Kaunas University of Technology

Faculty of electrical and electronics engineering

Studio of the quality of the electrical energy of a microgrid with distributed generation and modelling of the system in matlab-simulink

Master’s final thesis

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Abbreviations:

Assoc. prof. – associate professor;

Lect. – lecturer;

Prof. – professor.

DN – distribution network

R – resistance

H – heater

L – lamps

R+H – resistance + heater

R+L – resistance + lamps

H+L – heater + lamps

R+H+L – resistance + heater + lamps

THD – Total Harmonic Distortion

TDD – Total Demand Distortion

PCC – Point of Common Coupling

MPPT – Maximum Power Point Track

Abstract

Starting from a real installation, a microgrid with distributed generation from renewable sources (solar panels and wind turbines) with the possibility of storing energy in batteries and also connecting to the distribution network, the aim of this project is focused on the studio of the quality of the electrical energy of this installation by experimentally measuring diverse characteristic parameters in different scenarios. At the same time, it is intended to model the installation using the Matlab-Simulink simulation software and subsequently make an analysis of the results of the simulation and suggest possible corrective measures to improve the operation of the microgrid.

Introduction

Nowadays the microgrids are gaining importance in the current transformation of the electrical generation system, which is evolving from the traditional system (with few generators of high power where all energy is generated and then it’s transported to the consumers) to a new system with a lot of generators of small power but near of consumers, this system is known as distributed generation.

The most used way to integrate these small generators near of consumers is with a microgrid, a small electrical network that is composed by electricity sources and loads that is able to operate connected to the distribution network (DN) and also autonomously, in island mode.

In this type of networks contains different type of generators, but they are usually generators from renewable sources (solar panels, wind turbines, etc..) and on the one hand, the problem of these non-pollutant sources is the intermittent nature of their power, that makes power quality control a technical challenge to integrate these different technologies of distributed generation sources.

But on the other hand, this type of systems provides several benefits like reliability, security, and high efficiency of energy supply, while minimizing power losses and reducing carbon emission

The main objective of the microgrids is to be independent of the DN and to be self-sufficient with its own generators. To chieve this goal, is necessary to have an energy store (batteries) to compensate the difference between the irregular power flow from the renewable sources and the consume of the installation, as the pattern of consumption and generation are not usually the same.

So, to ensure a smooth operation of the microgrid, it has to control all the different generators, charge or discharge the battery, connect or disconnect to the DN, to supply all the loads complying with the minimum of power quality and with the highest possible efficiency of the system.

And in this project, we are going to analyse the behaviour of a real microgrid with distributed generation focussing on quality parameters and then develop a virtual model of the installation to simulate different scenarios and found some possible improvements in the microgrid.

1. Harmonics and power quality

The power quality is one of the topics that we will address in this thesis, so in this section we are going to talk about the parameters that characterizes the electric waves, the importance of the system waves being similar to the ideals, and how to analyse the distortion of these waves.

1.1. Electric wave

Currently the vast majority of the world’s electrical energy is supplied in alternant current, so to characterize the electric wave, we only need four parameters:

- Frequency
- Amplitude
- Form
- Symmetry

1.1.1. Frequency

Frequency is a magnitude that measures the number of repetitions per unit of time of any periodic event. In the electrical systems, the term of fundamental frequency is used to refer to the lowest frequency of a periodical waveform. The fundamental frequency is common in all the power systems, but, for historical reasons, not all have the same, for example in Europe and China the fundamental frequency is 50 Hz and in EEUU and Brazil is 60 Hz.

1.1.2. Amplitude

Amplitude of the wave can be defined as the maximum value reached with respect to an equilibrium point. In electric wave is very common to refer to effective value or RMS of the wave, it means, the amplitude divided by square root of two. The RMS value in alternant current corresponds with the equivalent of direct current on a purely resistive load, that makes easier the calculations of dissipated power.

The amplitude of the electrical wave depends on the point on the network that you are measuring. Such as, for transporting energy over long distances, it is done with a high voltage wave amplitude, so that the current amplitude is lower and the cable losses are minimal, while for distribution in consumption areas, the voltage wave amplitude is smaller in order to avoid electric shock and insulation failure.

1.1.3. Form

The waveform in alternant current systems is a pure sinusoidal wave, but is so difficult to find this type of form in a real installation, because due to different reasons like no lineal loads, breakdowns or atmospheric effects, this waveform is distorted. This distortion, how we will see later, can be quantified with the harmonics.

1.1.4. Symmetry

Three-phase systems are considered symmetrical when all the phases have the same module and are displaced 120º with each other. When this happens, it is said that the system is balanced, it means that the currents of each phase cancel each other, and the current through the neutral is zero.

This is especially complicate to achieve in the low voltage part of the DN, where there are single-phase loads connected between the phase and the neutral, such as houses. Even so, it is tried to distribute the loads as symmetrical as possible, making the balance of the system easier.

1.2. Harmonics

In this part, we are going to focus on the waveform. I have seen that the electric wave is a pure sinusoidal wave with a frequency of 50 Hz, if we are referring to Europe, and the amplitude depends on the different factors such as the load or the voltage of the system.

Nevertheless, actually this wave presents some disturbances in its form with respect to the ideal sinusoidal. These disturbances can be periodical or punctual.

When the disturbances are periodical, it's possible to study of this noise with the mathematical tool of the Fourier's series. The Fourier's series are trigonometrical series that allows to break down a complex periodical wave into an infinite o finite sum of sinusoidal functions, signals or waves, each with a different frequency, but always multiple of the fundamental frequency. And these sinusoidal waves witch frequency are multiple of the fundamental are called harmonics

The sum of all the harmonics gives us the distorted wave:

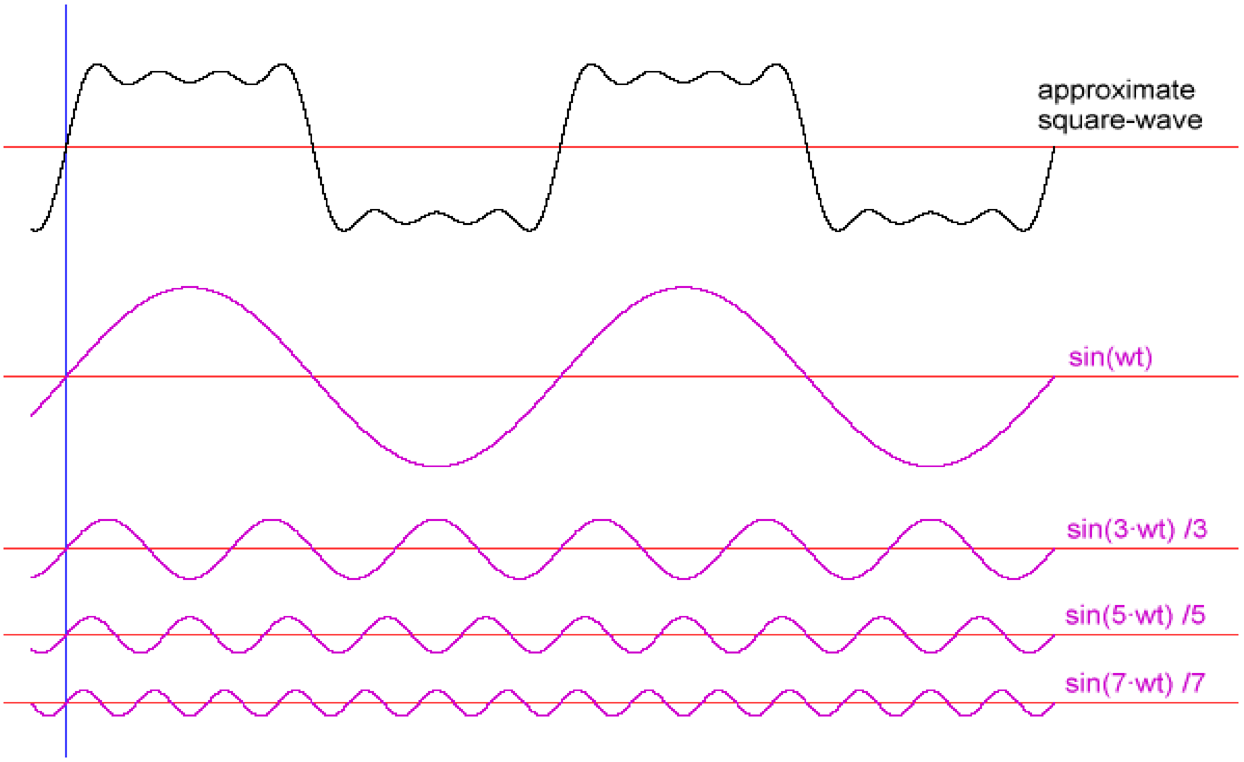

Figure 1:Harmonic waves sum, fundamental+3rd+5th+7th harmonic [1]

Mathematically, the development in Fourier's series consists of a summation of sinus and cosines with the following formula:

$$f(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} [A_k \cdot \cos\left(k \frac{2\pi}{T} t\right) + B_k \cdot \sin(k \frac{2\pi}{T} t)]$$

Where $A_k \cdot \cos\left(k \frac{2\pi}{T} t\right) + B_k \cdot \sin(k \frac{2\pi}{T} t)$ is the harmonic k, and $\frac{a_0}{2}$ is the average of the wave, and $\frac{2\pi}{T}$ is the angular speed of the fundamental ω_0

But this formula can be expressed only with one sinusoidal function. Applying trigonometrical relationships, we can achieve the expression that is usually used to work with currents with harmonics:

$$i(t) = I_m + \sum_{k=1}^{\infty} I_{kp} \cdot \sin(kw_0 t - \varphi_k)$$

Where I_m is the average or the continue component (k=0) of the current i, I_{kp} is the amplitude of harmonic k and φ_k is the phase in radians of the harmonic k.

1.2.1. How to measure harmonics

As we have commented before, we can obtain the effective value (RMS) of each harmonic of the current (I_k) as follows:

$$I_k = \frac{I_{kp}}{\sqrt{2}}$$

In the same way we can obtain the effective value of the complete current:

$$I = \sqrt{I_m^2 + I_1^2 + I_2^2 + I_3^2 + \cdots + I_k^2}$$

To express the distortion that each harmonic cause, we calculate the percentage respect to the fundamental harmonic with this ratio:

$$D_k(\%) = \frac{I_k}{I_1} \cdot 100$$

Another interesting ratio to measure harmonics is the Total Harmonic Distortion (THD), that is expressed with the formula:

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_k^2}}{I_1} = \frac{\sqrt{\sum_{k=2}^{\infty} I_k^2}}{I_1}$$

This parameter is very useful to know the effects that the harmonics can produce in our system, such as the increase in losses due to Joule effect in conductors:

$$I^2 = (THD^2 + 1) \cdot I_1^2$$

$$P_J = R \cdot I^2 = R \cdot (THD^2 + 1) \cdot I_1^2$$

Where the increase in losses due to the harmonics will be:

$$\Delta P_J = R \cdot THD^2 \cdot I_1^2$$

1.3. Detrimental effects of harmonics

When harmonics are high, they can cause not only losses, but also the tripping of protections that cut the supply or even the destruction of electrical equipment, such as capacitor batteries.

In the following table shows the main effects that the harmonics can cause in the different elements that we can find in the DN.

Element	Problems	Effects
Phase conductor	- Increased current - Increase of thermic losses (Joule effect) - Skin effect	- Conductor heating - Protection tripping
Neutral conductor	- Circulation of harmonics multiples of 3 - Return by the neutral conductor	- Overintensity of current circulating through the neutral conductor - Conductor heating - Premature conductor degradation - Protection tripping
Capacitor	- Increased current - Harmonics amplification	- Heating - Premature capacitor degradation - Destruction of the capacitor
Transformer	- Circulation of harmonic currents through the windings	- Winding overheating - Loss of thermal insulation due to heating - Loss in copper and iron (Hysteresis and Foucault) - Decreased performance - Saturation of the transformer
Motor	- Circulation of harmonic currents through the windings	- Winding overheating - Loss of thermal insulation due to heating - Loss in copper and iron (Hysteresis and Foucault) - Decreased performance - Shaft vibrations, mechanical wear on bearing and eccentricity - Reduction of torque
Generator set	- Distorted tension	- Difficulty of automatic synchronization and later switching

Table 1: Main problems and effects caused by harmonics in different elements [2]

1.4. Standards and regulations

Harmonics have been present since the origin of the electric grids, they have been increasing their presence little by little and with the changes that the electric system is experiencing, everything seems to indicate that this trend will be accentuated. For this reason, the rules that regulates harmonics have become more restrictive.

In Europe, the standard in charge of limiting harmonics that domestic and industrial consumers inject into the DN is EN-6100-3-2, but only affects devices with less than 16 A per phase.

On the other hand, the standard EN-50160 controls the quality of voltage supply in the DN, it only talks about voltage harmonics, but not the current harmonics.

Nevertheless, there is a standard that take into account the harmonic injection to the public grid, this is the standard IEEE 519-2014, in its third revision. In the current version harmonics are limited in the Point of Common Coupling (PCC), the point where the generating facility connects to the network, being responsible for these limits, both the operator and the user.

We are going to see in more detail these last two rules and the differences between them below.

1.4.1. EN-50160

In Europe EN-50160 is mandatory, a standard that regulates the quality of electricity supply throughout the European territory. This standard describes the limits or values within which the voltage characteristics can be expected to be maintained throughout the entire public DN.
Here we have an abstract of the limits of the standard EN-50160 [3]:

- Frequency (mean value of the fundamental frequency measured over 10 seconds)
  - Always: 50 Hz +4%/-6% (47≤f≤52 Hz)
  - In 99.5% of the year: 50 Hz ±1% (49.5≤f≤50.5 Hz)
- Voltage 1 phase (mean U_{RMS} value over 10 minutes)
  - Always: 230 V +10%/-15% (195.5≤V≤253 V)
  - In 99.5% of the week: 230 V ±10% (207≤V≤253 V)
- Voltage 3 phase (mean U_{RMS} value over 10 minutes)
  - Always: 400 V +10%/-15% (340≤V≤440 V)
  - In 99.5% of the week: 400 V ±10% (360≤V≤440 V)
- Unbalance voltage (mean U_{RMS} value of the inverse component over 10 minutes)
  - In 95% of the week: <2%
- Voltage Total Harmonic Distortion (mean THD_U value over 10 minutes)
  - In 95% of the week: <8%
- Individual harmonic voltage (mean U_{hn} value over 10 minutes)
  - In 95% of the week: less than the limits of the following table.

Odd harmonics				Even harmonics	
Not multiples of 3		Multiples of 3			
Order	Harmonic voltage (% U_N)	Order	Harmonic voltage (% U_N)	Order	Harmonic voltage (% U_N)
5	6,0%	3	5,0%	2	2,0%
7	5,0%	9	1,5%	4	1,0%
11	3,5%	15	0,5%	6..24	0,5%
13	3,0%	21	0,5%		
17	2,0%				
19	1,5%				
23	1,5%				
25	1,5%				

Table 2: Individual harmonic amplitude limits of voltage EN-50160 [3]

1.4.2. IEEE 519-2014

The IEEE 519-2014 standard describes the design goals of electrical systems including linear and non-linear, also describes the voltage and current waveforms that may exist, as well as the distortion limits of the waveforms in the Point of Common Coupling (PCC) [4].

