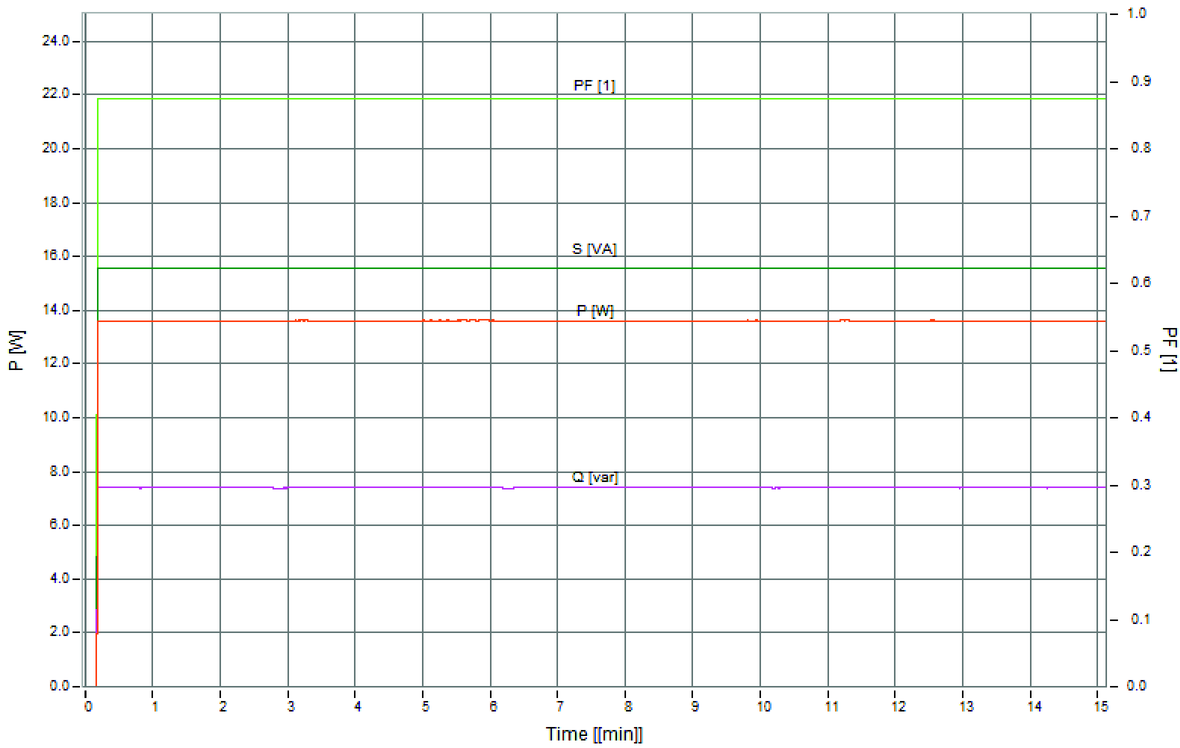

Figure 11. Root Mean Square of active power, reactive power, apparent power and power factor - 190 V

6.2.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 190.32	[V]	*****	0.00⁰
I L1 = 0.081	[A]	*****	28.56⁰

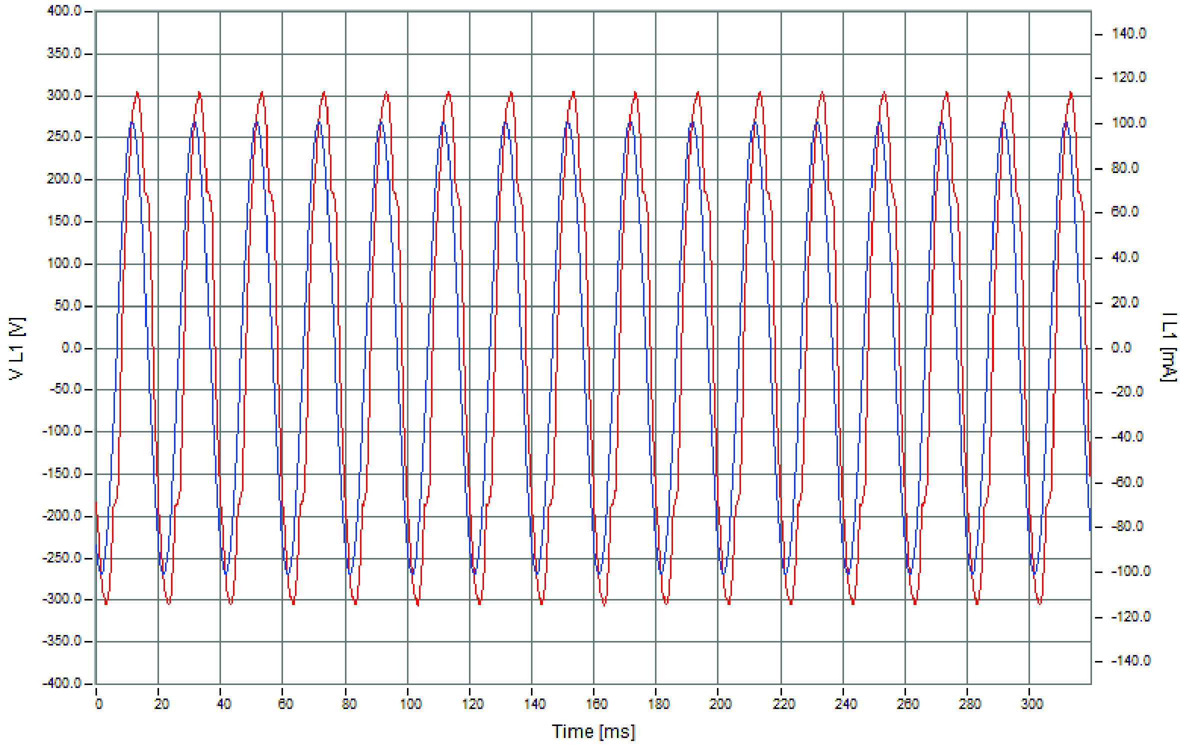

Figure 12. Current and voltage signal curve - 190 V

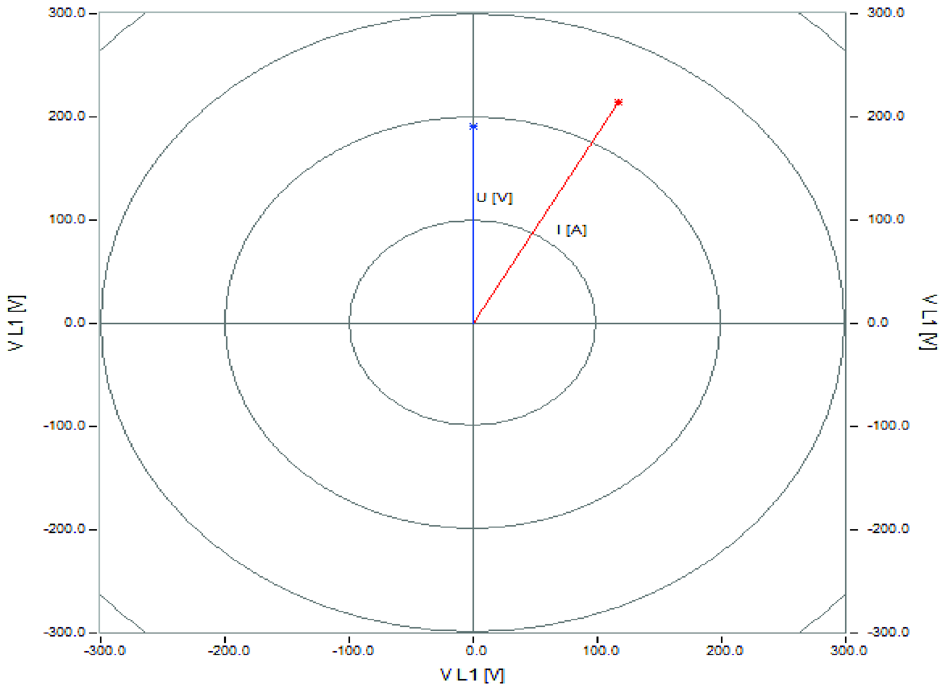

Figure 13. Voltage and current vectors - 190 V

6.2.3. Current harmonics

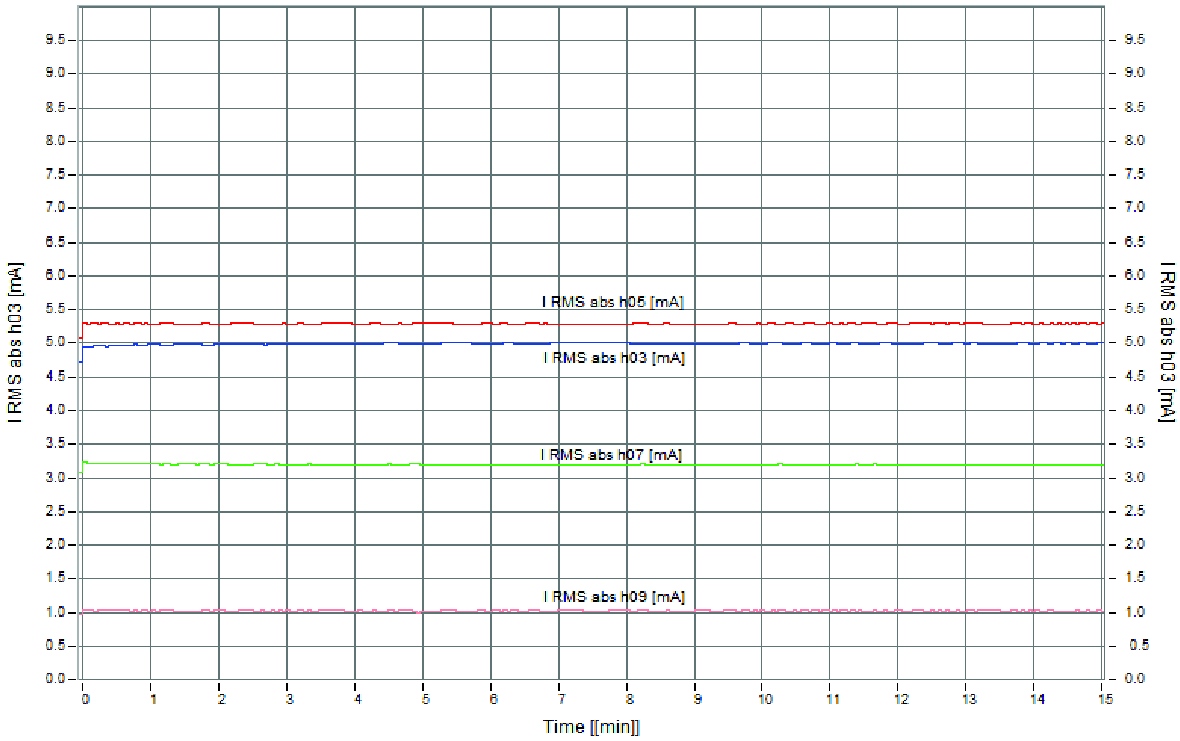

Figure 14. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 190 V

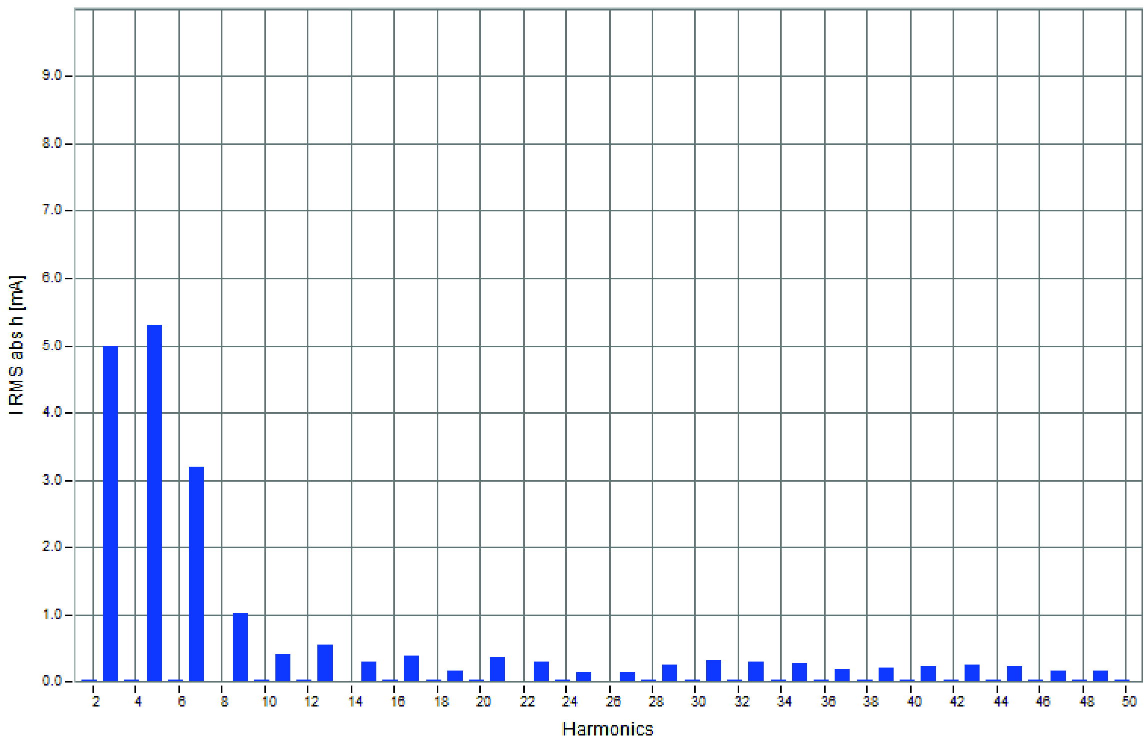

Figure 15. Root Mean Square absolute value of TDH of mA of the last minute - 190 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.97\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.91\ \%$$