The following table shows the voltage distortion limits established, taking into account that:

- 99% of the very short-term values (3s) observed daily should be less than 1.5 times the values given in table 1.2
- 95% of the short-term values (10 min) observed weekly must be lower than the values given in the table 1.2

Bus voltage (V) at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1$ kV	5.0	8.0
1 kV $< V \leq$ 69 kV	3.0	5.0
69 kV $< V \leq$ 161 kV	1.5	2.5
161 kV $< V$	1.0	1.5

Table 3: Voltage distortion limits of IEEE 519-2014 [4]

In case that the users inject power into the DN, the current distortion limits established for the PCC which voltage is between 120 and 69 kV, are in the following table, knowing that:

- 99% of very short-term values (3 s) observed daily should be less than 2 times the values given in table 1.3
- 99% of the short-term values (10 min) observed weekly must be lower than 1.5 times the values given in the table 1.3
- 95% of the short-term values (10 min) observed weekly must be lower than the values given in the table 1.3

I_{sc}/I_L	Individual harmonic limits (Odd harmonics)					TDD Required
	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h < 50$	
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 4: Current distortion limits of IEEE 519-2014 [4]

Where I_{SC} means the maximum short circuit current at PCC, I_L means maximum demand load current at PCC and TDD means Total Demand Distortion that refers to the per-phase harmonic current distortion against the full load demand of the electrical system.

$$TDD\ (\%) = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \cdot 100 = THD(\%) \cdot \frac{I_1}{I_L}$$

TDD indicates the impact of harmonic distortion in the system. For example, if your system is showing high THD values but a low demand, the impact of harmonic distortion on your system might be insignificant. However, at full load, the THD value for the current harmonics is equal to TDD, so this could negatively impact your system.

1.4.3. Standard used

In this project we are going to use the European standard (EN-50160) due to the installation under study is in Lithuania, but it’s true that this standard doesn’t talks about current harmonics, for this reason we have presented the American standard, because we are going to use the current distortion limits of the IEEE 519-2014 standard.

2. Description of the installation

Once we have the theorical basement of power quality, we are going to introduce the microgrid under study. It is located in Kaunas (Lithuania) on the Kaunas University of Technology campus, it belongs to Electrical Power Systems department and in this section, we are going to describe all the different components that make up this microgrid.

Figure 2:Laboratory building with the different generators of the microgrid on the roof

This installation is a microgrid with distributed generation, it means that we have different types of generators, exactly three different generators: two of them are solar power plants, with a nominal power of 3000 W each one, with the difference that one is static and the other follows the sun's position. The third generator is a horizontal axis wind turbine of 1000 W of nominal power.

Microgrid supplies the electric consumes of the third floor of the laboratory, this includes 3 electric radiators of 400 W, lightning of a room and the consume of electronic devices (computer, laptops, charge of measuring equipment, etc). All these loads are constant or cyclic, it means that the consume pattern is more or less constant during all the day, but the generation pattern depends on the sun and wind, so that during the sunny hours the generators will produce the most of the energy of the day, while during the night only the wind turbine can produce some energy. Due to this big difference between the consume and generation patterns, we have a set of 24 lead-acid batteries of 2 V, that have a capacity of 190 Ah to store the excess of energy and consume when the consume are bigger than the generation.

As normal, this microgrid is able to operate with two modes: connected to the DN and also autonomously, in island mode. This connection allows to supply loads directly from the DN when their consume is so high or to charge batteries when their state of charge is so low. Before making this connection, microgrid has to synchronize with the distribution grid and then the connection can be made, but this procedure is done by the master inverter automatically.

In the control part, we have 3 bidirectional inverters, one for each phase, it means that they are able to convert AC into DC and also the other way around, convert DC into AC. One of these three bidirectional inverters is the master, it controls the other two inverters. This master inverter is the responsible to manage all the microgrid, it means that it's in charge to connect to the DN when the battery capacity is lower than the minimum, or change to island mode when the state of charge of the battery exceeds the upper limit or simply loads consume are smaller than the generation. Also is the responsible to maintain the quality parameters of the microgrid, such as frequency, voltage, harmonics, etc. within the allowed limits.

To have better idea of how the installation under study is like, here we have in the following figure the single line diagram of the electric connections of the microgrid, where we can see how all the elements of the system are connected:

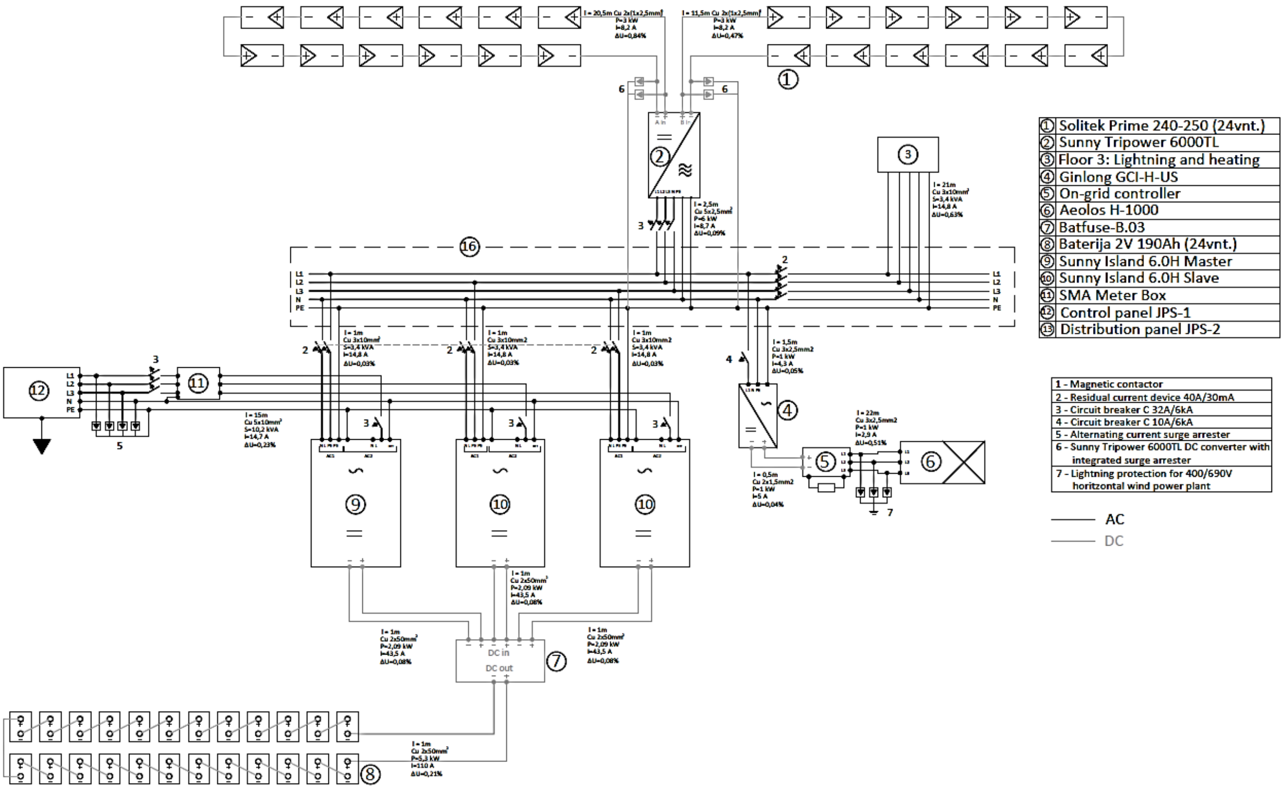

Figure 3:Single line diagram of the electric connections of the microgrid

Below we have a more detailed description of each element:

① Solar panels: there are two types of solar power plant, one is mounted on a static structure and the other is mounted on a structure that follows the movement of the sun by electric motors that move the entire structure (solar tracker).

Figure 4:Front of the two solar power plants

Figure 5:Structure of both solar power plants

Both solar power plants use the same model of solar panel: Solitek Prime 240-250, with the following characteristics [5]:

- Rated Maximum Power at STC: 250 Wp
- Open Circuit Voltage: 37.9 Voc/V
- Maximum Power Voltage: 30.7 Vmp/V
- Short Circuit Current: 8.6 Isc/A
- Maximum Power Current: 8.1 Imp/A
- Module Efficiency: 15.08 %

Each structure has 12 modules of 250 W, so the nominal power of each power plant is 3000 W, it means that the installation can generate 6000 W from the sun.

②Three-phase Sunny Tripower inverter: Is a transformerless PV inverter of 6000 W of nominal power, with 2 MPP trackers that converts the direct current of the PV array to three-phases alternating current and feeds it into the microgrid. Both solar power plants are connected to this inverter, that is the responsible to extract the maximum power from the solar panels by the two MPP trackers. [6]

Figure 6:Sunny Tripower inverter

Figure 7:Display detail of Sunny Tripower inverter

Is well known that depending on the irradiance the solar cell produces more or less intensity of current, but also depending on the voltage, there is a zone that current is independent of the voltage, as we can see in the graphic of Current–Voltage of our solar panel model (picture 8), but when the voltage is higher, current decrease exponentially, so this phenomenon affects especially to generated power, we can see in the graphic Power–Voltage that the maximum power point is in this region where the voltage has quite influence on the current. And we can see that the voltage of the maximum power point isn't always the same, it depends on the irradiance.

So, to achieve the maximum possible power of the solar cells we need to adjust and control the voltage of the cells, and the MPPT (Maximum Power Point Track) is the responsible to do that, changing the voltage of the terminals of the solar array to generate the maximum possible power in each moment. This inverter has 2 MPPT and is able to manage two different arrays to get the best efficiency of each one and then convert this DC power in three-phases AC power and to inject into the microgrid.

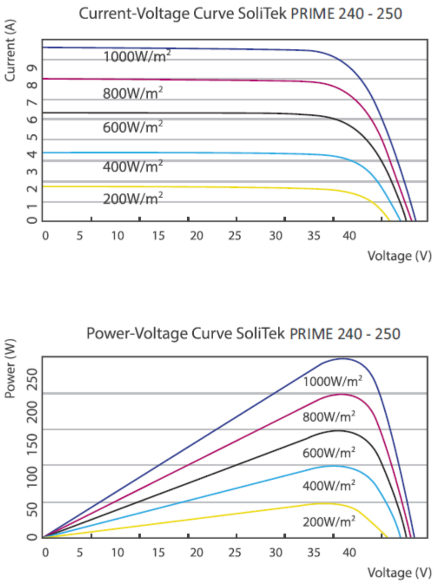

Figure 8: Current-Voltage curve and Power-Voltage curve of Solitek PRIME 240-250 [5]

③Loads: Microgrid supplies the lightning and the heating system (three radiators) of the 3rd floor of the laboratory's building and also some computers and small loads. Loads are distributed among the three phases so that the system is as balanced as possible. This is the point where we will connect different type of loads to measure the behaviour of the microgrid. Later we will introduce these loads and all their characteristics.

④One-phase Ginlong inverter: Is a single-phase hybrid inverter that can work for both PV and wind system, it has two different MPP trackers, one for PV input and the other for wind input. The inverter can transfer DC power from PV panels and wind turbine into AC power and feed into microgrid. But in this installation, we are using this inverter for the horizontal axis wind turbine. Also, this converter has brake function which can stop the wind turbine in high wind speed conditions. [7]

⑤⑥Wind turbine and its controller: Is a horizontal axis wind turbine with a nominal power of 1000 W and with an integrated controller, that with the help of the MPPT of the inverter, generates the maximum power for the different wind speeds, as we can see in the figure 11. This wind turbine is composed by a tower of 9 meters, a 3.2 meters diameter rotor of diameter with blades made of fiberglass rotating at 350 rpm, and a three-phase permanent magnet generator that has an efficiency higher than 96%. This device transforms wind power into DC current with 48 V of voltage and it can work with wind speeds from 3 m/s until 19 m/s, where 10 m/s is the nominal wind speed [8].

Figure 11: One-phase Ginlong inverter

Figure 10: Horizontal axis wind turbine

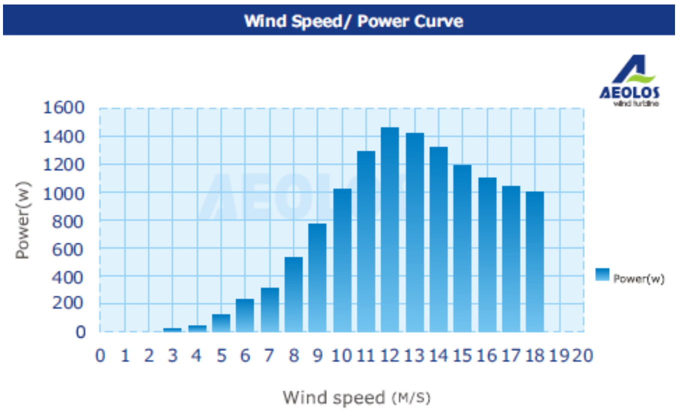

Figure 9: Wind speed - Power curve of Aeolos H 1 KW [8]

⑦⑧Battery and fuse box: The energy storage system is composed by 24 lead-acid batteries of 2V in serial connection, with 190 Ah of capacity each one, it means that we have a capacity of 190 Ah with a voltage of 48V. This type of batteries needs maintenance, because it has a electrolyte that is consumed with charging cycles, so we have to ensure that the quantity of the electrolyte is sufficient and also that its density is correct to guarantee the good performance of the batteries. Another important component is the fuse box, it is a system protection measure to protect the batteries from a high current. [9]

Figure 12: Battery set of the microgrid

Figure 13: Detail of a battery of 2 V

⑨⑩ Sunny Island bidirectional inverters: Are 3 one-phase bidirectional inverters, one for each phase, that convert the DC power from the batteries into AC power, and vice versa. One of this 3 inverters is the master, who manages all the microgrid and the power flows. For example, it is the responsible to connect the microgrid to the DN when the level of battery capacity is so low, and disconnect when the charge is complete. The same occurs when the different power plants are generating more than the loads are consuming, and if the batteries are charged, it connects the microgrid to the DN to inject the excess of energy. Another task of this master inverter is to maintain constant the values of voltage and frequency and within the established limits. [10]

Figure 14:Three Sunny Island bidirectionals inverters. Master inverter on the right and two slaves inverters on the left and the Sunny Remote Control between the master and the first slave inverter

The way to set the parameters and control manually the microgrid is through the Sunny Remote Control, that is the grey small box that we can see in the figure 14. With this device you can set all the control and operating parameters of the microgrid.

⑪ Meter box: thanks to this device we can have all the main parameters of the installation monitored and we can see the instant values of the voltage of the microgrid, or the current generated by the solar power plant or even the irradiance or temperature outside the lab at this moment, remotely through a monitoring website. And then you can download this data and analyse the behaviour of microgrid, and it is very useful to find the cause of some problems. [11]

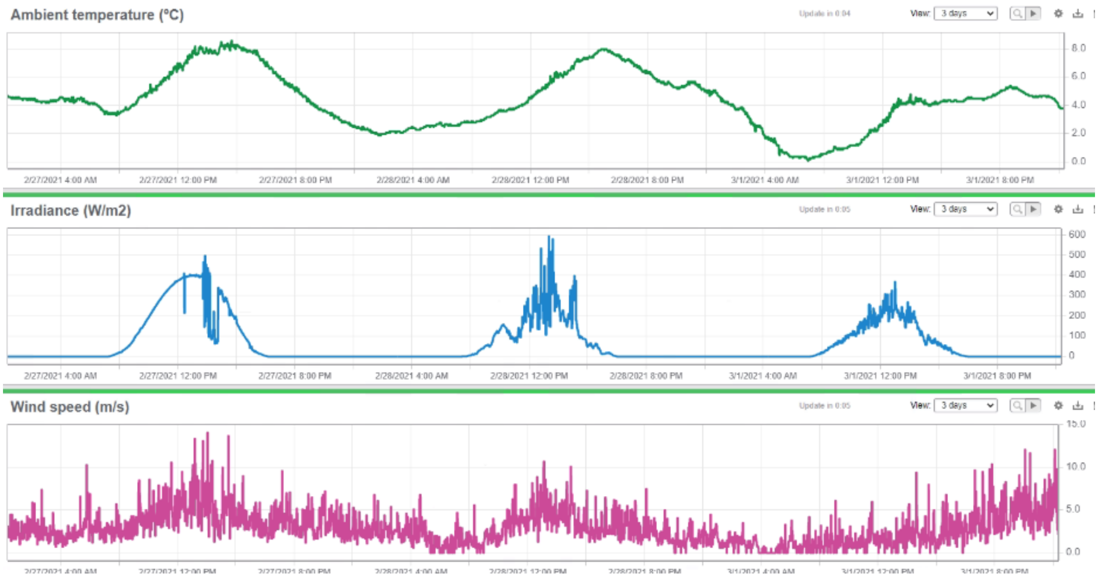

Figure 15:Monitoring website capture. Evolution of temperature ambient, Irradiance and wind speed of the last three days

⑫⑬ Connection to the DN: This is the point where the microgrid connects to the external DN. Here in Kaunas, the DN has a nominal voltage of 230 V, and in this case is a three-phase connection so the voltage between phases is 400 V. As we said before, this microgrid is able to operate with two modes: connected to the DN and in island mode. This connection allows to supply loads directly from the DN when their consume is so high or to charge batteries when their state of charge is so low. Before making this connection, microgrid has to synchronize with the distribution grid and then the connection can be made, but this procedure is done by the master inverter automatically, that when both grids are synchronized, it sends the order to close the switch.

3. Measurements

Now we are going to enter one of the mean parts of this thesis, the experimental measurements. In this part we introduce how we have made all the measurements, with which equipment have made them, which hypothesis and simplifications have assumed and finally the analysis of the results of the measurements of the microgrid under study.

3.1. Simplifications and hypothesis

Firs of all we have to clarify the conditions that we are going to analyse, because this is a very complex system and we have to assume some simplifications.

For this project, in order to reduce the number of data, 3 different modes of working have been considered:

- Consuming/On-grid: When the loads are bigger than the generation and microgrid is connected to the DN.
- Consuming/Off-grid: When the loads are bigger than the generation and microgrid is disconnected to the DN, it means that batteries supply the loads.
- Generating/On-grid: When the generation is bigger than the loads and microgrid is connected to inject power to the DN.

We have not considered the mode when the generation is bigger than the loads and microgrid is disconnected to DN (Generating/Off-grid), because the microgrid's behaviour is very similar to the Generating/On-grid mode, the only difference is that the excess of produced energy is injected to the public grid.

3.2. Procedure

In order to test the system under different conditions, we have 3 different type of loads each one with a different power factor, that are the following:

- Transformer 380/38 V (k=10) + 3 resistors of 9.8 Ω: three-phase load composed by first a transformer with star-star (Y-Y) connection and then 6 resistors (3 of 2.8 Ω and 3 of 7 Ω) connected in serial the form 3 resistors of 9.8 Ω and at the same time connected these 3 resistors in star to the transformer. Both parts of the transformer with neutral connection. Connected to the DN this load consumes:
  - P = 190 W   Q = 200 Var   Cos (ϕ) = 0.7 (i)

- Transformer 380/113 V (k=3.385) + heater with fan: three-phase load composed by first a transformer with star-star (Y-Y) connection and then a three-phase heater with a resistance and a fan. Both parts of the transformer with neutral connection. Connected to the DN this load consumes:
  - P = 65 W   Q = 800 Var   Cos (ϕ) = 0.08 (i)

- Three lamps of fluorescent tubes: three-phase load composed by 3 single-phase lamps of fluorescent tubes star (Y) connected and with neutral connection. Connected to the DN this load consumes:
  - P = 205 W   Q = 35 Var   Cos (ϕ) = 0.99 (i)

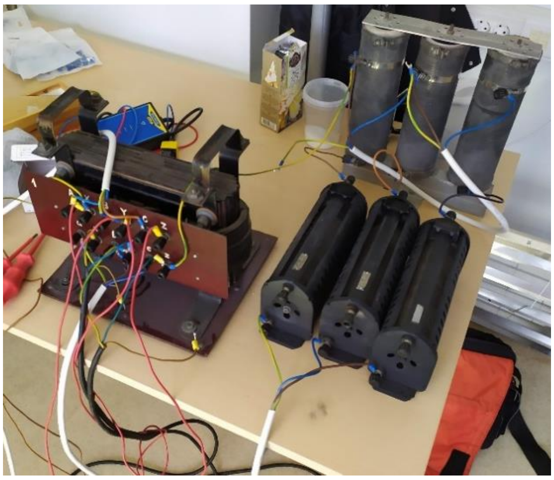

Figure 16: Resistance (R) = Transformer 380/38 V + 3 resistors of 9.8 Ω

Figure 18: Heater (H) = Transformer 380/113 V + heater with fan

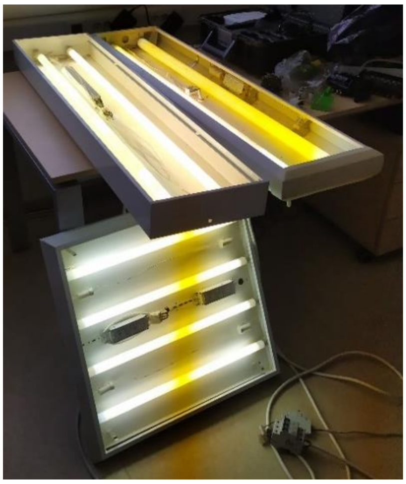

Figure 17: Lamps (L) = Three lamps of fluorescent tubes

With the combination of these three loads, we can obtain 7 different scenarios to test our microgrid with different power factor, in the following table we can see all the characteristics of each scenario:

	P (W)	Q (Var)	Cos (φ)
Resistance (R)	190	200	0.7 (i)
Heater (H)	65	800	0.08 (i)
Lamps (L)	205	35	0.99 (i)
Resistance + Heater (R+H)	260	1020	0.25 (i)
Resistance + Lamps (R+L)	390	285	0.81 (i)
Heater + Lamps (H+L)	265	870	0.29 (i)
Resistance + Heater + Lamps (R+H+L)	455	1050	0.39 (i)

Table 5:Power consumption and power factor of each scenario

In the following pages we will use the abbreviations in parentheses to refer the type of scenario we are talking about, in order to simplify nomenclature.

The main objective of these measurements is to see the power quality of the microgrid and if it meets standards. To do that, we will record, apart from the basic parameters, the harmonic content in both current and voltage, in such a way for each scenario we will measure the following parameters: voltage, current, active reactive and apparent power, power factor and frequency, we are interested in the content of harmonics, so we have measured the main parameters to count the level of harmonics that there are in each point, and these parameters are:

- Voltage
- Current
- Frequency
- Active power
- Reactive power
- Apparent power
- Power factor
- THD of voltage
- THD of current
- TDD of current
- Amplitude of the first 50 harmonics of voltage
- Amplitude of the first 50 harmonics of current

As the EN-50160 standard advises, all these parameters will be taken in samples of 10 minutes, enough time for the sample to be representative to analyse the power quality parameters.

3.3. Measuring equipment

A very important part of the measurement is the measuring equipment, in this case we have used two different equipment of the same company, Metrel:

- MI-2892 Power master: is a multifunction handheld device for network analysis and energy efficiency measurements with 4 voltage channels with a wide measurement range (up to 1000 Vrms), 4 current channels with automatic clamp recognition and scale selection, and with microSD memory card for easy and powerful data logging. Fully complies with the energy quality standard IEC 61000-4-30 Class A

- MI-3108 Eurotest PV: is a portable and multifunctional test instrument designed to perform all measurements in low voltage AC electrical installations and DC photovoltaic systems. It is capable of measuring voltages, current, frequency and power in photovoltaic systems and calculation of efficiencies (inverter and photovoltaic panels).

The first device (MI-2892) was the one we used to record all the parameters of the AC part of the installation, while the MI-3108 has been used for the DC part and also to calculate the efficiency of the inverters.

Figure 20: Metrel MI-3108 Power master

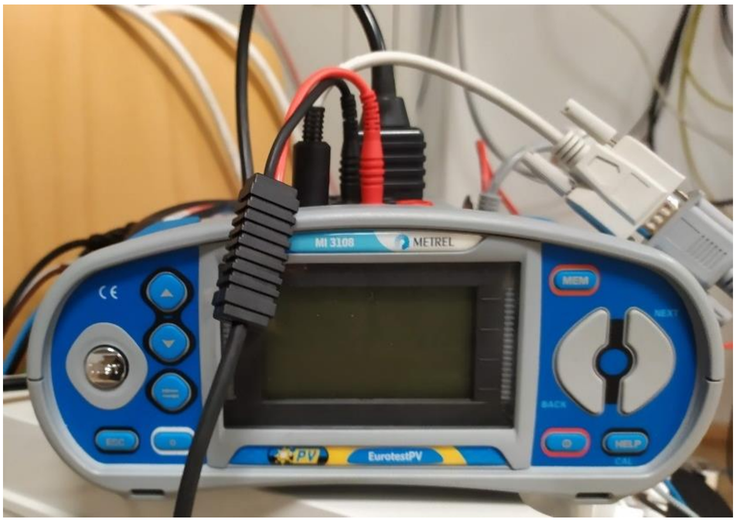

Figure 19: Metrel MI-2892 Eurotest PV

3.4. Results

In this part of the thesis, we are going to expose and comment the results that we have obtained, comparing the values with the limits of the standards and with the different scenarios and microgrid operating modes

3.4.1. Consuming / On-grid

The first operating mode that we are going to analyse is Consuming / On-grid, it means that loads consume more than the generators produce and also microgrid is connected to the DN, because the battery has low capacity and it is being charged by the grid.

In this mode, we have made measurements in three different points:

- Loads: immediately before than the loads connection, at this point we are controlling only the consumption of our loads, and analyse the power quality that they are receiving.
- Microgrid: the point where the generators, loads and the bidirectional inverters are connected to charge the batteries or connect the microgrid to the DN.
- Distribution network: the connection with the public grid before the bidirectional inverter, where in this case, the power flows towards the microgrid, to charge batteries and satisfy the loads consumption.

Frequency

The first quality parameter is frequency, the control of this variable is essential for a good power quality, because the loads are designed for a nominal frequency, so a slight deviation in frequency cause malfunction even serious problems. So, this is why the frequency limits are so narrow, that as we say before, are the following:

- Always: 50 Hz +4%/-6% (47≤f≤52 Hz)
- In 99.5% of the year: 50 Hz ±1% (49.5≤f≤50.5 Hz)

In the following graphic, frequency at three measurement points with the seven different scenarios in each point are represented:

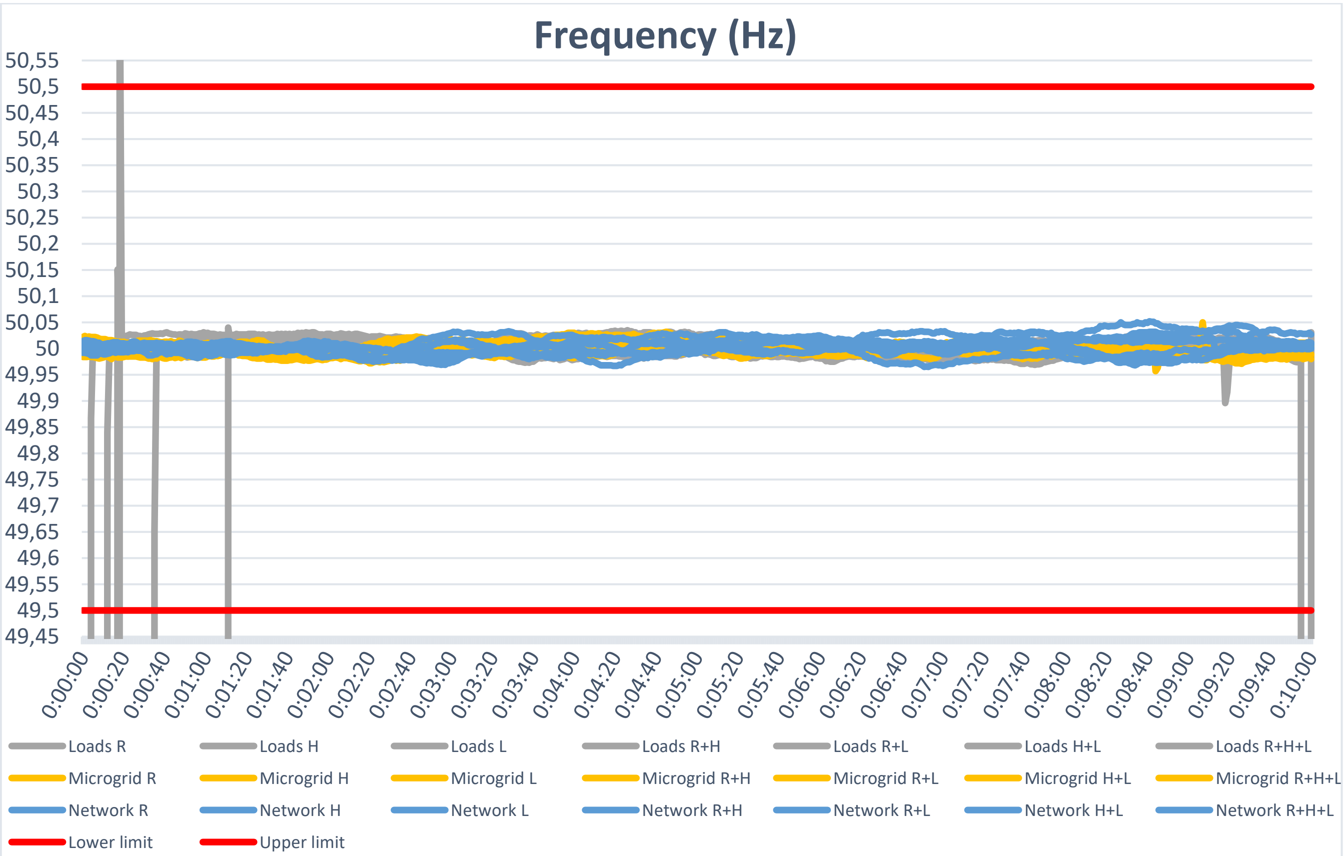

Figure 21: Frequency at the three measurement points with the seven different scenarios in each point. Mode 1

We can see that all the 21 cases are within the limits, and very near to the nominal value. Comment that the stripes at the beginning and at the end in the Loads measurement point values is due to the loads are not connected in the instant 00:00, so the first stripes are when close the circuit breaker of the 7 scenarios and the last stripes are when the loads are swich off. So, we can conclude that in this operating mode, frequency is well controlled and it meets the requirements of the European standard.