6.3. Voltage lower than nominal (0.86 p.u. ; 200V)

Average value from last five minutes of measurement:
Voltage: U = 200.33 V
Current: I = 0.081 A
Active Power = 13.99 W
Reactive Power = 8.2 var
Apparent Power = 16.32 VA
Power Factor = 0.85

6.3.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

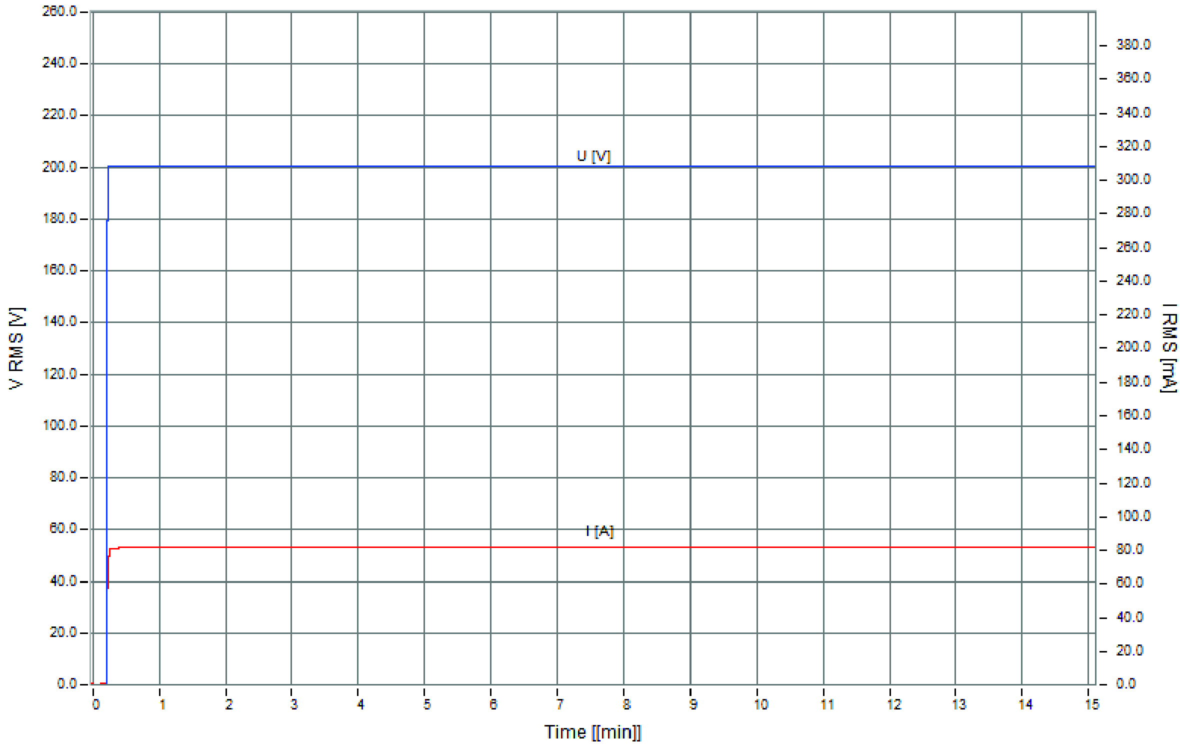

Figure 16. Root Mean Square of voltage and current - 200 V

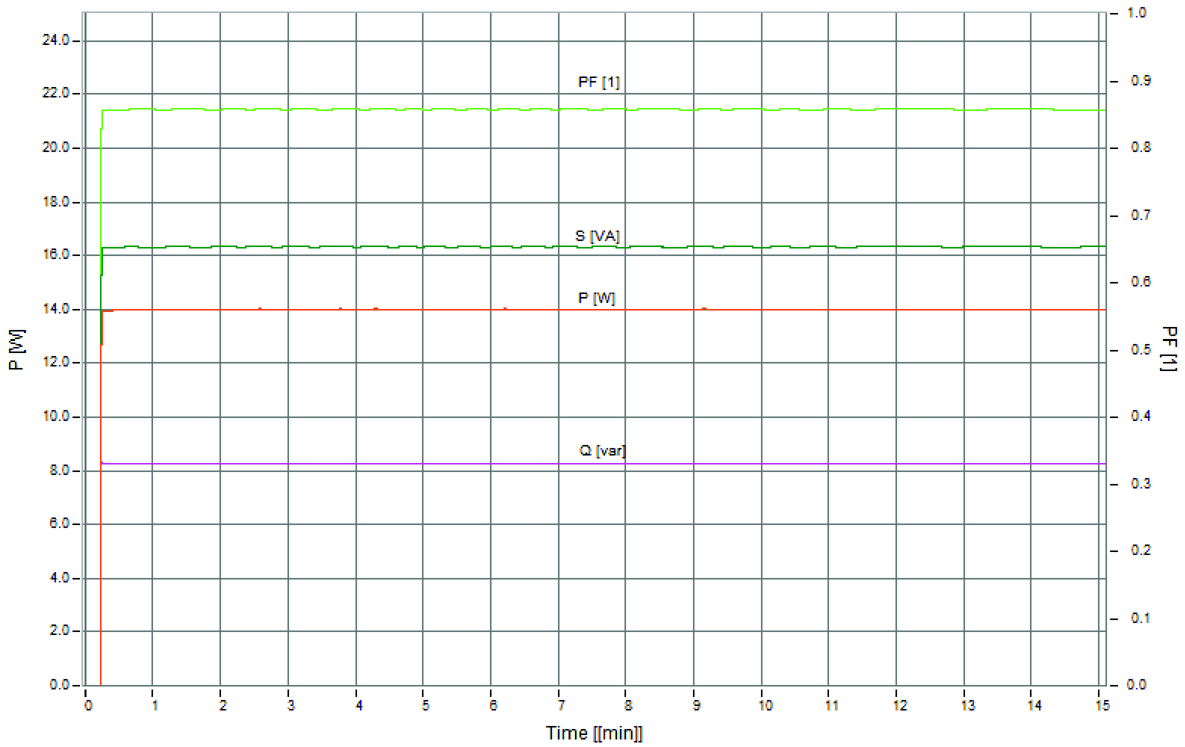

Figure 17. Root Mean Square of active power, reactive power, apparent power and power factor - 200 V

6.3.2. Oscilloscope results:Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 200.34	[V]	*****	0.00⁰
I L1 = 0.081	[A]	*****	30.47⁰