Voltage

The next parameter to comment is voltage, it is very important to maintain the voltage constant because the microgrid has some sensitive loads (like computers and electronic devices) and a sudden variation in voltage can produce irreversible damage to the devices. For this reason, the EN-50160 standard place limits on these variations, which, as we saw previously, are the following:

- Always: 230 V +10%/-15% (195.5≤V≤253 V)
- In 99.5% of the week: 230 V ±10% (207≤V≤253 V)

In this case we are going to analyse each measuring point separately, starting by the Loads point, with its 7 different types of loads. In this graphic we can see the voltage of the 3 phases that the different combinations of loads are receiving in the ten minutes samples:

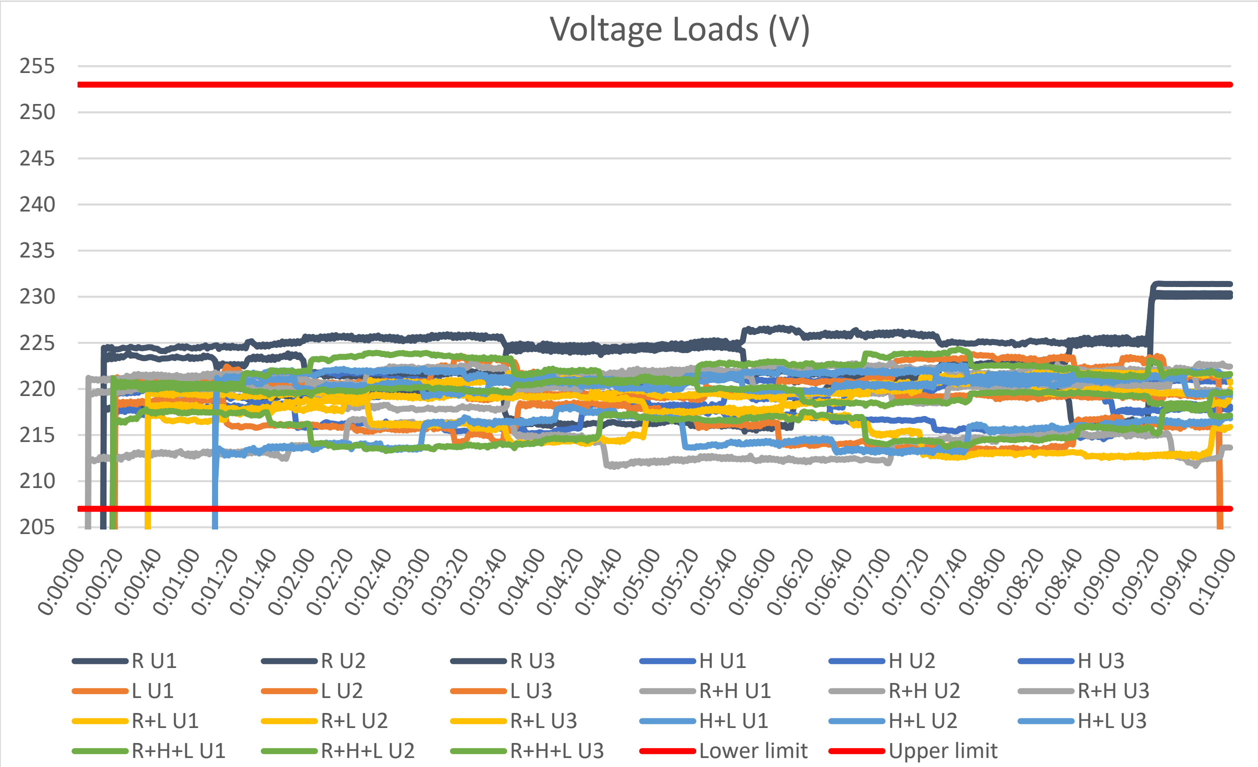

Figure 22: Voltage of the 3 phases of the 7 different scenarios in the Load measurement point. Mode 1

We can observe that all values are between the limits, but there is a small voltage gap, ±7 V around the nominal voltage (220 V), that in principle, should not affect the performance of the loads, but denotes a not very strict control. It should be to noted that, at approximately 9:20 minutes, there is a step in the Resistance (R) voltage, this is due to the fact that at that moment the system goes from the charging mode to the island mode, disconnecting from DN and switching to supply the loads from the batteries, and when the microgrid is in island mode the master bidirectional inverter is the responsible for voltage control, and the reference voltage is 230 V, as discussed below.

Now we are going to analyse the same parameters but in the microgrid measurement point, at this point are connected all the inverters from the generators and all the lightning, heating and different loads of the third floor of the lab building apart from our calibrated loads. And the results are the following:

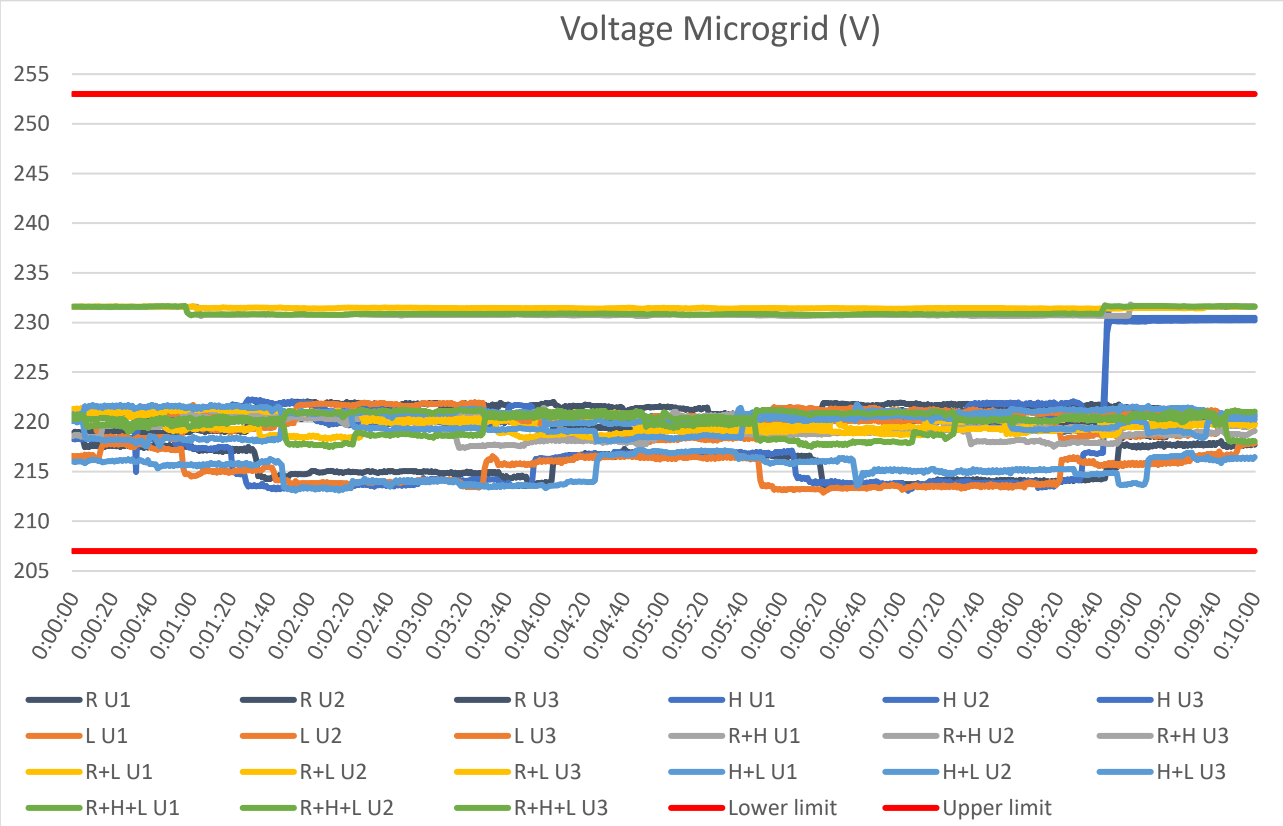

Figure 23:Voltage of the 3 phases of the 7 different scenarios in the Microgrid measurement point. Mode 1

Again, we can see that all the values are within the limits and the voltage gap around the nominal voltage remains more or less the same. And we have another time the voltage step at the end of the sample, this time in the Heater (H) load, and the cause is the same fact, the automatic switch to island mode.

And in this graphic also we can check abnormal behaviour of the voltage, there are two cases (R+L and R+H+L) that one phase has much higher voltage than the other two, and in both cases the same phase (U2), and the cause of this problem was the one-phase Ginlong inverter, which is connected to this phase, and when the power generation is so far of its nominal value, it generates a large amount of reactive power.

We can see this phenomenon in the picture 24, for one of these cases (R+L), where the reactive power in each phase is represented, and the reactive power of the phase 2 is abnormally negative, which means that reactive power is being generated, when most of the connected loads are inductive.

This may be due to the power electronics that uses the inverter, because it works well, this the unique inconvenient, or some parameter that is wrongly configured, but this fact is repeated several times as we will see later.

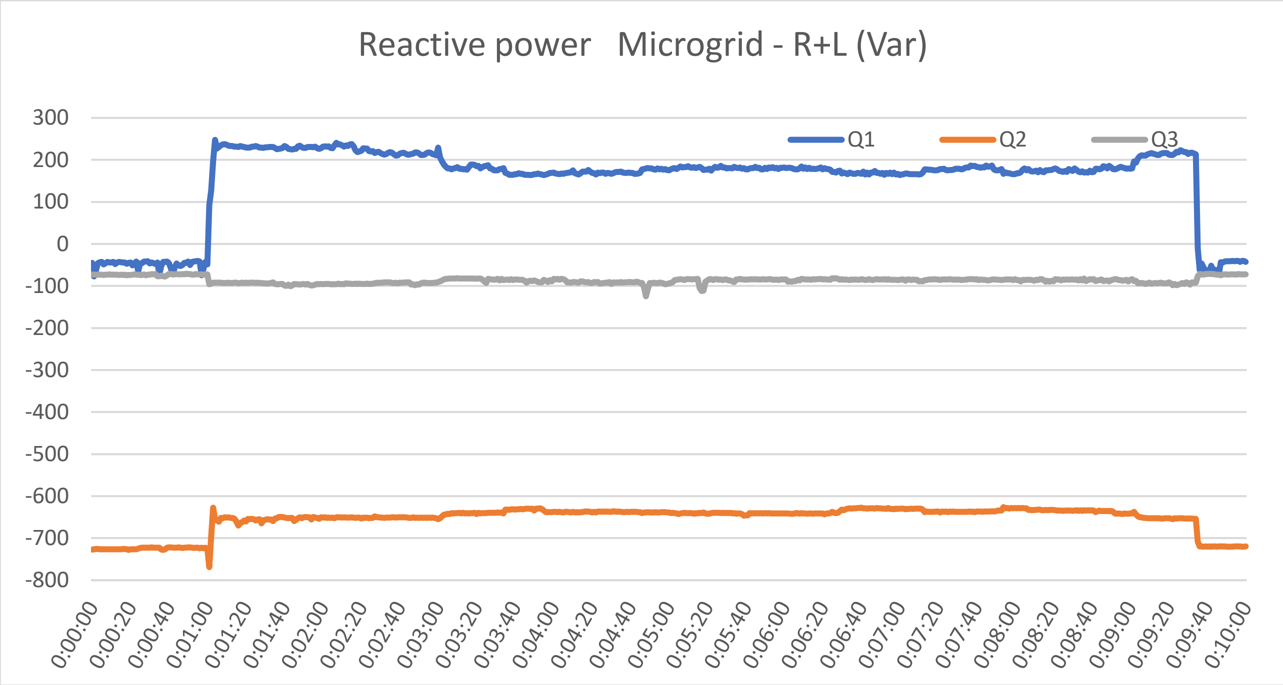

Figure 24:Reactive power of the 3 phases with the R+L load (Resistance +Lamps) in the Microgrid measurement point. Mode 1

And finally, the last measuring point is the connection with the distribution network, in the picture 25 are represented the same parameters of voltage of the 7 different scenarios:

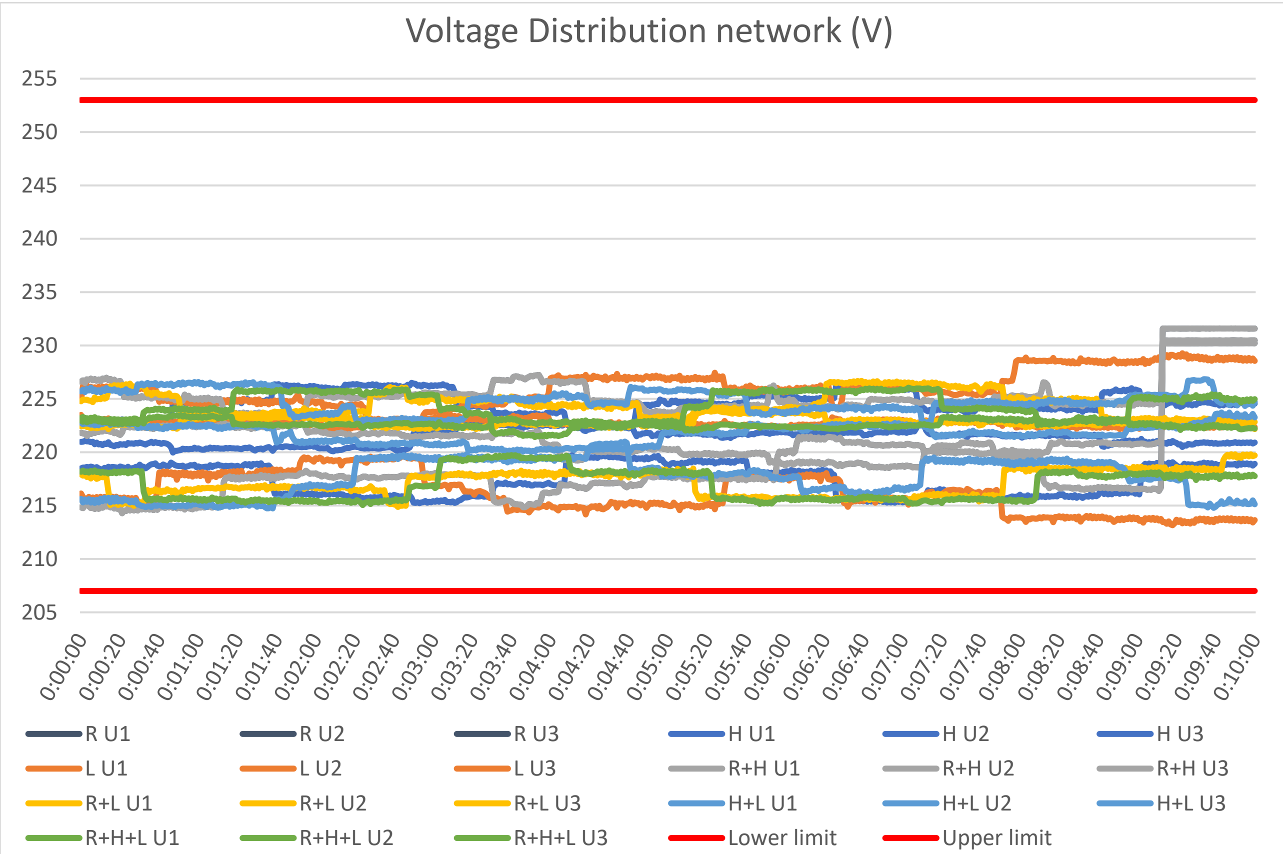

Figure 25:Voltage of the 3 phases of the 7 different scenarios in the Distribution network measurement point. Mode 1

Here we can see that the distribution company complies with the EN-50160 standard, with regard to voltage limits, also the automatic change to the island mode in R+H load, and you can see again the gap of ±7 V around the nominal value (220 V). This confirms that when microgrid is connected to the grid, the master inverter does not control the voltage, so the responsible of this voltage variation is the distribution company, that, as we have just verified, complies with the established voltage limits.

Voltage THD

The Voltage THD is an indicator that measures the content of harmonics in the voltage waveform, as we said before a high level of harmonics can be detrimental to the system, and the european standard sets some limits for it:

- In 95% of the week: <8%

We are going to analyse this parameter like the previous one, with the data if each of the three measuring points separately.
The following picture represents the THD of the voltage of each phase of the 7 different loads at the Loads measuring point.

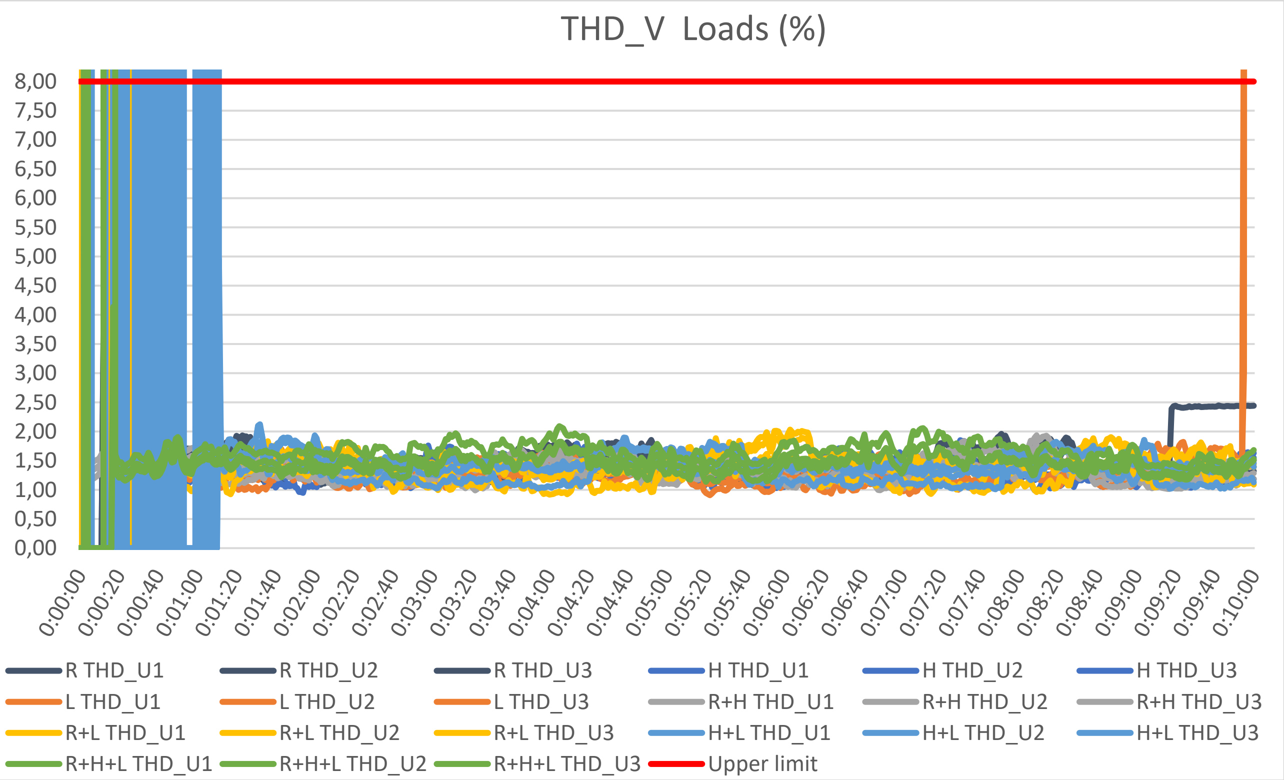

Figure 26:Voltage THD of the 3 phases of the 7 different scenarios in the Load measurement point. Mode 1

The graphic indicates that all the values are under the maximum permitted, it means that the quality of the voltage that reaches the loads is good and they do not produce many harmonics. We can observe the phenomenon of the stripes at the beginning and end of the samples, that we have explained before, due to the switching of the loads. And also, at the end, the change to the island mode in the R load.

The same parameters but at the Microgrid measurement point are represented in that graphic:

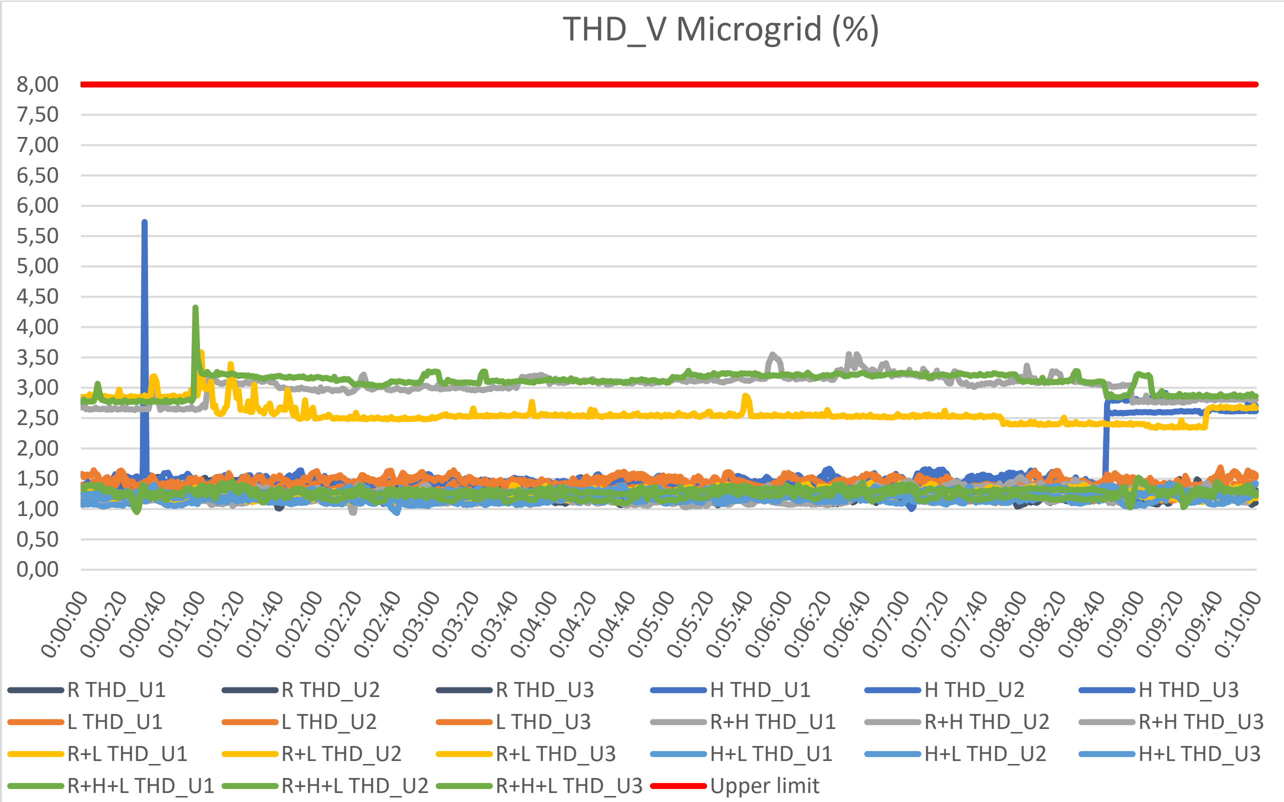

Figure 27:Voltage THD of the 3 phases of the 7 different scenarios in the Microgrid measurement point. Mode 1

Now we can observe the influence of the effect the abnormal situation of the reactive power production from one-phase Ginlong inverter in the voltage THD, it's again the phase number 2, which has higher values of the Total Harmonic Distortion of the voltage, and the reason is the same that we have explained in the previous situation at this measuring point. Despite this all the values are within the limits and if we ignore these anomalous data, the level of the quality of the voltage at this point is quite good.

And we finish this parameter, with the data of the Distribution network measuring point (picture 28), where we can see that in all the cases the voltage THD are more or less between 1 and 2 %, and as the limit is 8%, it means that the distribution company complies also with the condition of the quality of the voltage waveform. At the end we can see the swich to the island mode one more time in the R+H load.

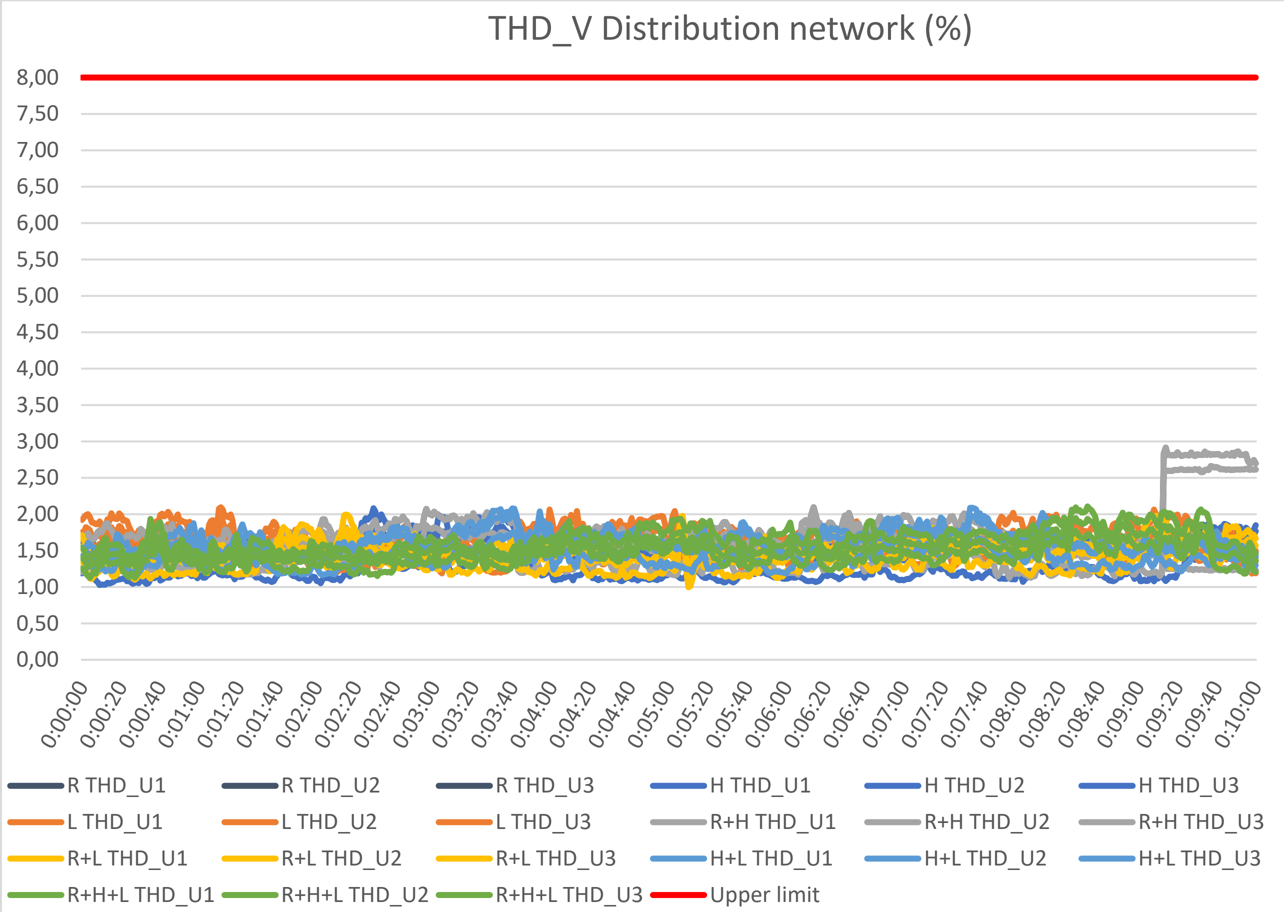

Figure 28: Voltage THD of the 3 phases of the 7 different scenarios in the Distribution network measurement point. Mode 1

After analysing the different points of the installation, we can conclude that voltage parameters, both the tension level and the harmonic content, are quite good in all points of the microgrid and for different type of loads.

Current THD

Now we are going to analyse the current quality parameters, and we start with the Total Harmonic Distortion (THD), that, as with voltage, is an indicator to evaluate the harmonic content in the current. We will proceed in the same way as with the voltage, we will analyse the three measurement points separately.

This parameter is not regulated by the European (EN-50160) nor by the American standard (IEEE 519-2014), but is a good indicator to see the quality of the current and where in the installation the current harmonics are being produced

We start with the Loads measuring point, and the following graphic shows the current THD of the three phases of the 7 different scenarios in samples of 10 minutes, as standard advises:

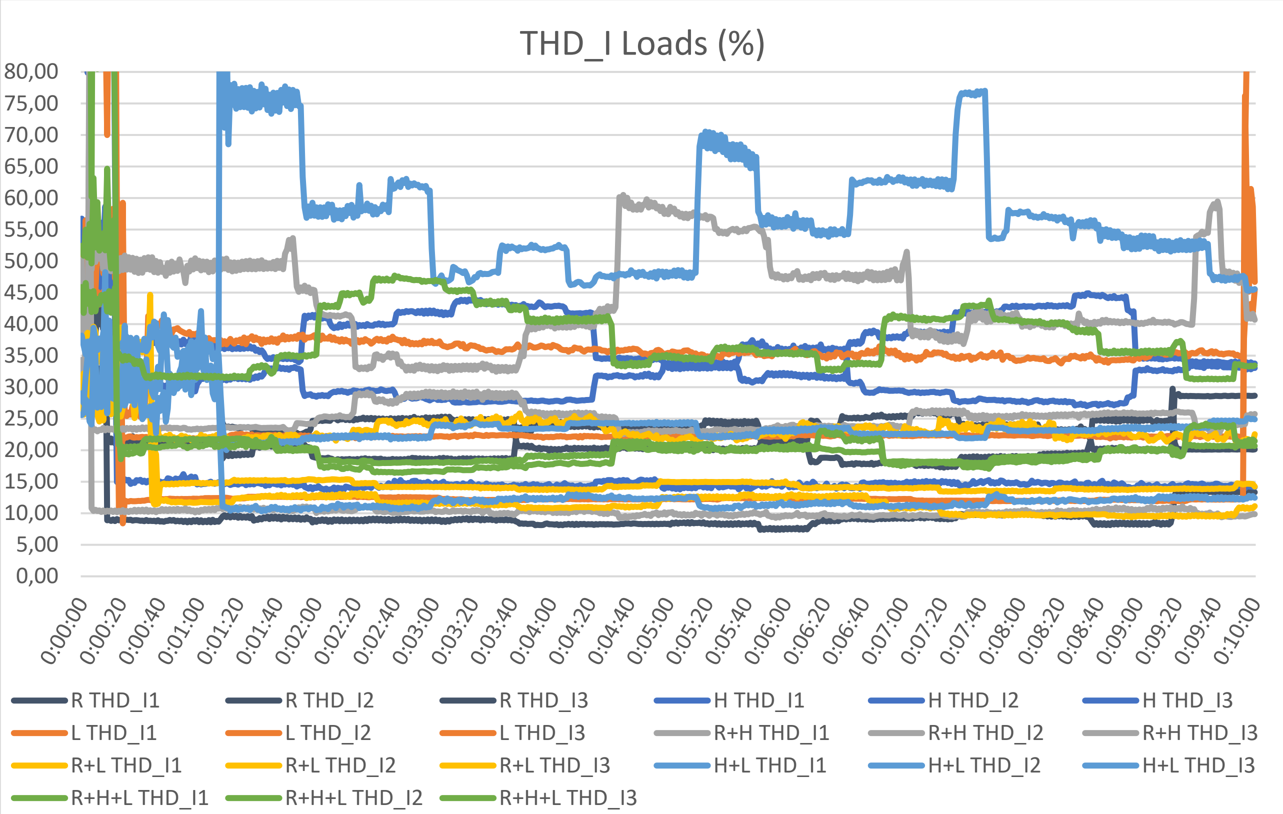

Figure 29: Current THD of the 3 phases of the 7 different scenarios in the Load measurement point. Mode 1

We can see that the values of the current THD are much higher than the voltage, it means that the current has higher content of harmonics and a waveform that differs more from a sinusoidal than from voltage. We can observe a little relationship between the type of load and the THD value, we can see that the four scenarios with the highest THD (H+L, R+H, H, R+H+L), share always the Heater load, and the Lamps load is present in 3 of the 5 scenarios with more presence of harmonics.