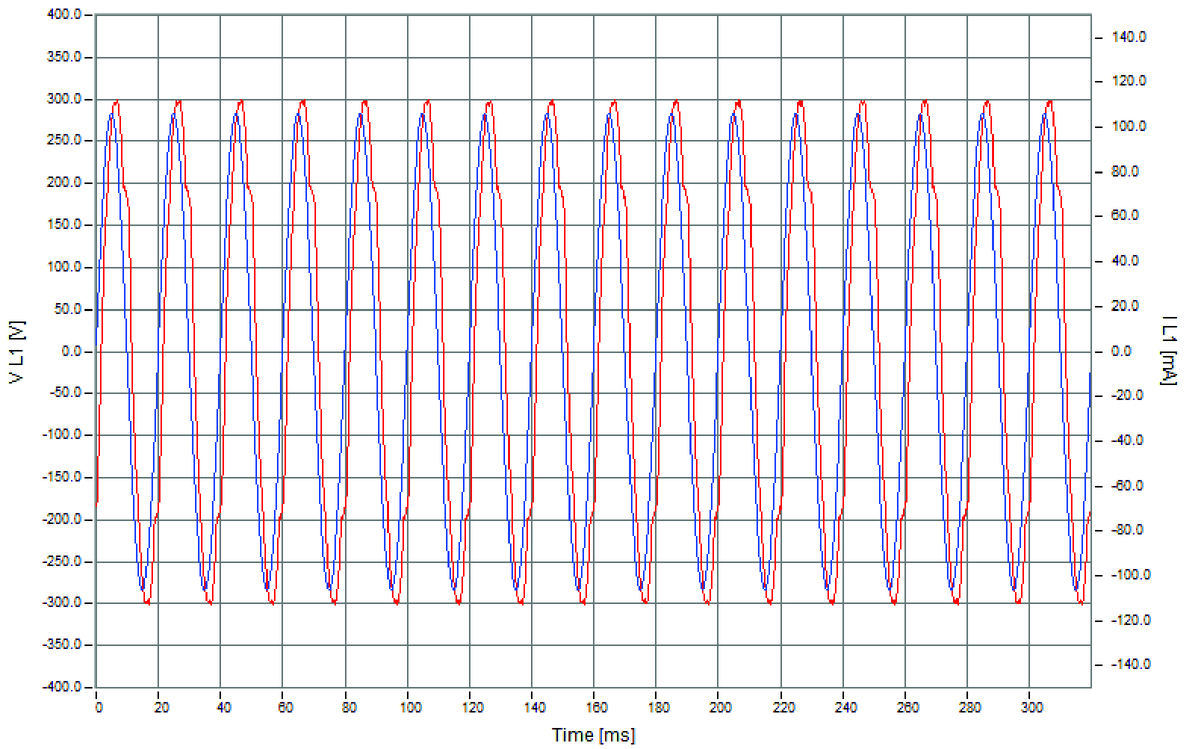

Figure 18. Current and voltage signal curve - 200 V

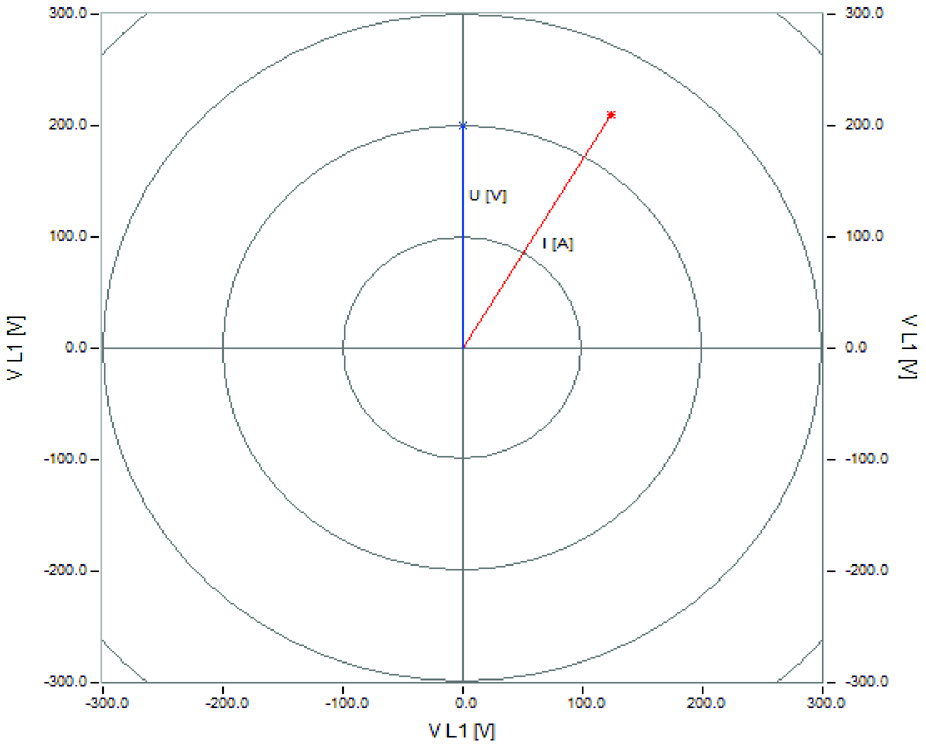

Figure 19. Voltage and current vectors - 200 V

6.3.3. Current harmonics

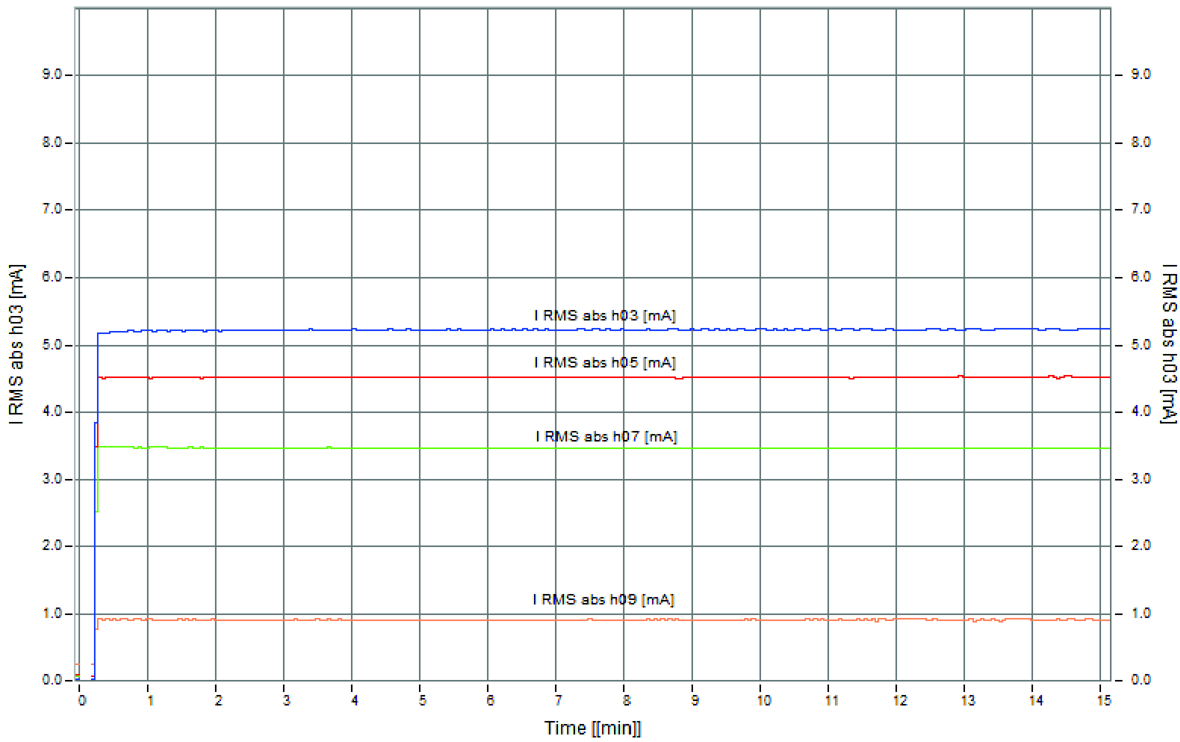

Figure 20. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 200 V

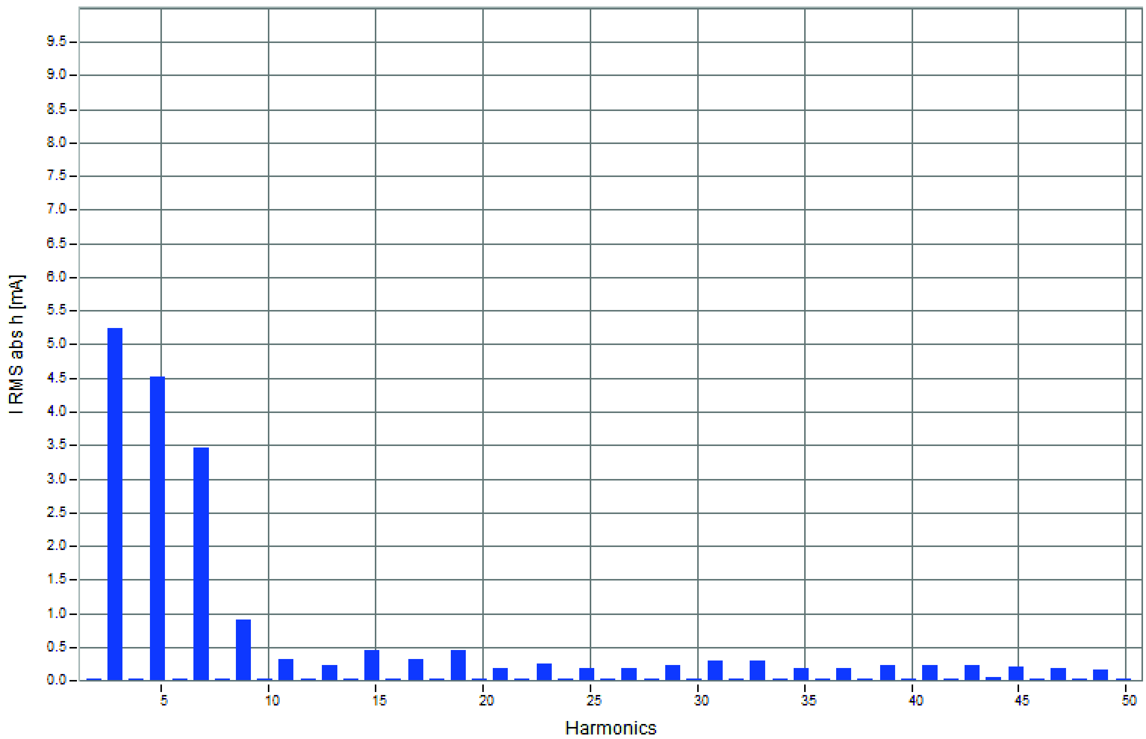

Figure 21. Root Mean Square absolute value of TDH of mA of the last minute - 200 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.71\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.65\ \%$$

6.4. Voltage lower than nominal condition (0.91 p.u. ; 210 V)

Average value from last five minutes of measurement:
Voltage: U = 210.35 V
Current: I = 0.081 A
Active Power = 14.41 W
Reactive Power = 9.14 var
Apparent Power = 17.14 VA
Power Factor = 0.84

6.4.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

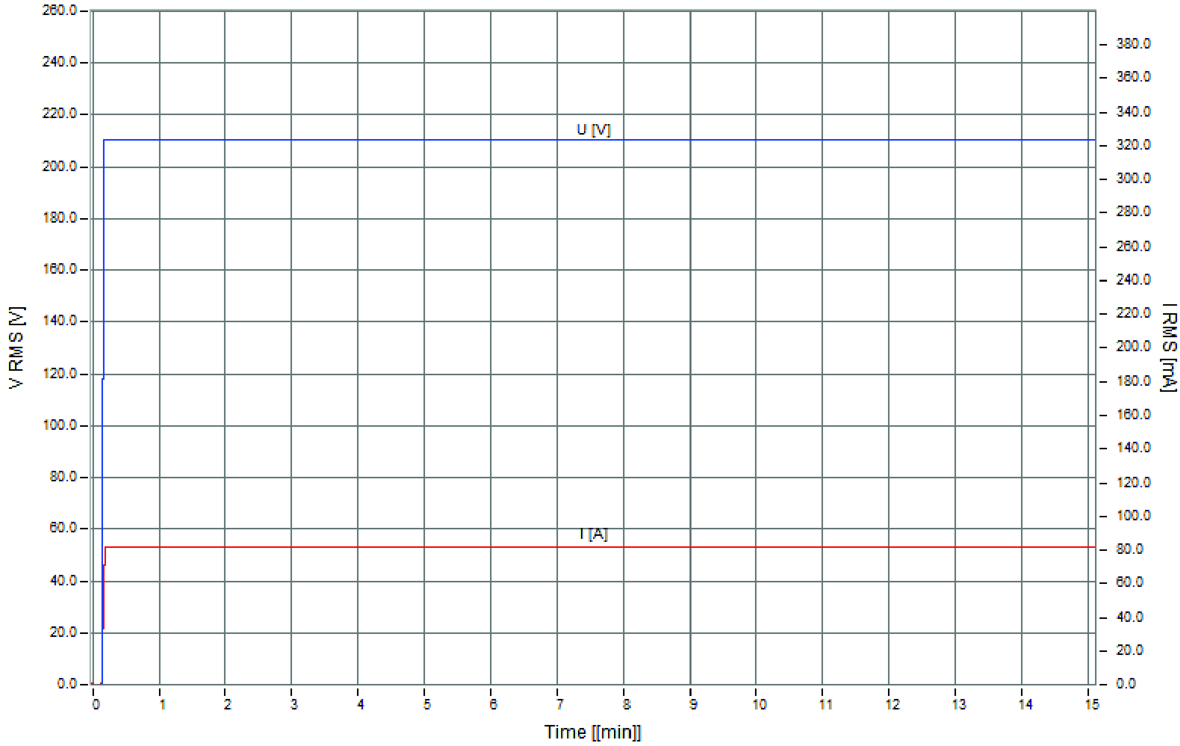

Figure 22. Root Mean Square of voltage and current - 210 V

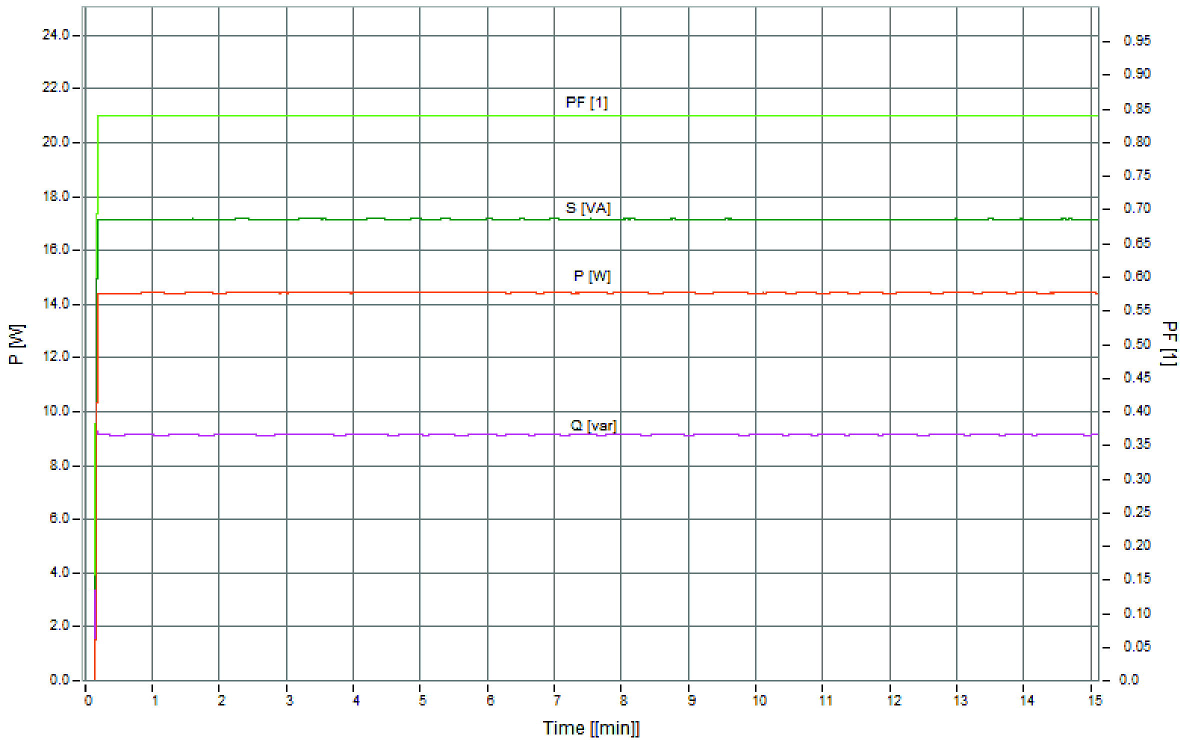

Figure 23. Root Mean Square of active power, reactive power, apparent power and power factor - 210 V

6.4.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 210.35	[V]	*****	0.00^0
I L1 = 0.081	[A]	*****	32.40^0