A stronger relationship is the one that has the harmonic content with the phase conductor, if we eliminate the data from phase number 2, the result that we obtain is the following:

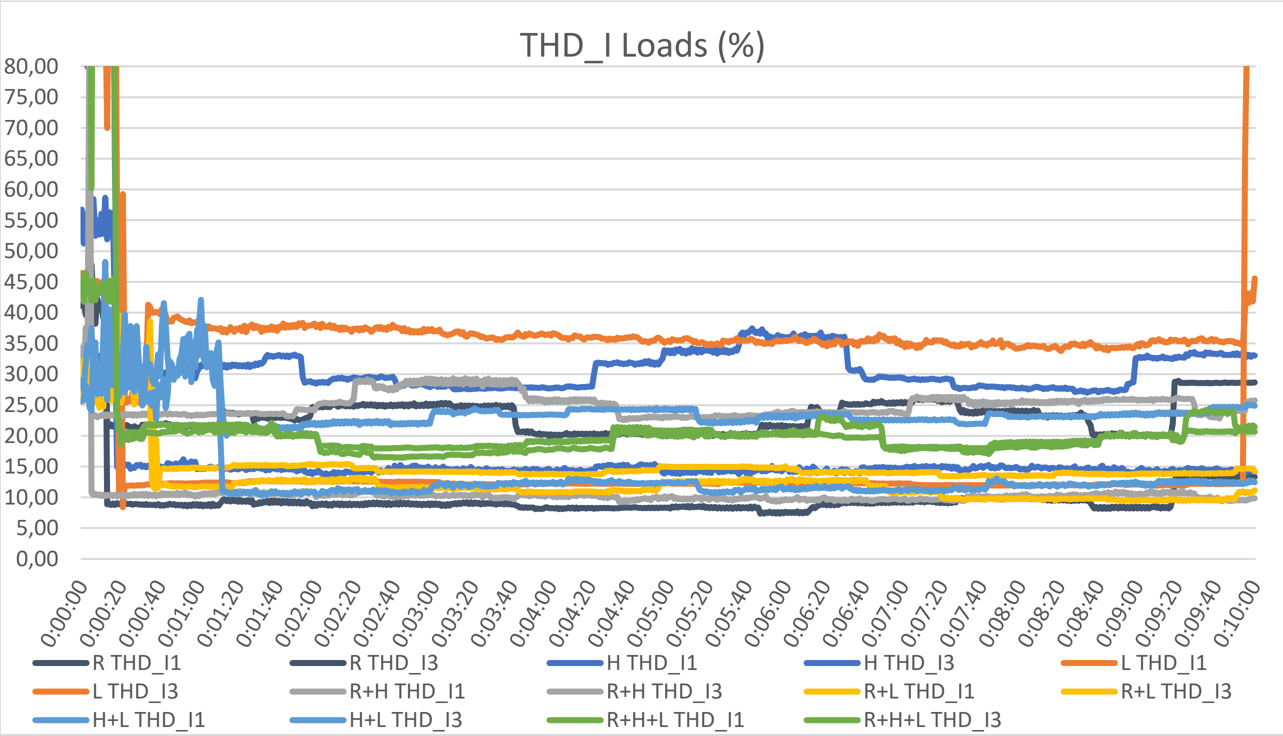

Figure 30:Current THD of phases 1 and 3 of the 7 different scenarios in the Load measurement point. Mode 1

All the values are lower than 40%, and all higher THD samples disappear. So we can conclude that in the phase number 2 there are some device that are creating many harmonics, and the influence is higher when the Heater load is connected.

Now we change the measuring point and we move to the microgrid, and the results of the current THD at this point are the following:

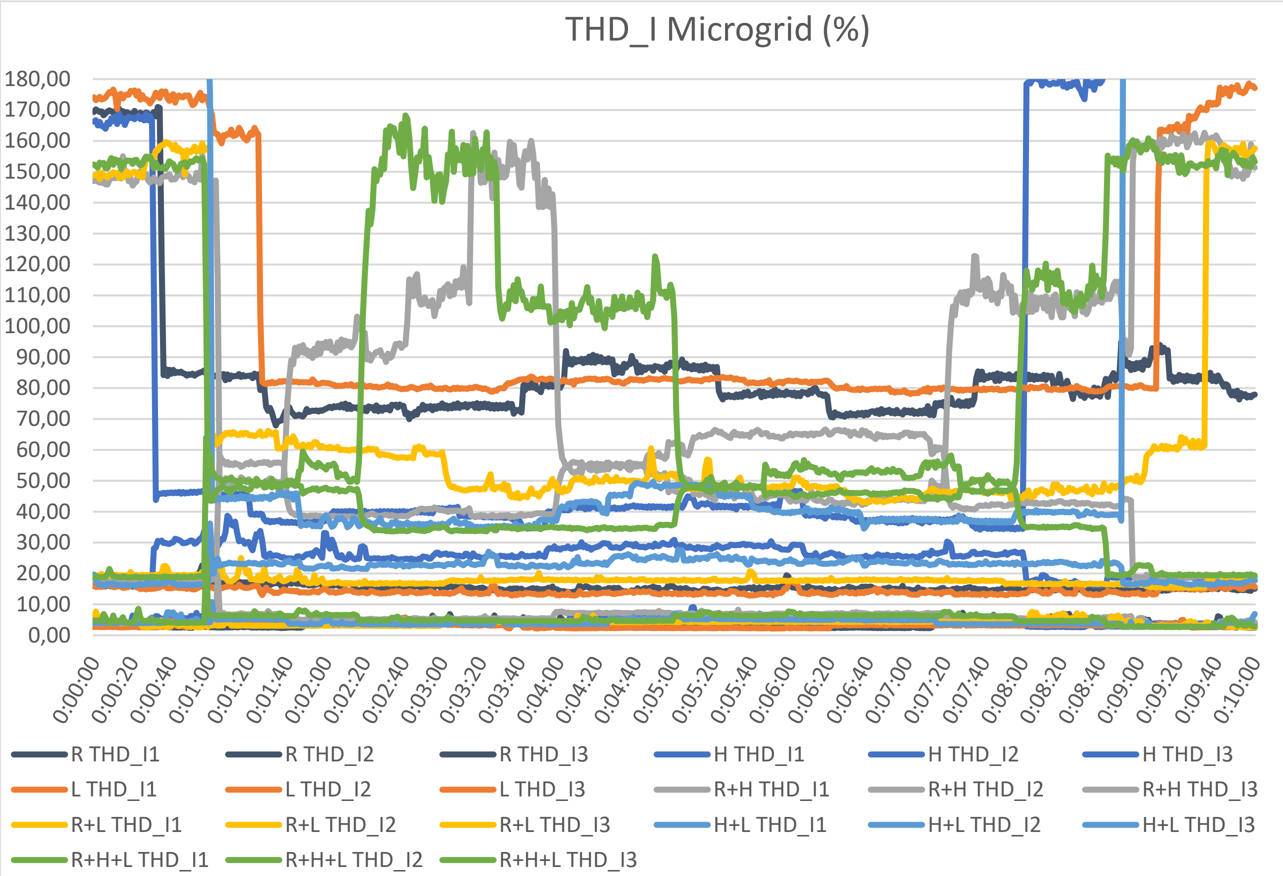

Figure 31: Current THD of the 3 phases of the 7 different scenarios in the Microgrid measurement point. Mode 1

Here the values of the distortion are bigger than in the Loads measuring point, this is because at this point there are many electronic devices connected, the inverters are the ones that usually cause this distortion in the current waveform, since, when the wave that is generated by inverter is not perfectly sinusoidal, harmonics are generated that deform this waveform.

Now the scenarios with higher THD are R+H and R+H+L again, now the relation between the THD values and the type of load, is quite weak. Conversely, the relationship of the distortion and the phase conductor, is appreciable here too, in the figure 32 the same data is represented without the values of phase number 2.

We can observe a great reduction of the levels of the current distortion, since the maximum value goes from 160% with phase nº 2, to 65% without it. So now it's more evident that only in phase 2 there is something that produces a very high number of harmonics in the current, and the responsible of this effect is the single-phase Ginlong inverter, which is connected to this phase, because all the other inverters that are connected to the microgrid are three-phases inverters.

The most probable is that this abnormal operation is due to the fact that it is working far from its nominal power, but due to the lack of sunny days in the measurement campaign it has not been possible to verify this assumption.

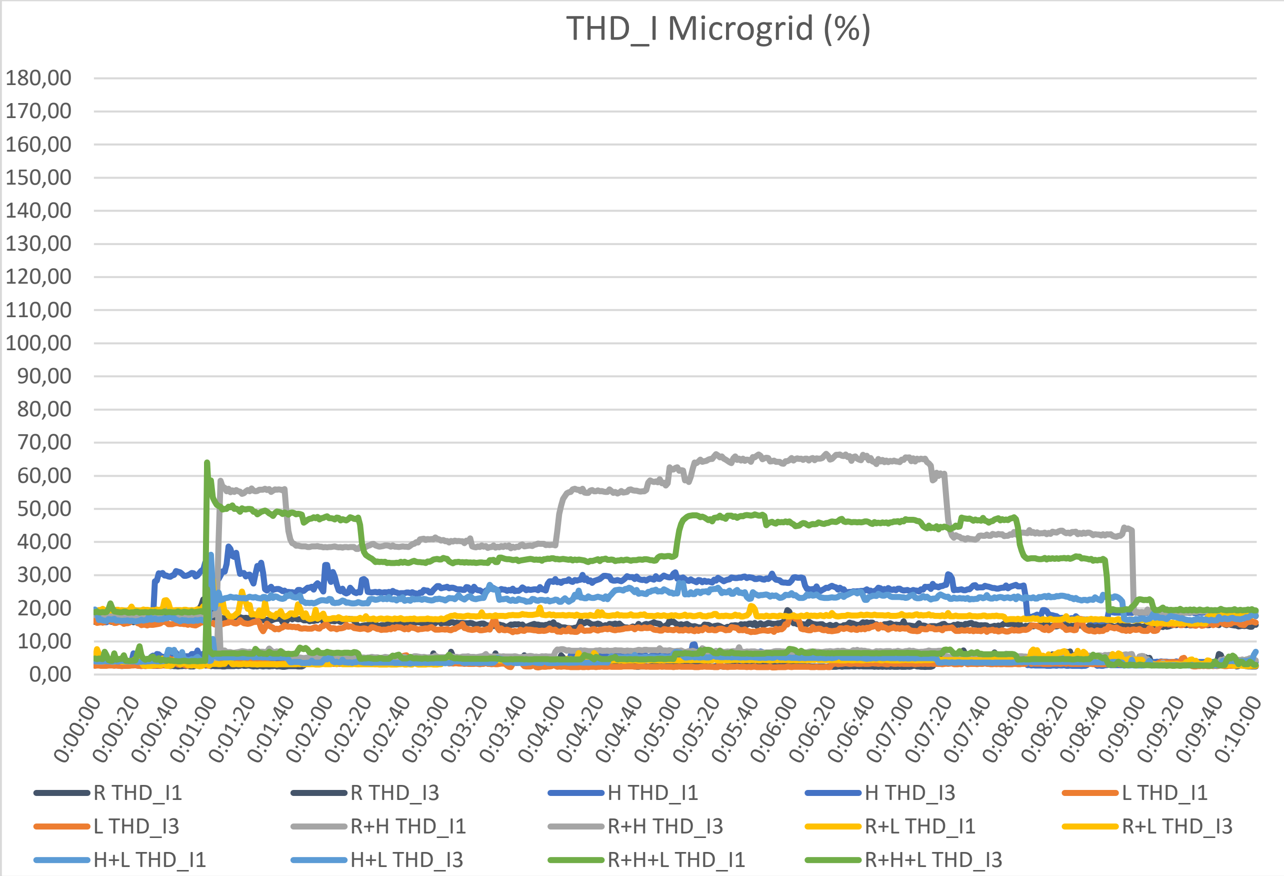

Figure 32: Current THD of phases 1 and 3 of the 7 different scenarios in the Microgrid measurement point. Mode 1

And finally, the picture 33 shows the current THD in the Distribution network measuring point:

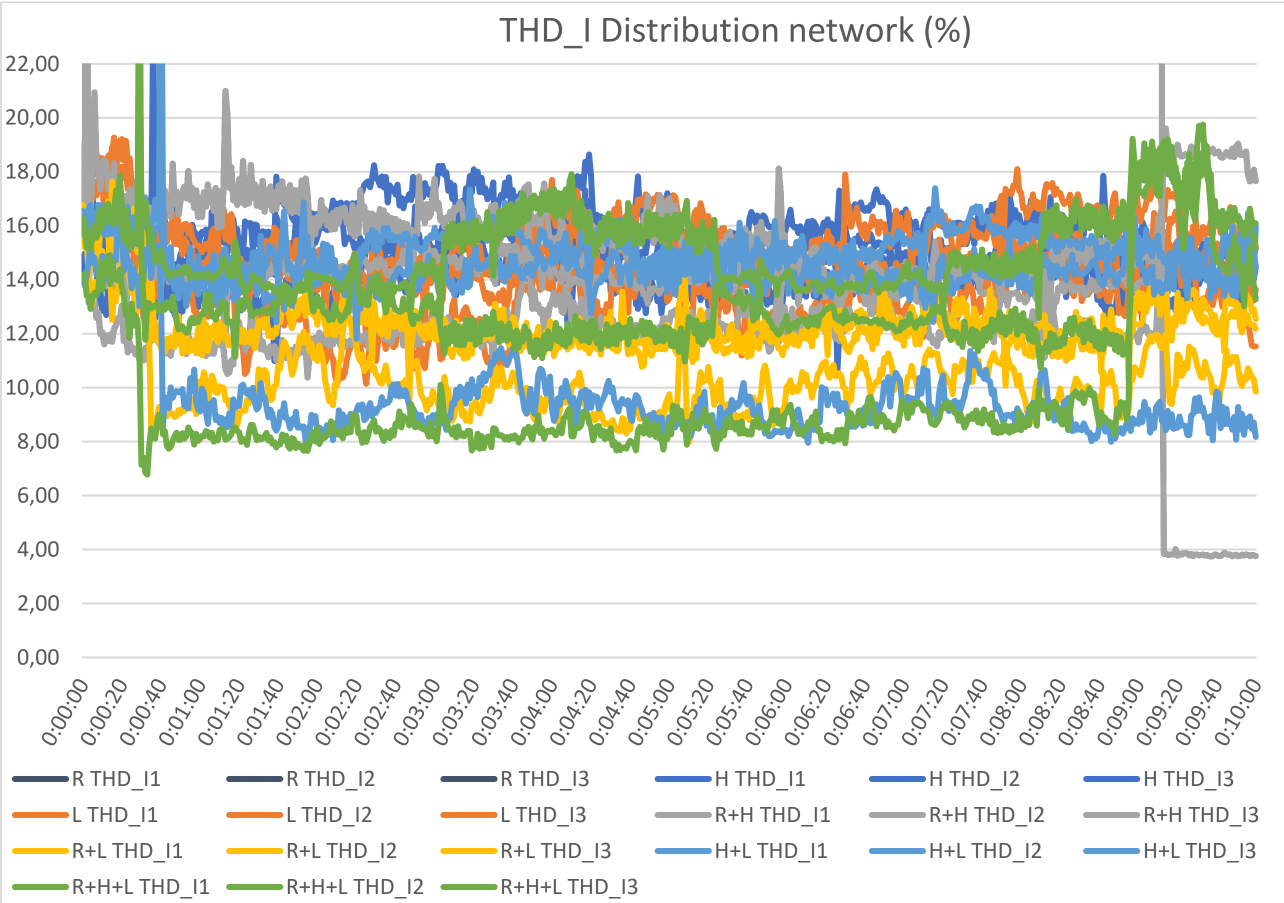

Figure 33: Current THD of the 3 phases of the 7 different scenarios in the Distribution network measurement point. Mode 1

At this point we can see that the current has a much less harmonic content than in the previous two, it means that the transformers of the bidirectional inverters work well, because one the missions of this inverter component is to avoid the transmission of harmonic currents, and how we can check this harmonic isolation makes that the harmonics that are generated within the microgrid are not injected into the distribution network.
We can conclude that at this point there is no longer any relationship between the current distortion and the typo of load connected, not between the phase of the conductors, we can see that all the values are in the range between 8 and 18%.

The next picture shows the amplitude of the first 50 harmonics referred to the fundamental during 10 minutes sample of one of the scenarios with more current distortion (Microgrid_R+H+L_phase 2)

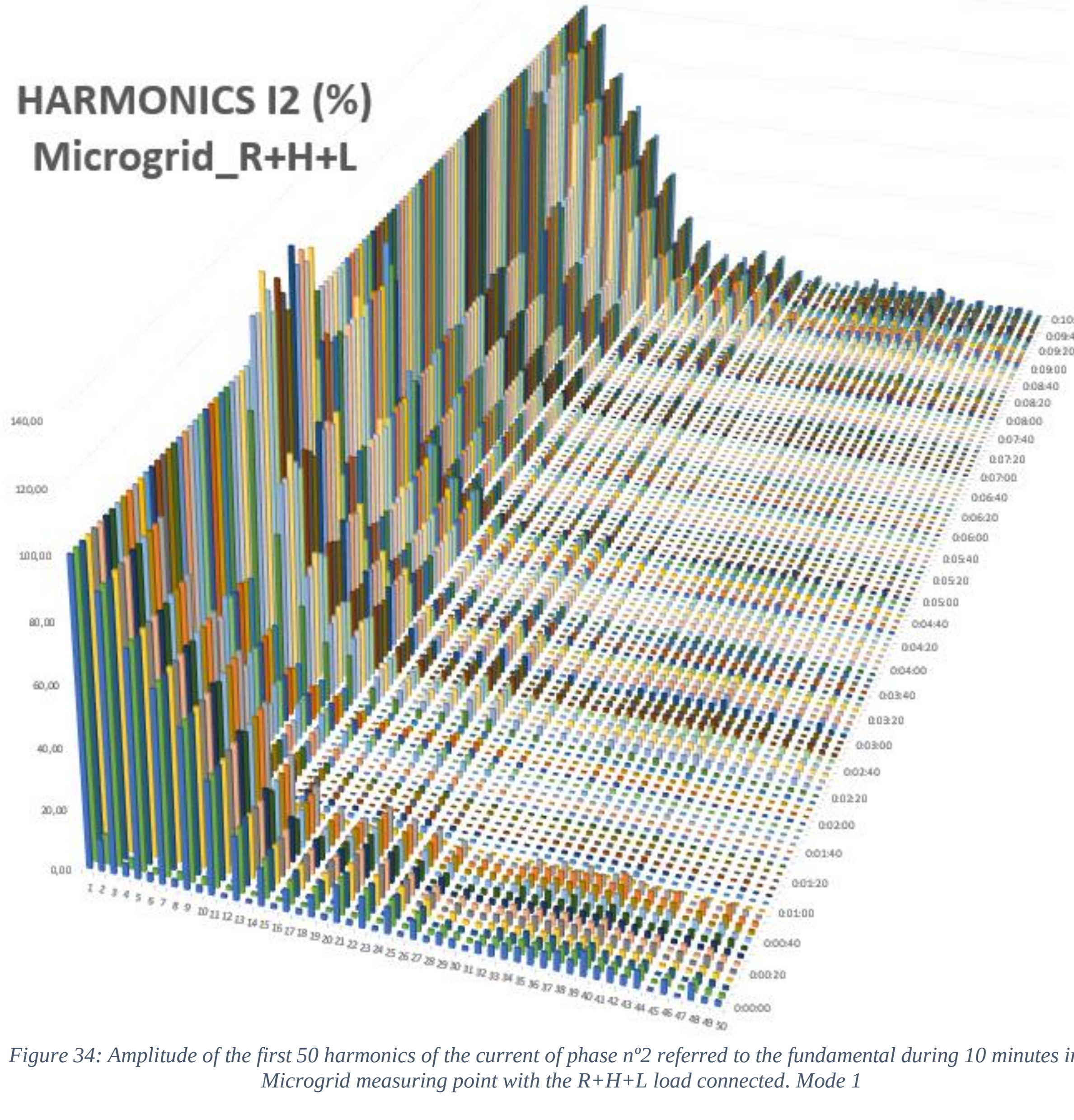

Figure 34: Amplitude of the first 50 harmonics of the current of phase nº2 referred to the fundamental during 10 minutes in the Microgrid measuring point with the R+H+L load connected. Mode 1

We can see that the amplitude of the low frequency harmonics is so high, there is even a moment when the value of the third harmonic exceeds that of the fundamental. This sample at its maximum distortion point reaches a current THD of 170 % as we can see in figure 31 (green line), a value very far from the levels recommended by the standards for the proper operation of an electrical installation.

Current TDD

The last parameter that we are going to analyse is the Total Demand Distortion (TDD) that is related with the current THD and the instant current, and TDD indicates the impact of harmonic distortion in the system.
This indicator is not regulated by the European standard, but in IEEE 519-2014 standard recommends not to exceed certain limits at Point of Common Coupling (PCC) for a good operation of the distribution network. Specially the recommended limits, as explained in section 1.4.2, are as follows:

- In 95% of the week: <15% (only in the PCC)

So, how this limit is only applicable for the PCC and in our installation this point is the connection with the distribution network, we are going to comment only the data of the distribution network measuring point, the following picture shows the current TDD of the 3 phases in the 7 different scenarios at this point:

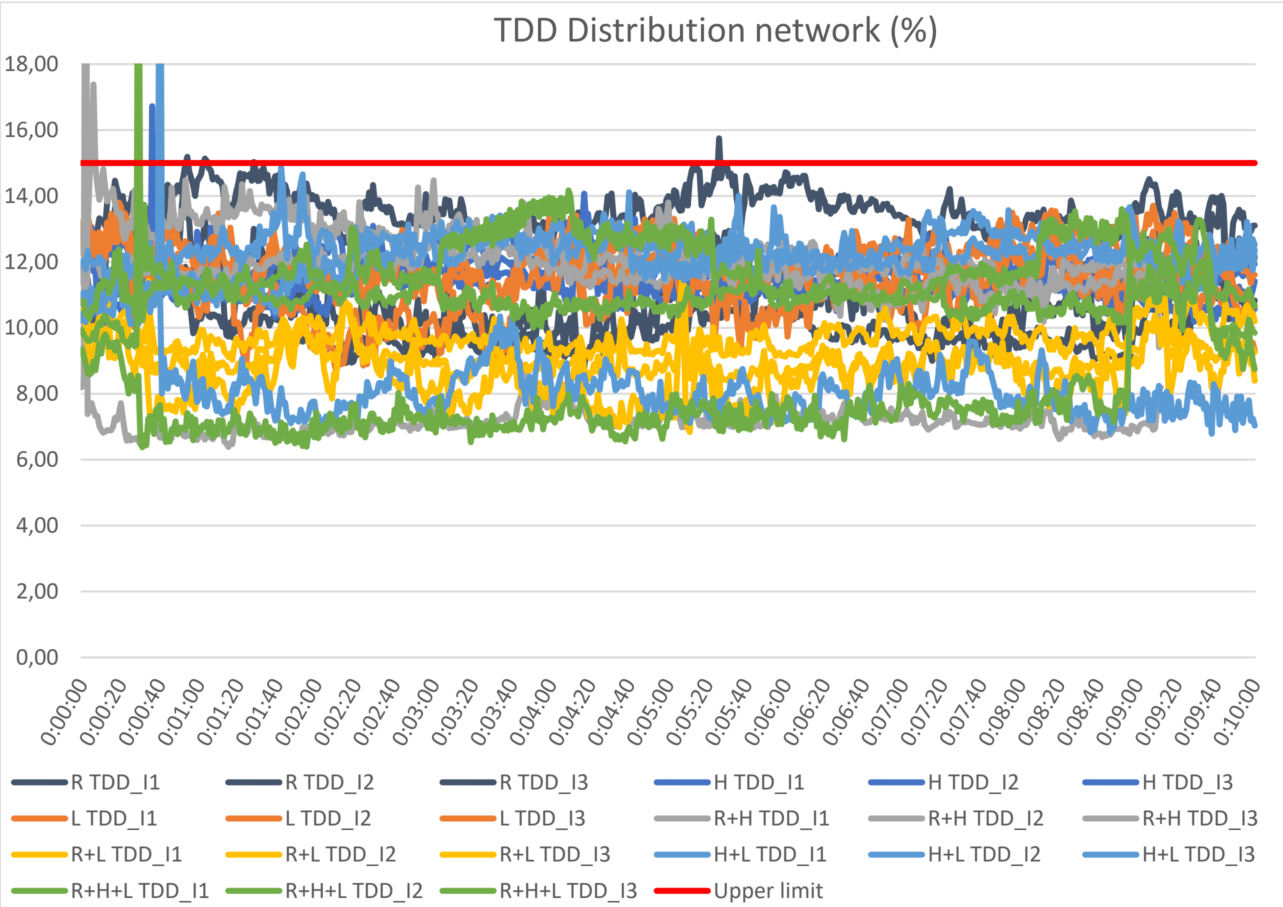

Figure 35:Current TDD of the 3 phases of the 7 different scenarios in the Distribution network measurement point. Mode 1

We can see that more or less all the values are under the limit, so we can conclude that the distribution company also complies with the recommended limits of harmonic content in the current.

And with the analysis of this last parameter, we conclude this first mode of operation of the microgrid.

3.4.2. Consuming / Off-grid

The next operation mode that will be analysed is Consuming / Off-grid, it is when the loads consume more than the generators produce and microgrid in not connected to the DN, it means it is working in island mode, and the loads are supplied by the batteries.

This time we have considered only one measuring point, the same that in the previous mode was called microgrid, the point where the inverters of generators, loads and the bidirectional inverters are connected.
We will follow the same method as in the previous section analysing each parameter separately and comparing the results with the previous operating mode. And as we have already commented on the limits of the regulation we are using, and they are the same for all operating modes, in this section and the next we will limit ourselves only to commenting on the results obtained.

Frequency

The first parameter is frequency, and in this graphic is represented the frequency of the 7 different scenarios and the limits of the European standard:

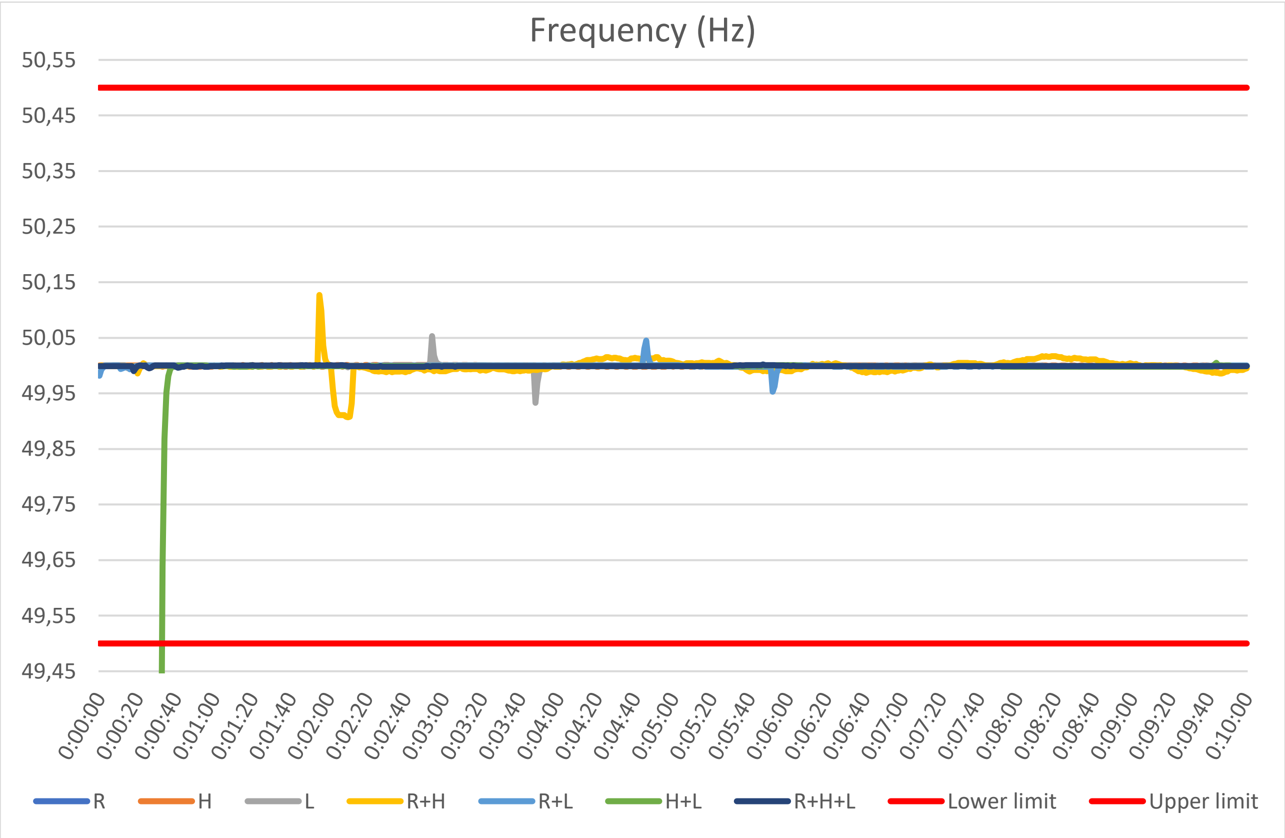

Figure 36: Frequency of the seven different scenarios in the Microgrid measurement point. Mode 2

We can see that the frequency control is practically perfect, there are some peaks but always within the limit values, if we compare with the previous operating mode (figure 21 yellow line) we can see that this time the values differ very little from nominal value (50 Hz). This is because in the on-grid mode, the DN sets the frequency and the voltage, and now the master bidirectional inverter is the responsible of the frequency control, and we can conclude that this control is quite good.