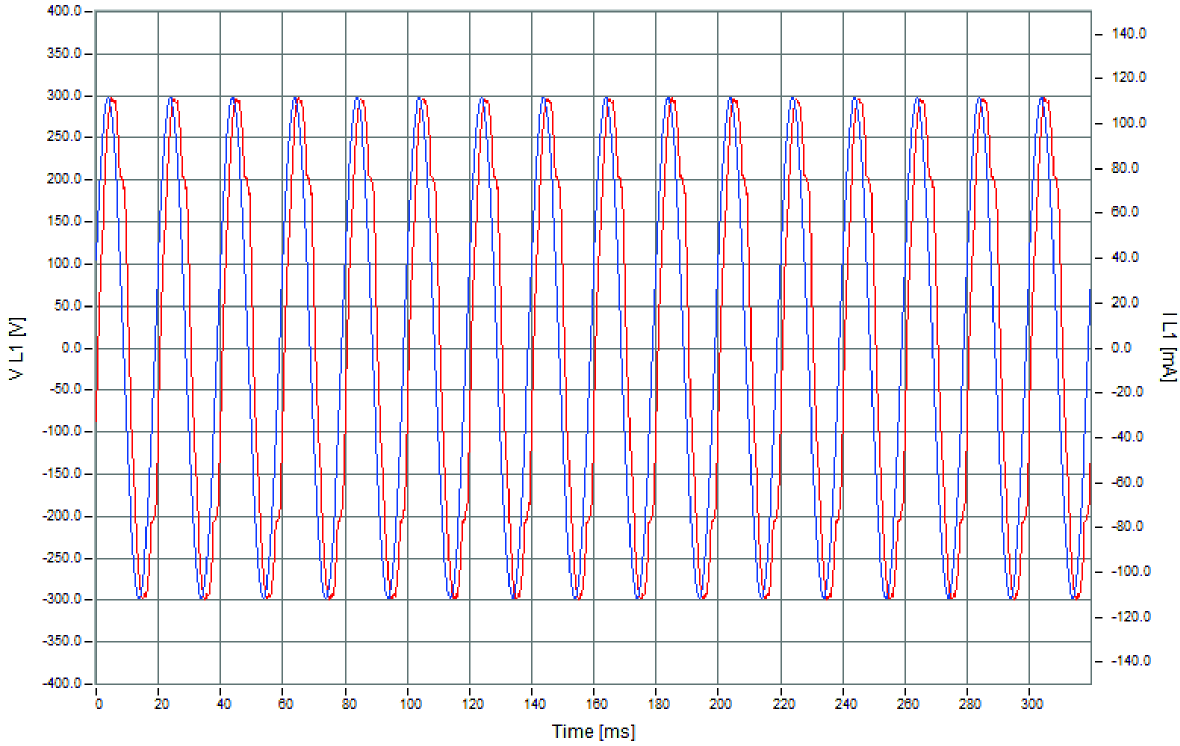

Figure 24. Current and voltage signal curve - 210 V

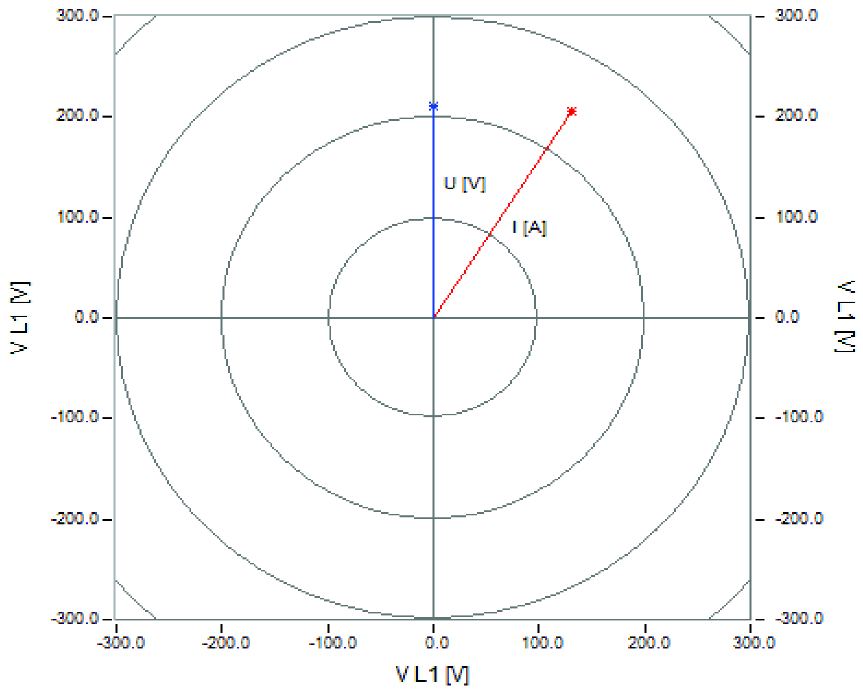

Figure 25. Voltage and current vectors - 210 V

6.4.3. Current harmonics

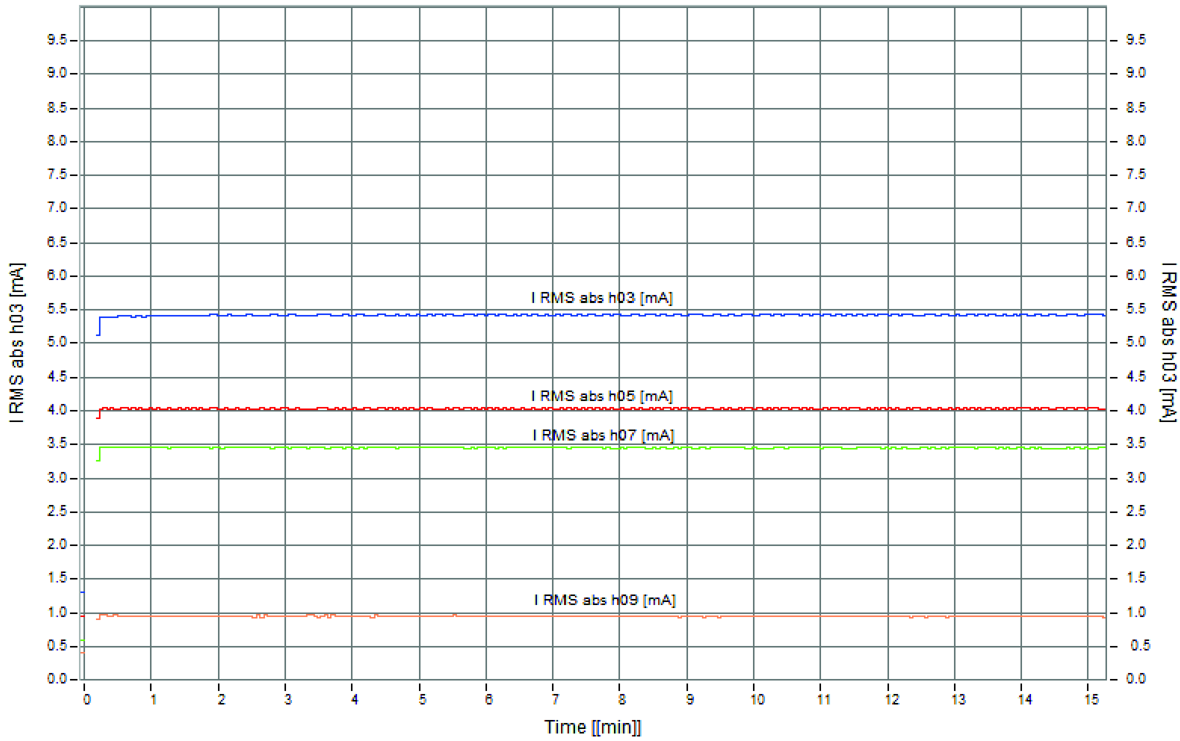

Figure 26. Time Curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 210 V

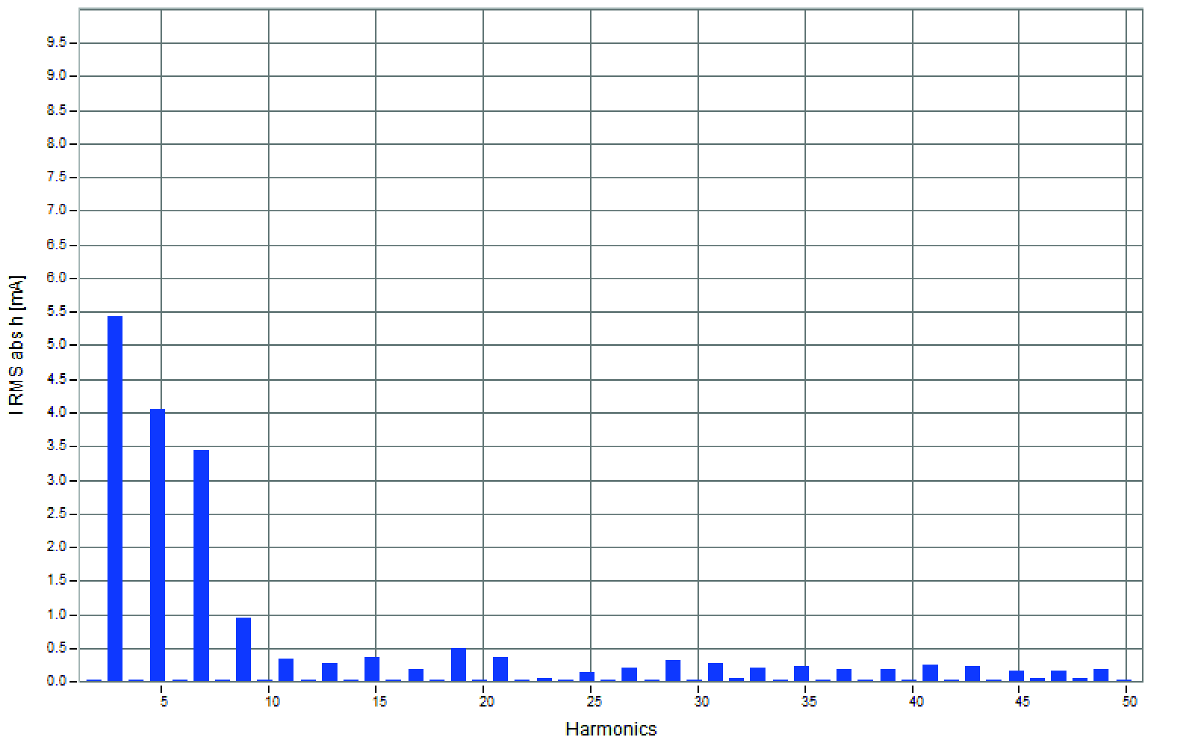

Figure 27. Root Mean Square absolute value of TDH of mA of the last minute - 210 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.53\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.48\ \%$$

6.5. Voltage lower than nominal condition (0.95 p.u. ; 220 V)

Average value from last five minutes of measurement:

Voltage: U = 219.39 V

Current: I = 0.0.082 A

Active Power = 15.02 W

Reactive Power = 10.02 var

Apparent Power = 18.14 VA

Power Factor = 0.82

6.5.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

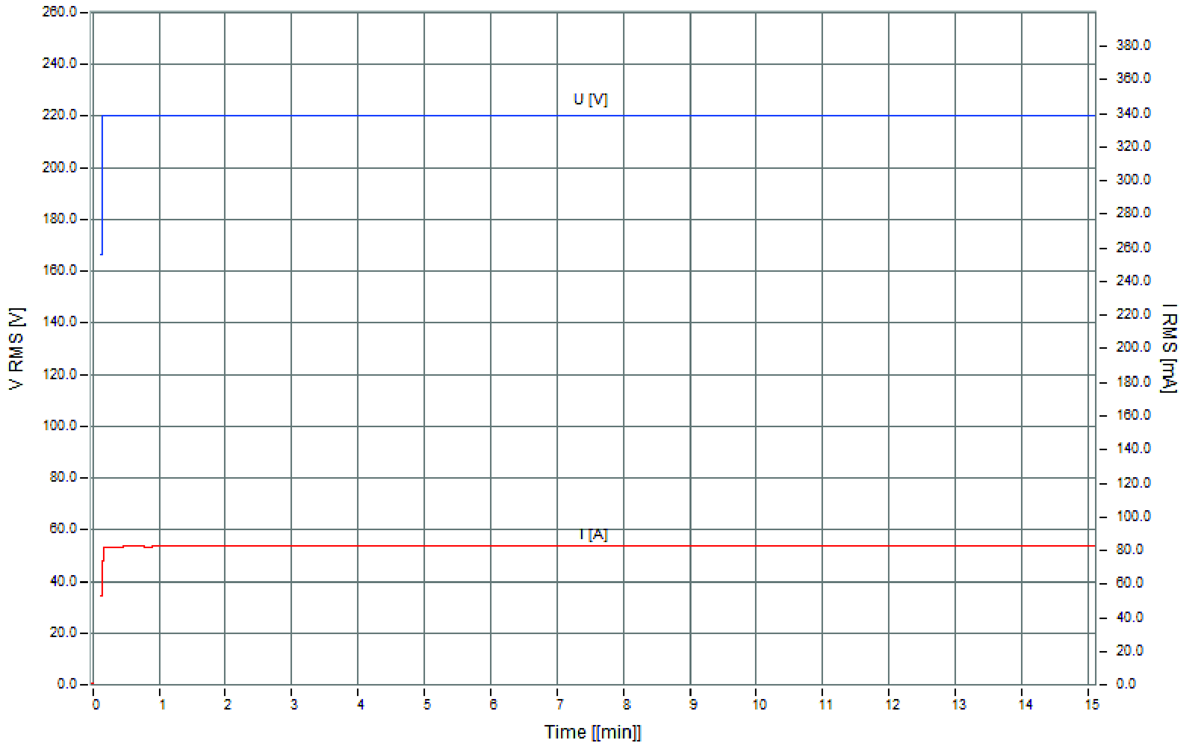

Figure 28. Root Mean Square of voltage and current - 220 V

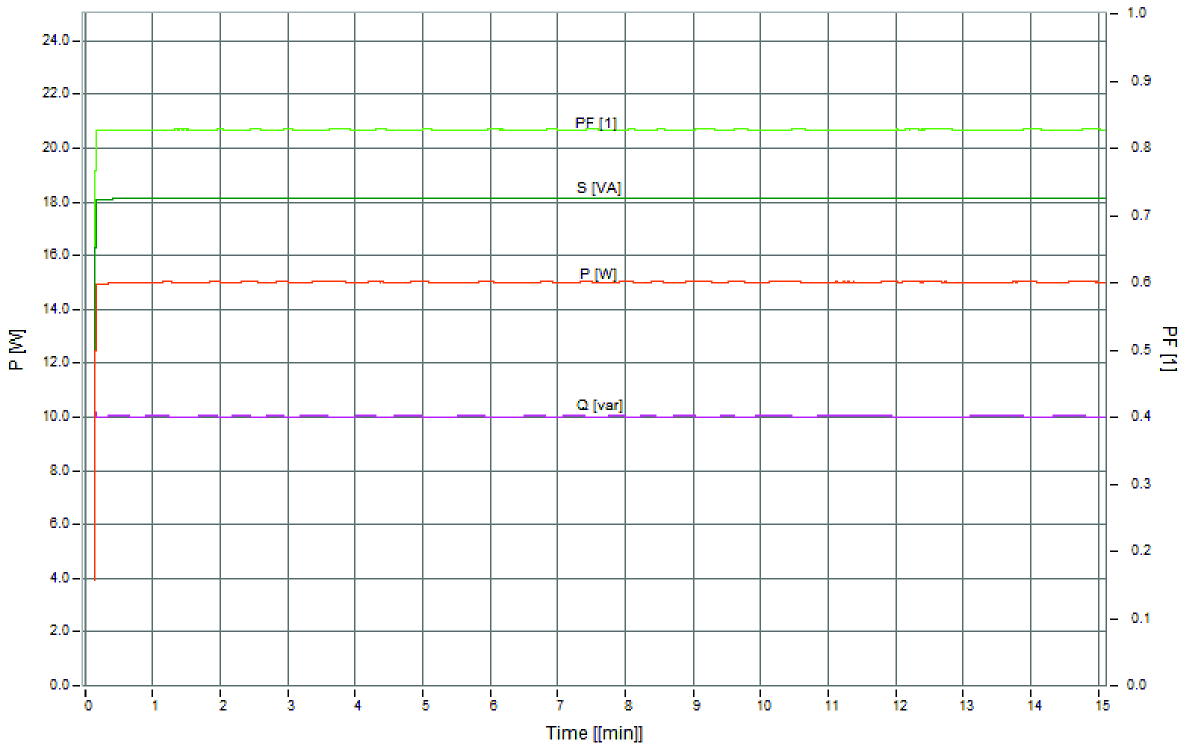

Figure 29. Root Mean Square of active power, reactive power, apparent power and power factor - 220 V

6.5.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 220.41	[V]	*****	0.00^0
I L1 = 0.081	[A]	*****	33.73^0

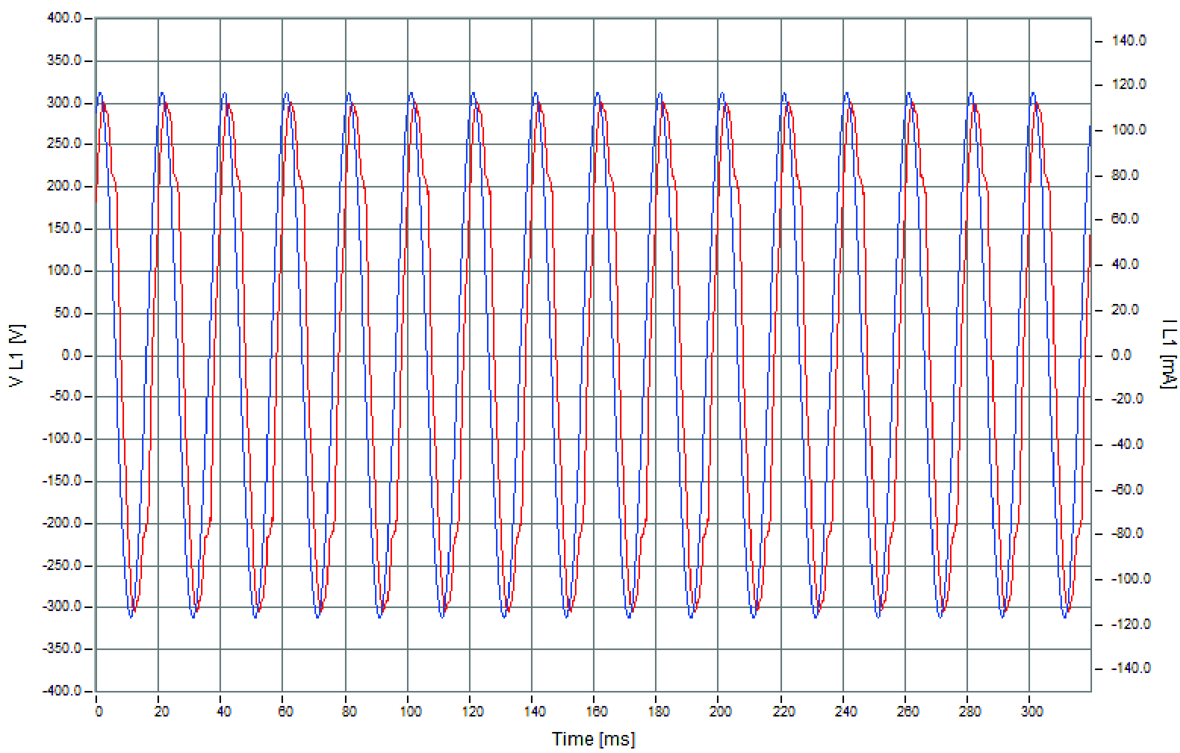

Figure 30. Current and voltage signal curve - 220 V

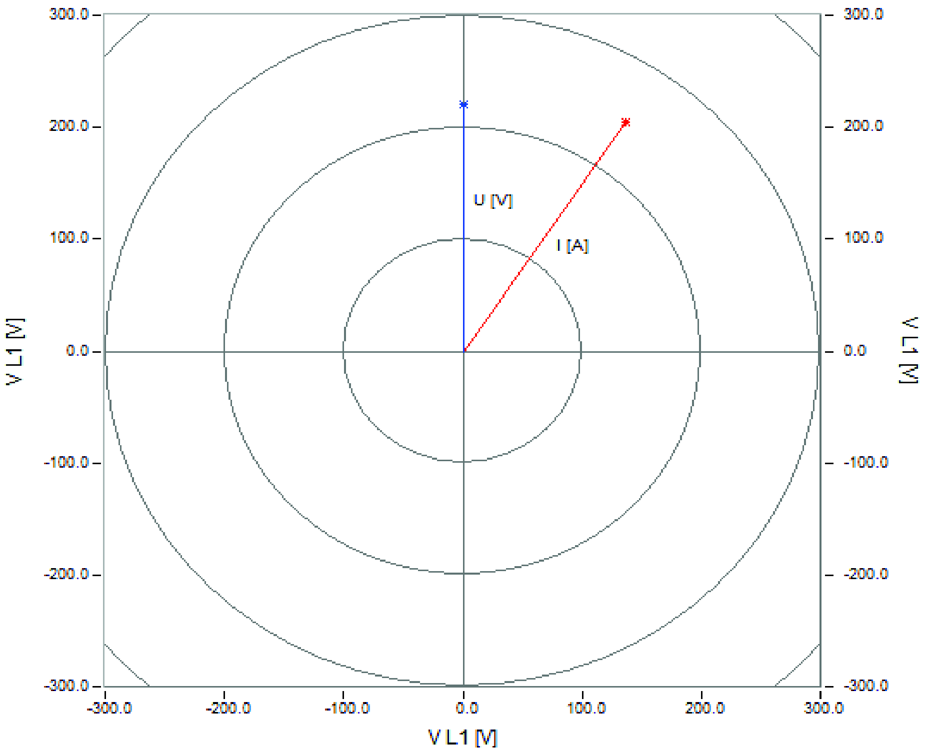

Figure 31. Voltage and current vectors - 220 V

6.5.3. Current harmonics

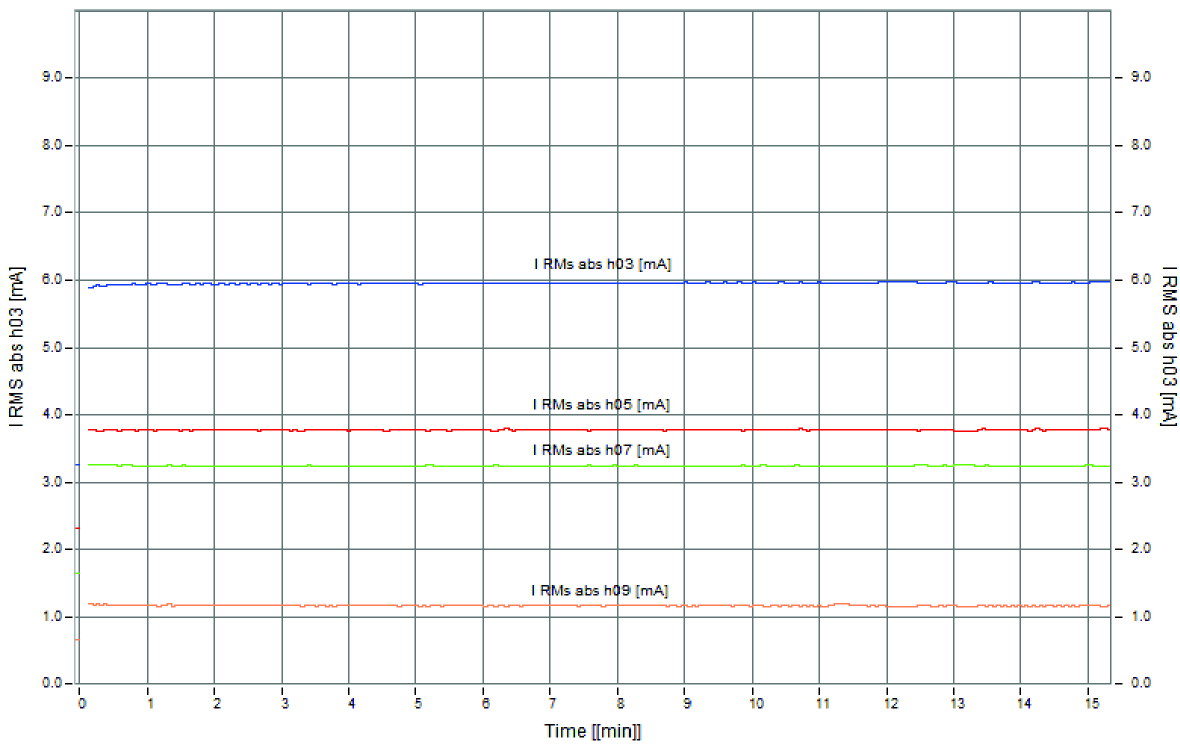

Figure 32. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 220 V

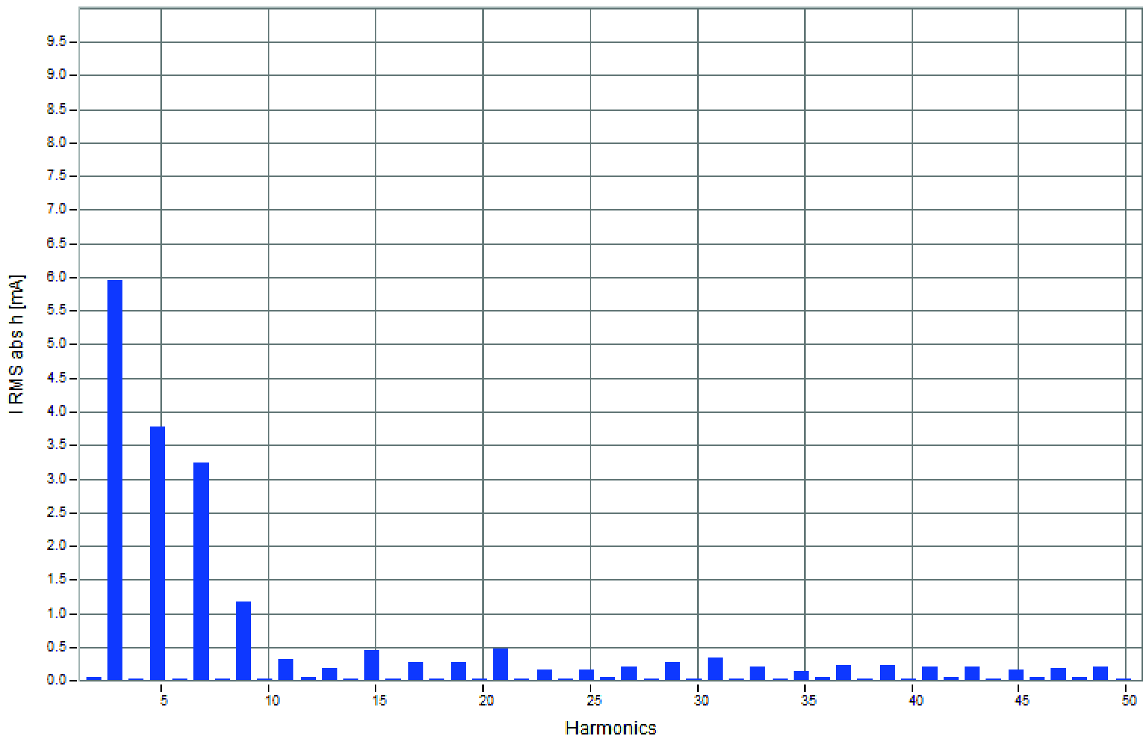

Figure 33. Root Mean Square absolute value of TDH of mA of the last minute - 220 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.68\%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.63\ \%$$

6.6. Voltage higher than nominal condition (1.04 p.u. ; 240 V)

Average value from last five minutes of measurement:
Voltage: U = 240.40 V
Current: I = 0.083 A
Active Power = 15.87 W
Reactive Power = 12.18 var
Apparent Power = 20.10 VA
Power Factor = 0.78

6.6.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

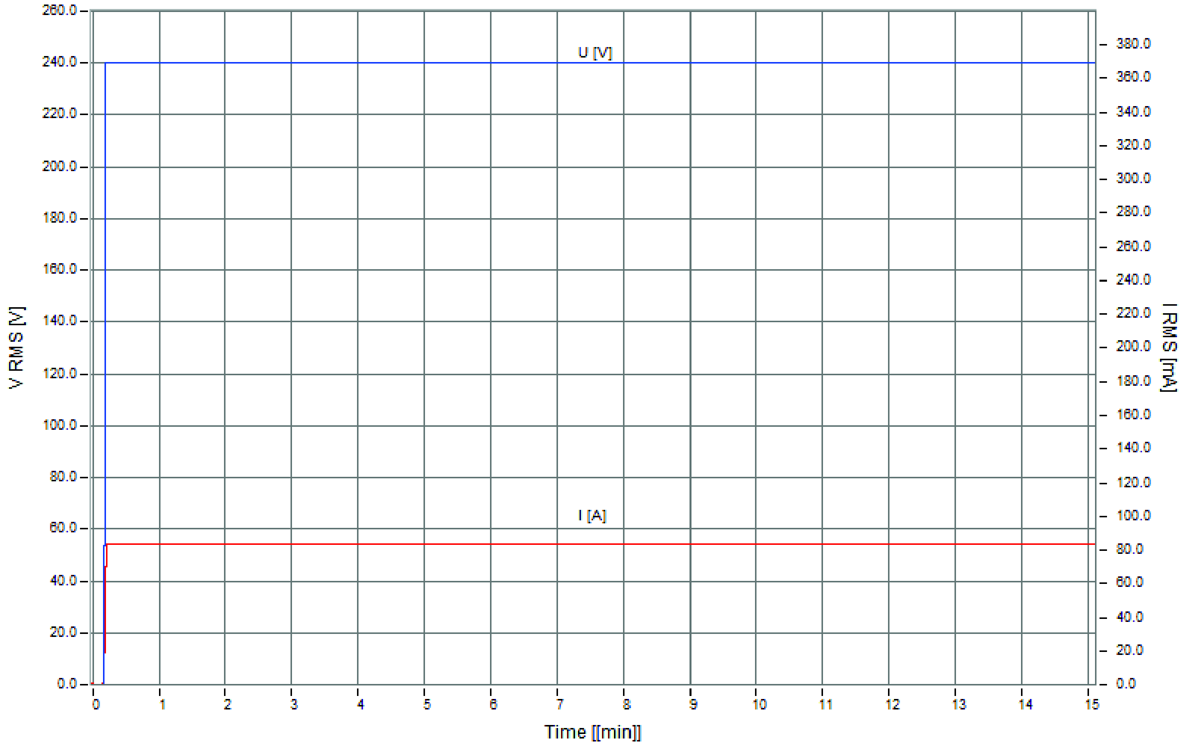

Figure 34. Root Mean Square of voltage and current - 240 V

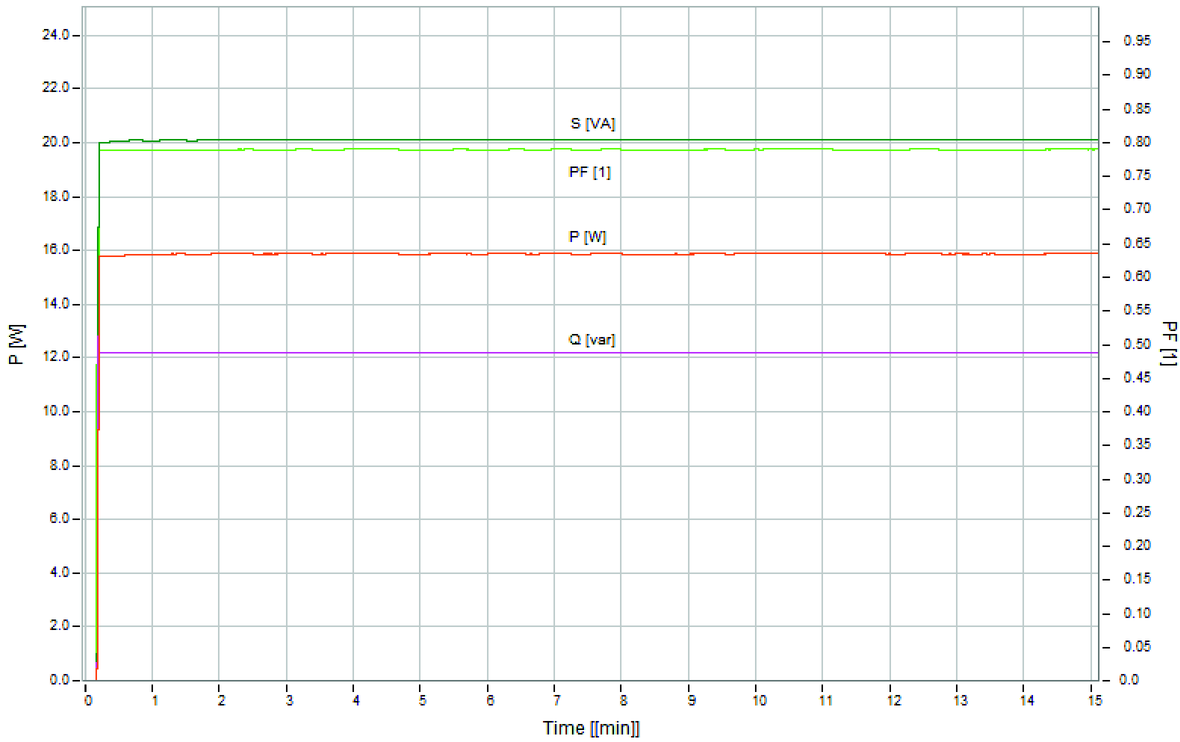

Figure 35. Root Mean Square of active power, reactive power, apparent power and power factor - 240 V

6.6.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 240.41	[V]	*****	0.00^0

I L1 = 0.083	[A]	*****	37.49⁰

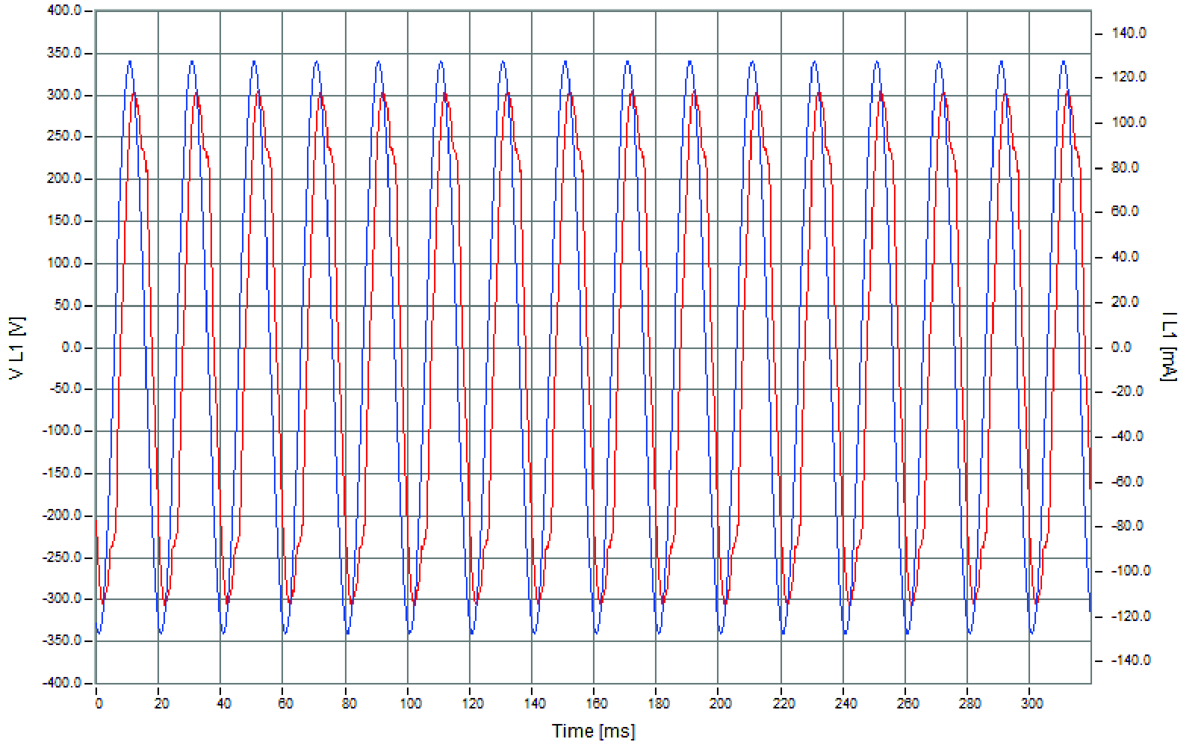

Figure 36. Current and voltage signal curve - 240 V

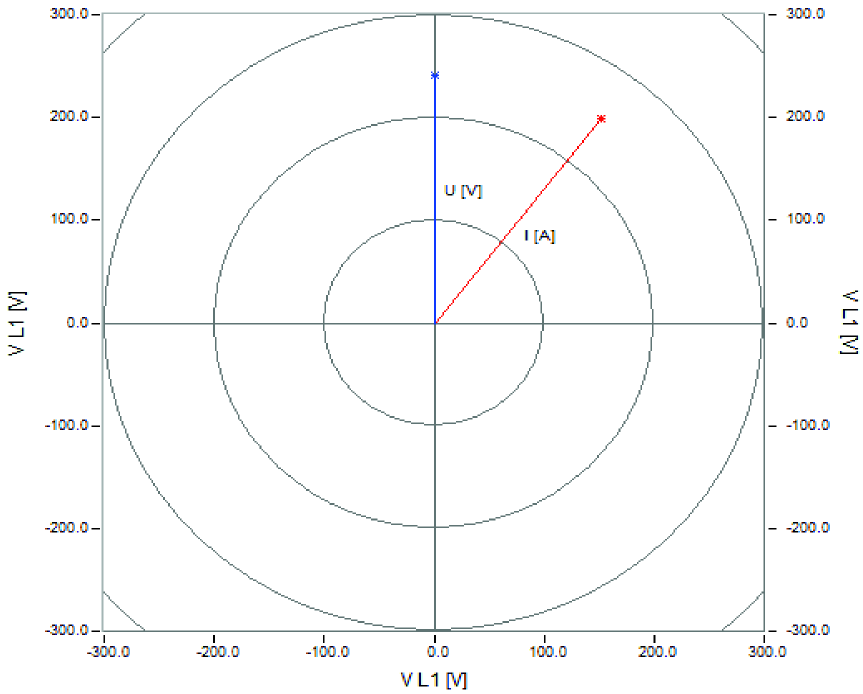

Figure 37. Voltage and current vectors - 240 V

6.6.3. Current harmonics

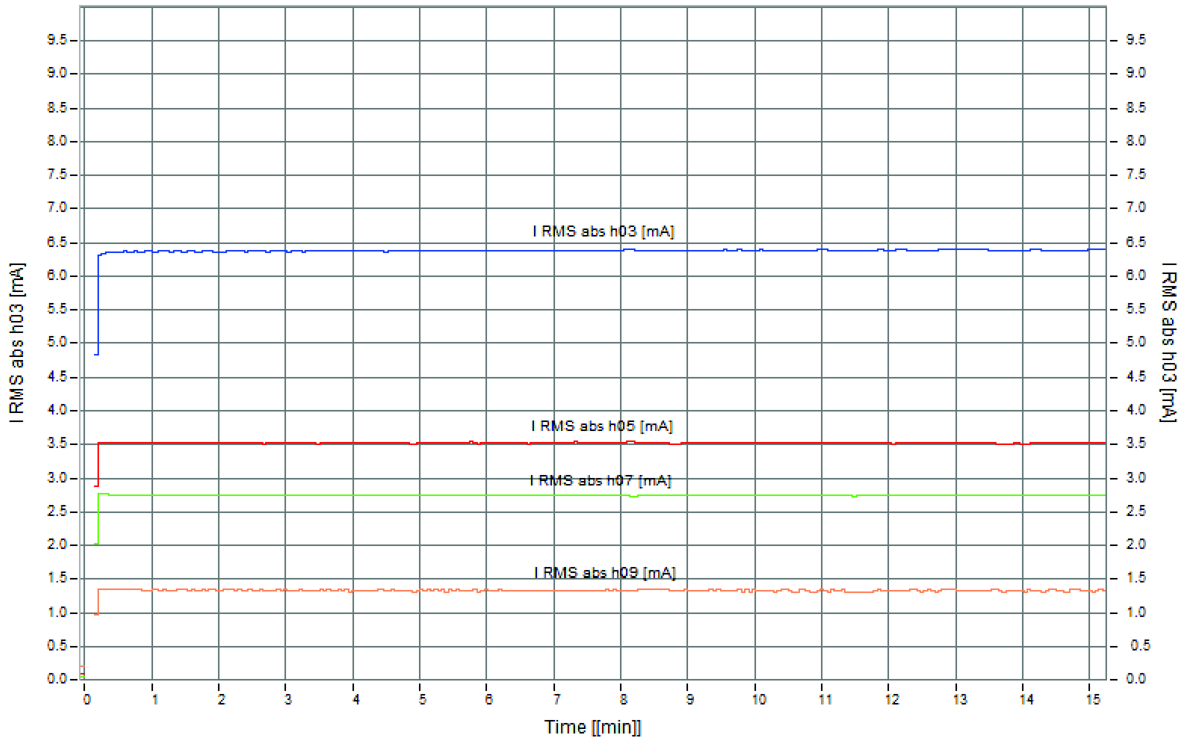

Figure 38. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 240 V

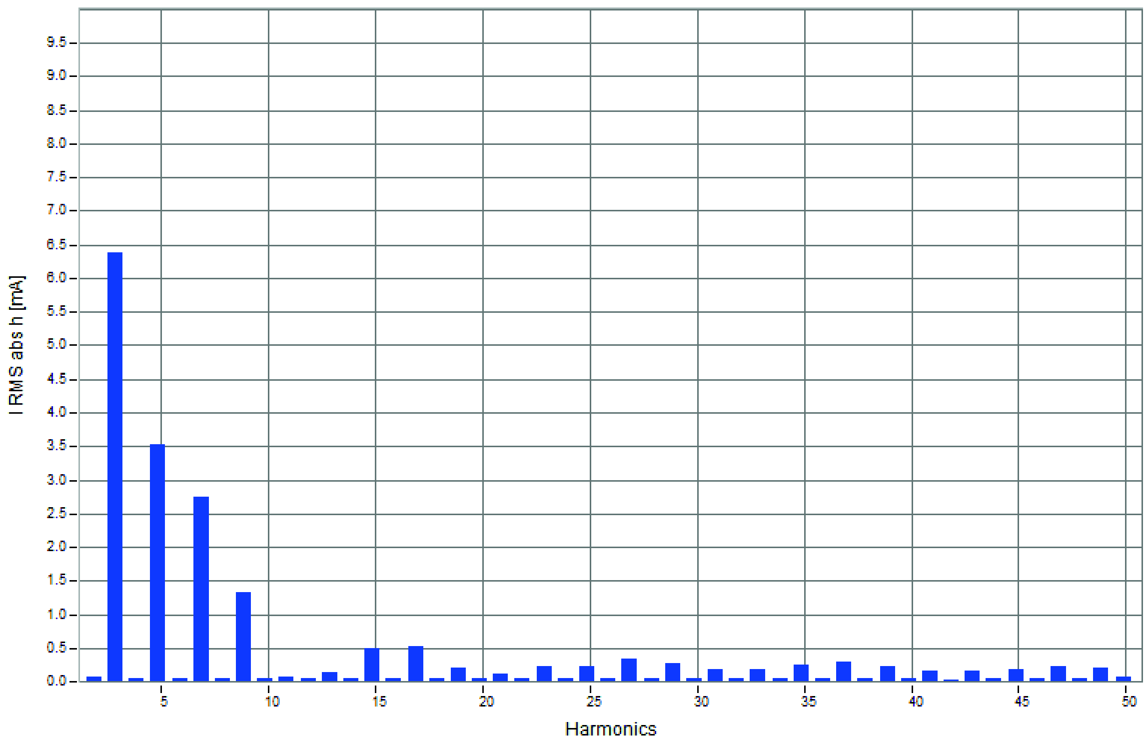

Figure 39. Root Mean Square absolute value of TDH of mA of the last minute - 240 V

THD according IEEE 1035:1989 of the last minute:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 9.60\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 9.56\ \%$$

6.7. Voltage higher than nominal condition (1.08 p.u. ; 250 V)

Average value from last five minutes of measurement:

Voltage: U = 250.47 V

Current: I = 0.085 A

Active Power = 16.65 W

Reactive Power = 13.08 var

Apparent Power = 21.29 VA

Power Factor = 0.78

6.7.1. Root Mean Square: Voltage, current, active power, reactive power, apparent power, power factor

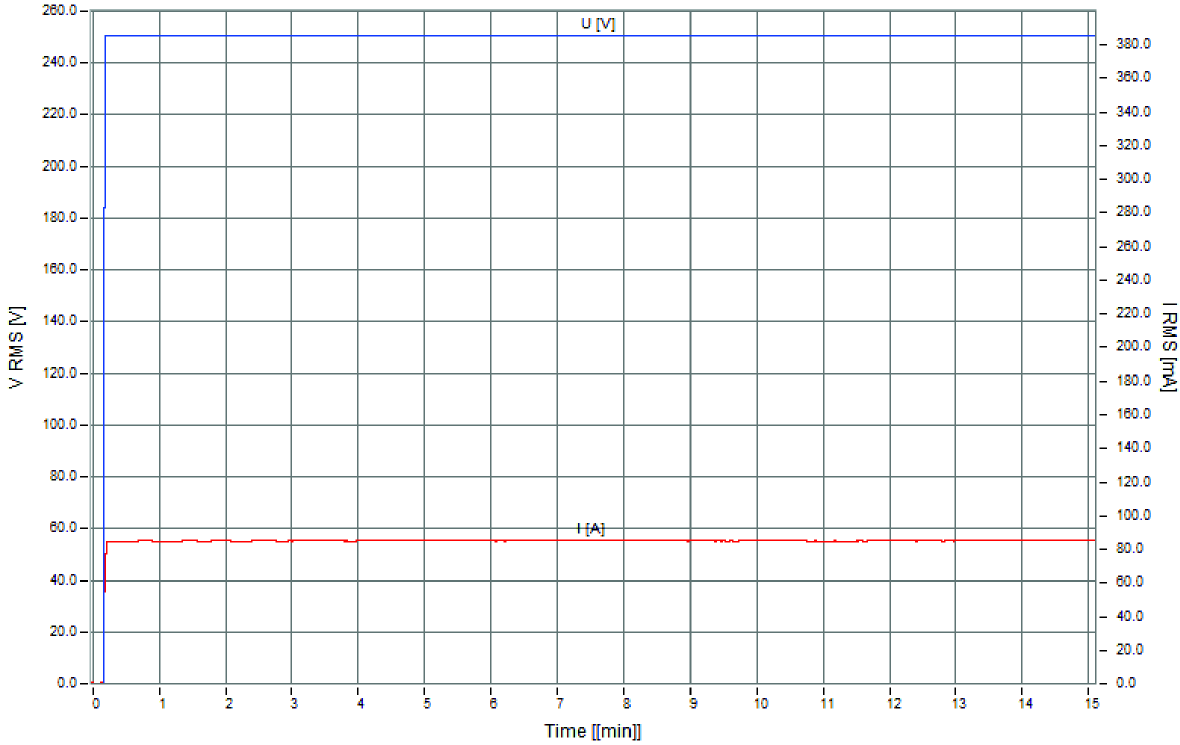

Figure 40. Root Mean Square of voltage and current - 250 V

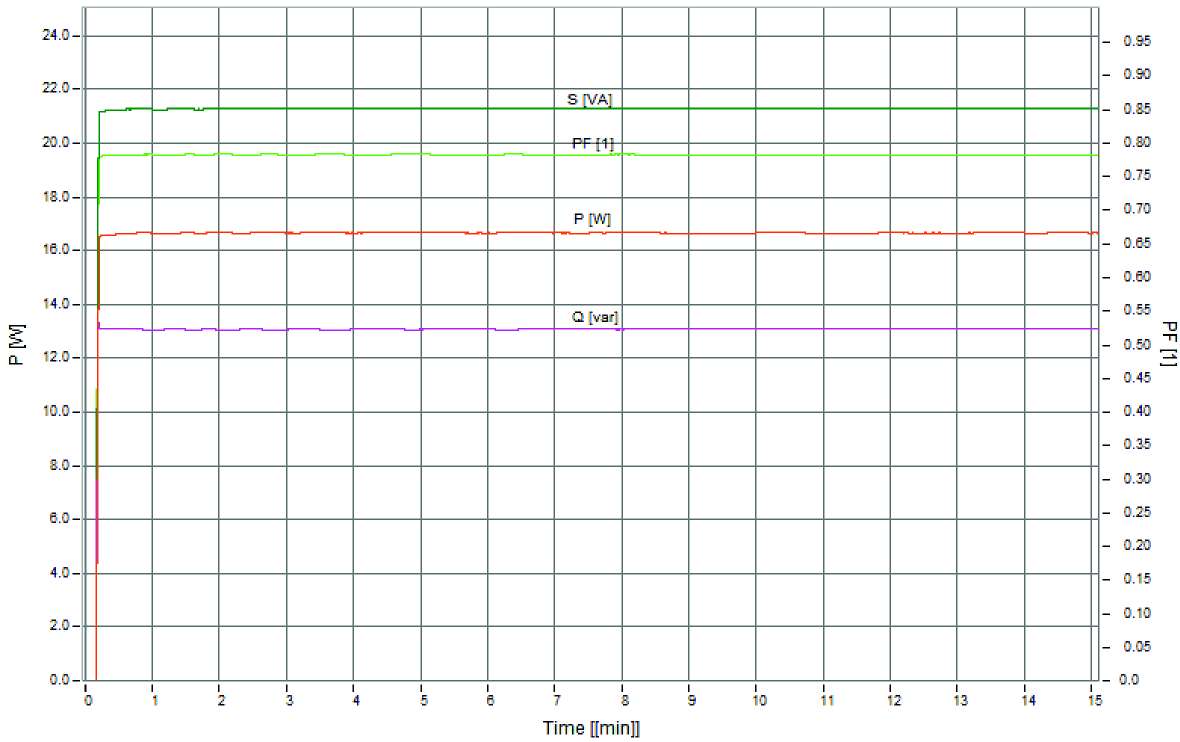

Figure 41. Root Mean Square of active power, reactive power, apparent power and power factor - 250 V

6.7.2. Oscilloscope results: Voltage, current and phasor view

Quantity	Unit	Plot	Phasor
V L1 = 250.62	[V]	*****	0,00⁰
I L1 = 0.084	[A]	*****	38.17⁰

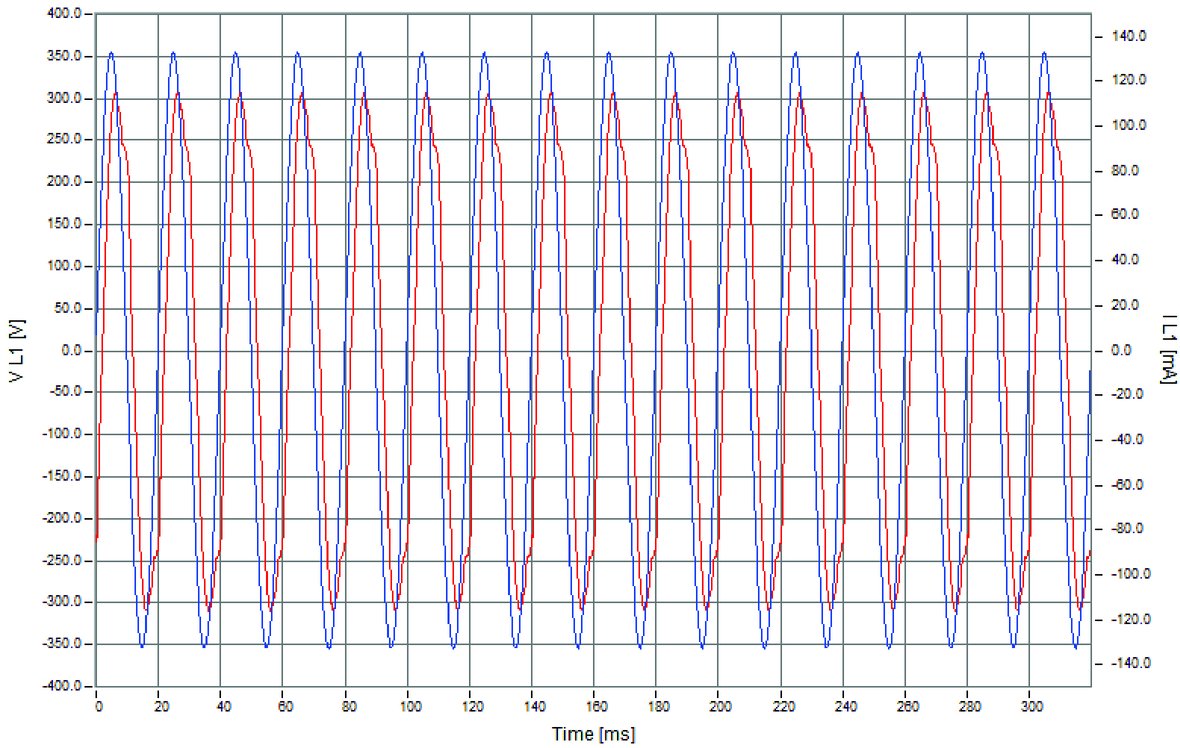

Figure 42. Current and voltage signal curve - 250 V

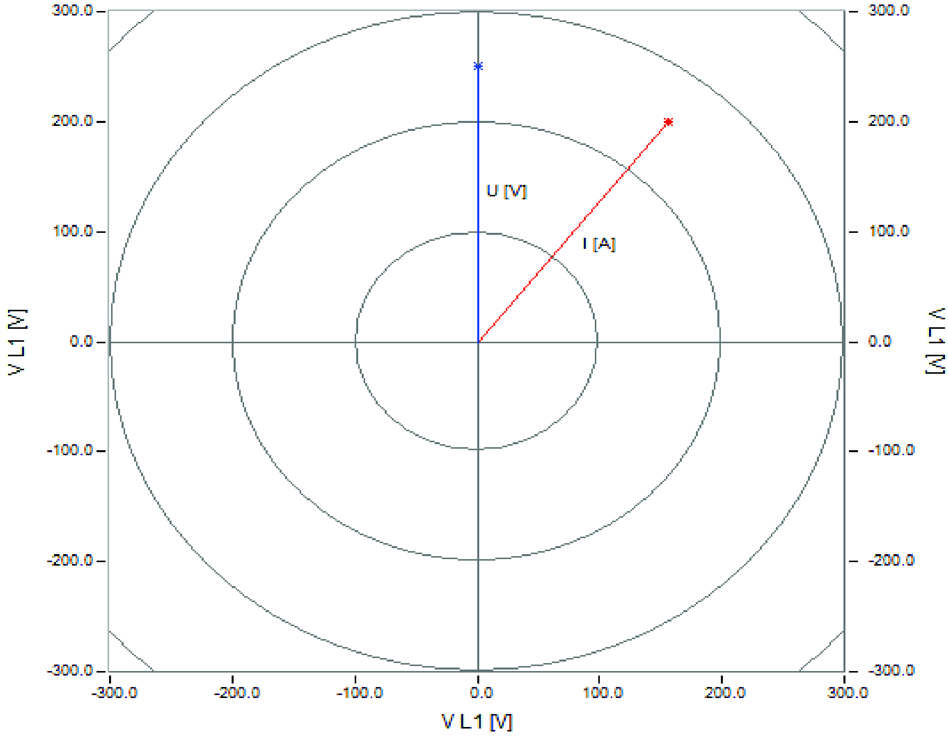

Figure 43. Voltage and current vectors - 250 V

6.7.3. Current harmonics

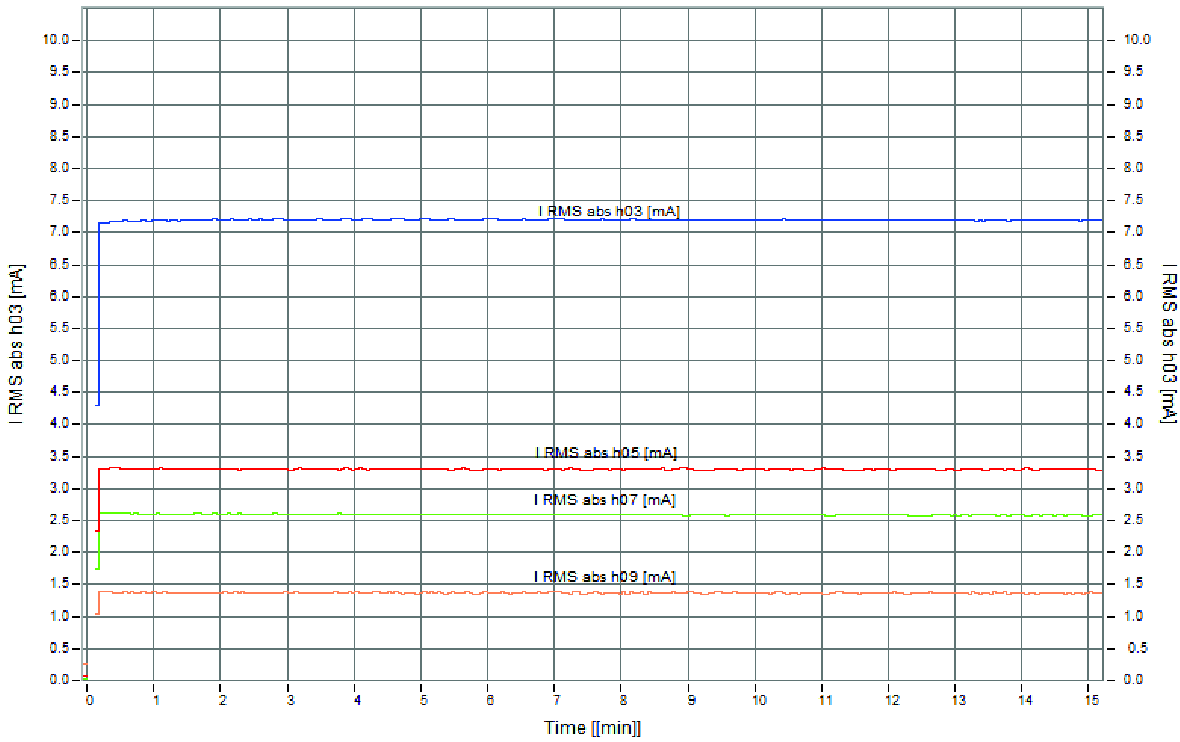

Figure 44. Time curve of 3rd, 5th, 7th and 9th harmonic current of 15 min measurement - 250 V

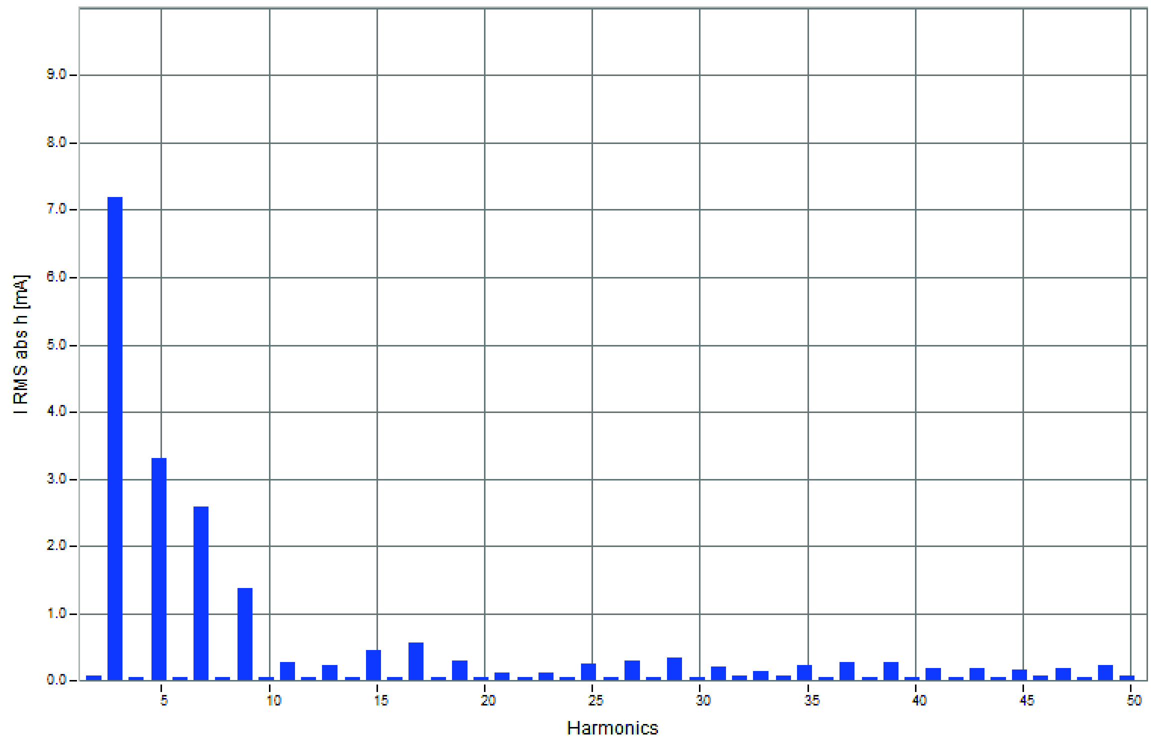

Figure 45. Root Mean Square absolute value of TDH of mA of the last minute - 250 V

THD according IEEE 1035:1989 of the last minute

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2}} \times 100\% = 10.08\ \%$$

THD according IEC:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}}{\sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + \cdots + I_{50}^2}} \times 100\% = 10.02\ \%$$

6.8. Measurements results summary

In the following is given a summary of measurements results the harmonics.

Figure 46. shows the relationship of TDH (calculated according to the IEEE 1035) to the voltage. THD reached the maximum value, 10.08%, for the maximum voltage, 1.09 p.u.. The minimum THD, 9.53%, is measured for the voltage 0.91 p.u..

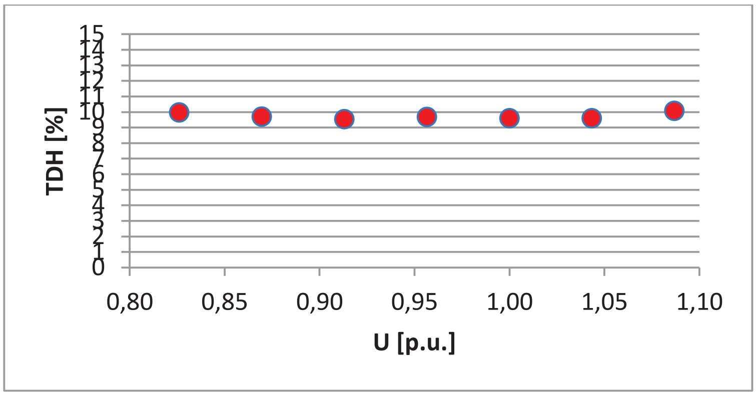

Figure 46: Relationship of THD (according to IEEE) to the voltage in room temperature

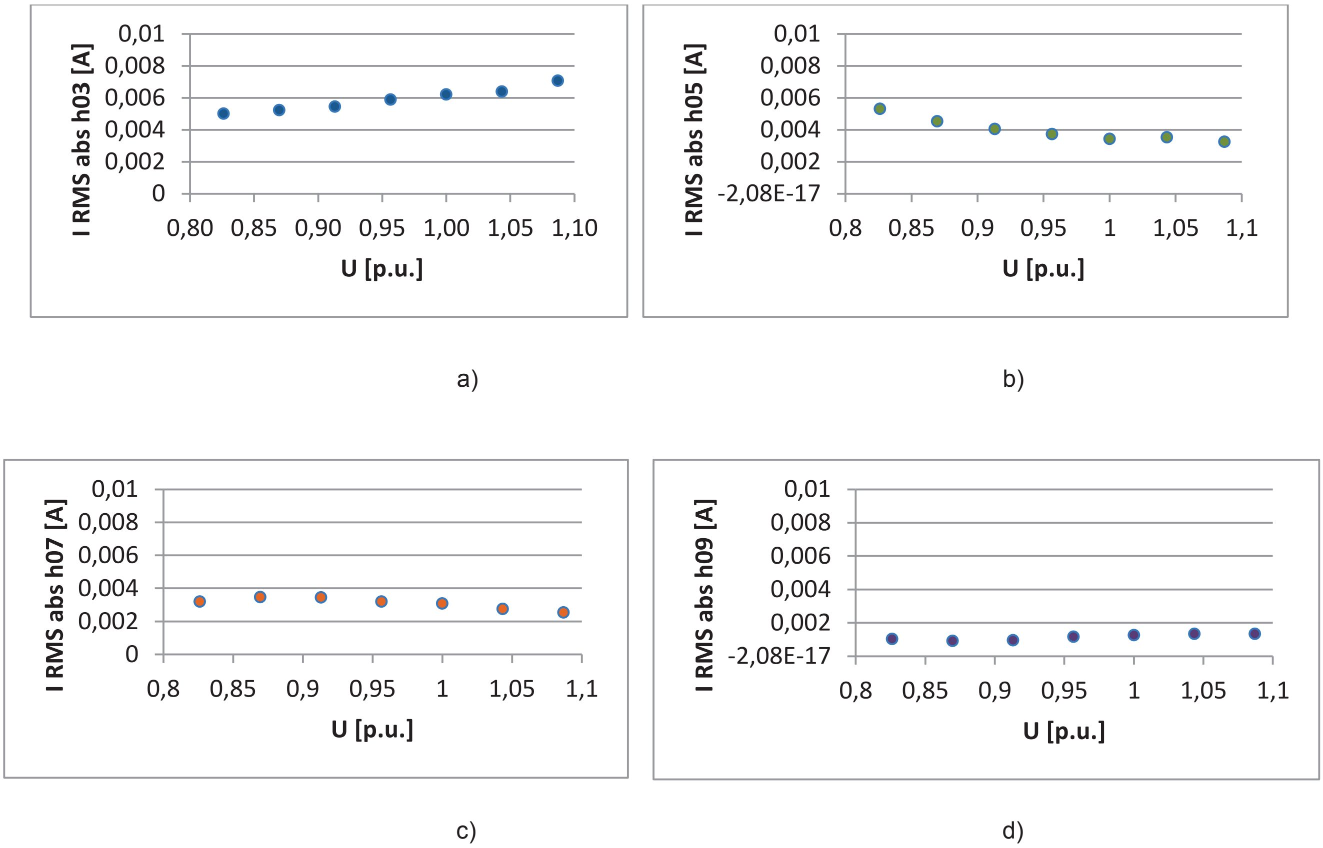

Figure 47. The evolution of different harmonics in function of voltage: a) 3d, b) 5th, c) 7th and d) 9th harmonic.

Figure 47. shows the evolution of different harmonics in function of voltage. Figure 47. a) shows the 3d harmonic, which increases with the voltage increase. Figures 47. b) and c) shows the 5th and the 7th harmonic respectively, which have exponential falling behaviour . In both cases the harmonic values are decreasing with the voltage increase. Figure 47. d) shows 9th harmonic which increases marginally with the voltage increase.