Voltage

We continue with the voltage of the three phases of the seven different type of loads, that are represented in the following picture:

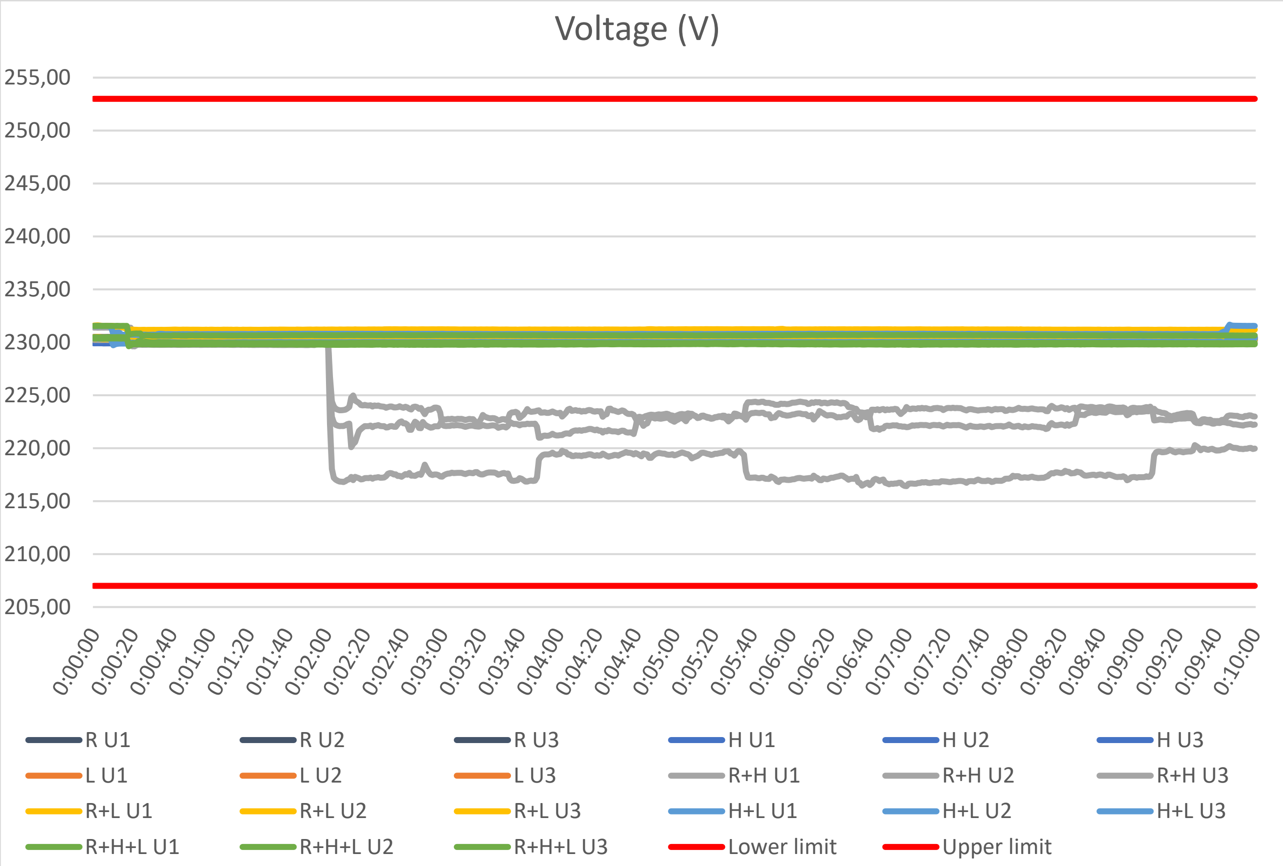

Figure 37:Voltage of the 3 phases of the 7 different scenarios in the Microgrid measurement point. Mode 2

As in the frequency, it is observed that the voltage is practically constant, it hardly has variations, the range on variation is less than ± 2 V around the nominal voltage (230 V), while in the mode 1, this range in the same situation was ± 7 V (Figure 23). This is due to voltage control from master bidirectional inverter that, as we can check works very well, keeping all values within the limits with a fairly large margin, regardless of the connected load.

We can see in the R+H load the automatic swich from the island mode to the on-grid mode, that as we discussed earlier, this jump is due to the fact that these modes do not have the same nominal voltage, when the microgrid is connected to the DN, the nominal voltage is 220 V and when it works in island mode it is 230 V.

THD Voltage

Now it is the turn of the quality parameters, starting with the voltage THD, the values of this indicator of the three phases in the seven different loads are represented in this graphic:

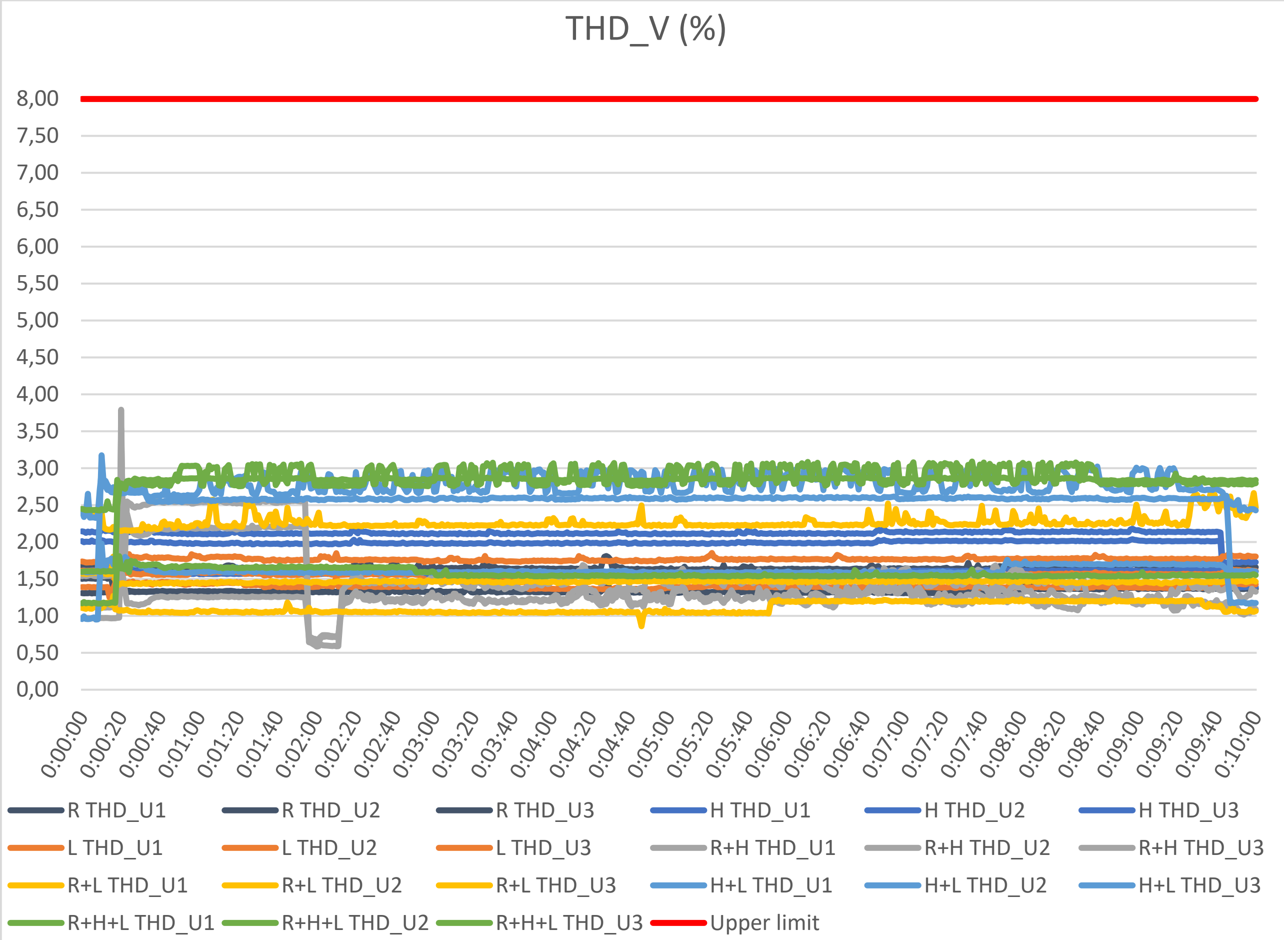

Figure 38:Voltage THD of the 3 phases of the 7 different scenarios in the Microgrid measurement point. Mode 2

All the values are very far of the maximum permitted, regardless of conductor phase or connected load, and the values are in the same range more or less, than in the mode 1 (Figure 27). In conclusion, we have a good quality in the voltage waveform when microgrid works in island mode.

THD Current

We continue with the current Total Harmonic Distortion (THD), the figure 39 shows the different values of this parameter for the three phases in the 7 scenarios under study.

In this graphic we can see high levels of current distortion, but lower than in the previous operating mode in the same situation (Figure 31), and as in that case, there is a direct relationship between the current THD and the phase conductor, the phase number 2 again, has the highest levels of harmonics, and if we delete its data, we obtain the figure 40, where we can see that, except for some peaks, all other values are less than 45 %. The relationship between the distortion and the type of load connected, in that case, is very low.
We can conclude that, as in on-grid mode, we have a harmonic content problem in phase 2, it seems to be a little less important in island mode, but current THD values are still far from recommended.

The current TDD parameter is not analysed in this operating mode since the regulations only apply when the installation is connected to the DN, therefore it does not make sense in this mode.

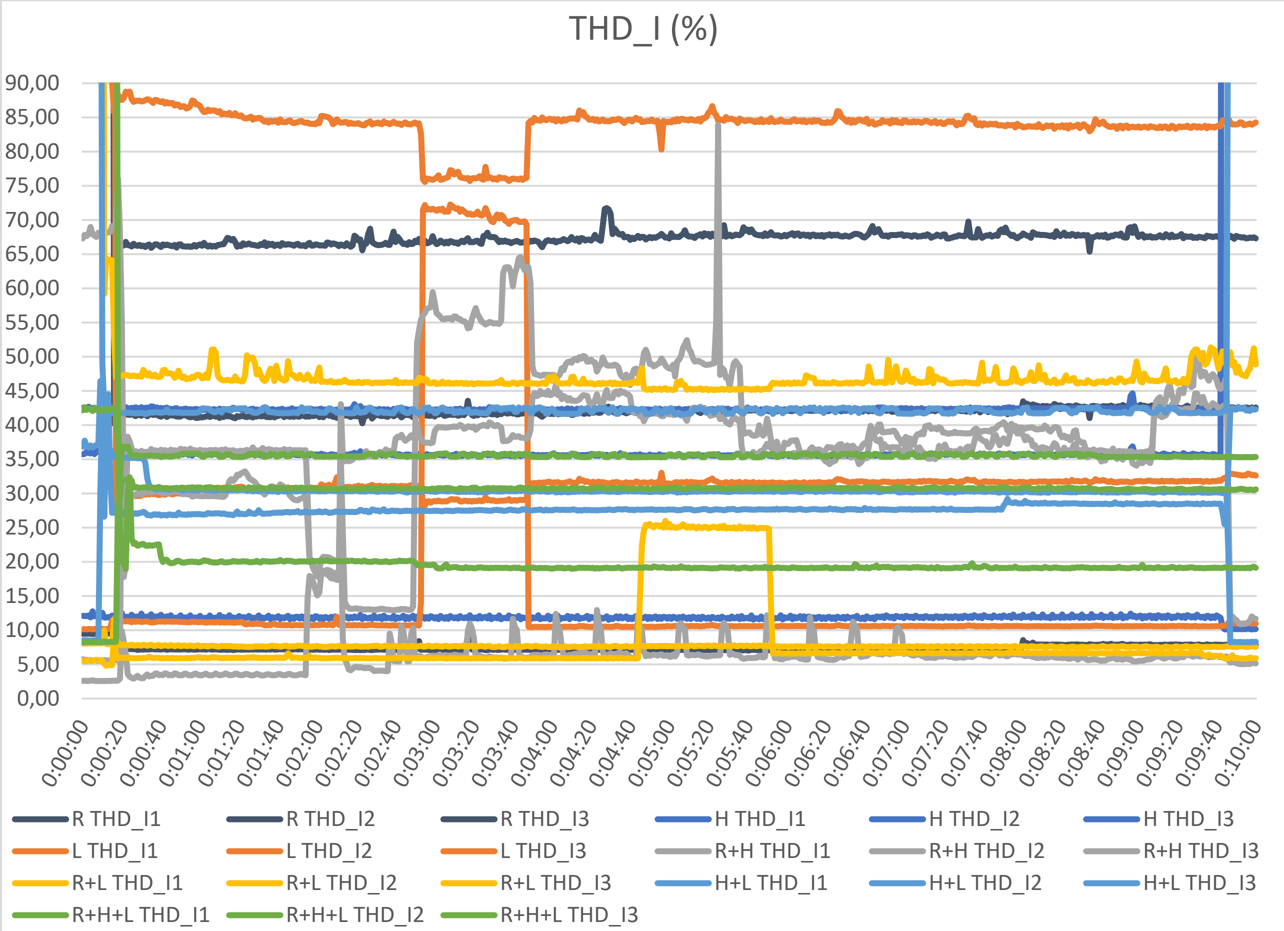

Figure 39: Current THD of the 3 phases of the 7 different scenarios in the Microgrid measurement point. Mode 2

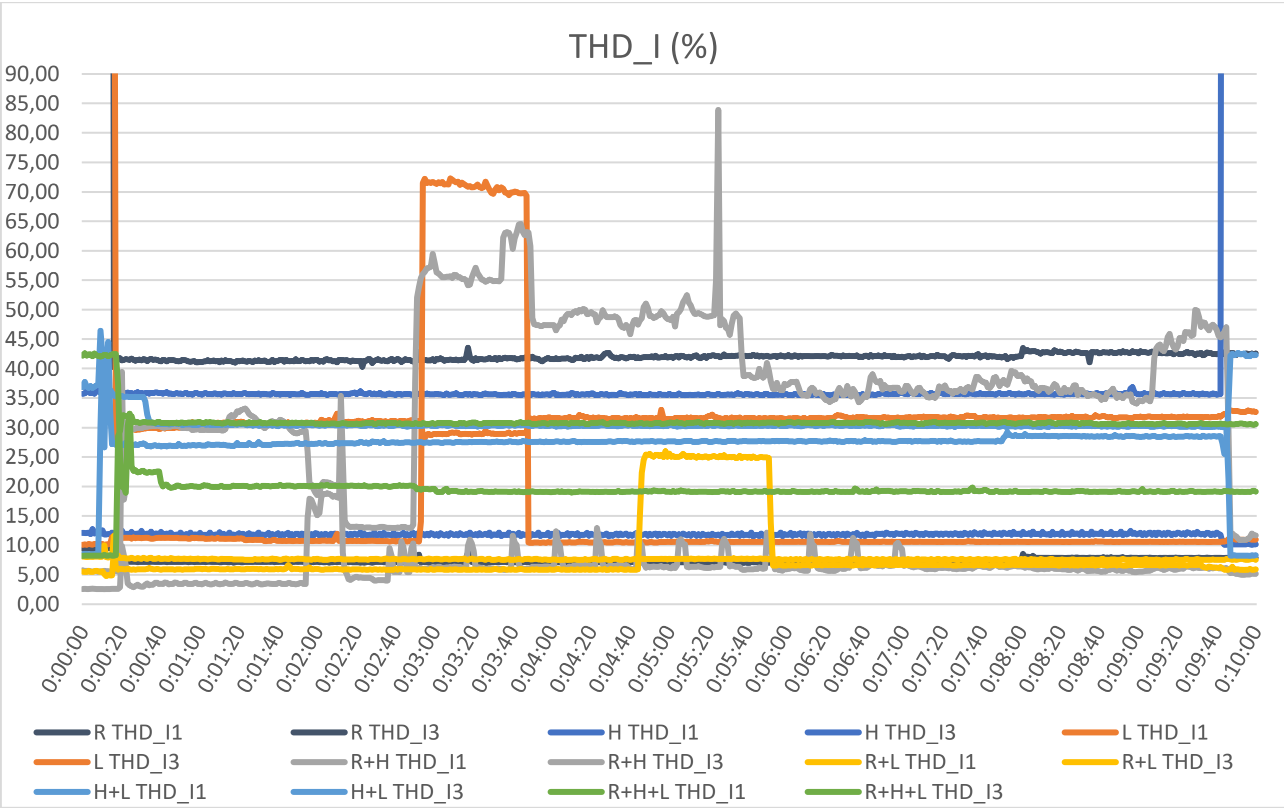

Figure 40: Current THD of phases 1 and 3 of the 7 different scenarios in the Microgrid measurement point. Mode 2

3.4.3. Generating / On-grid

We go to the last operating mode that is going to be analysed in this project, Generating / On-grid where the generators are producing more energy than the system consumes and also, the microgrid is connected to the grid because the batteries are full and the energy excess is injected to the DN.
In this mode, only one measurement point has been considered, which was defined as a distribution network, since there have been very few opportunities to force the system to analyse this operating mode, due to the bad weather conditions that he had during the measurement campaign: almost total absence of sunny days for almost 2 month, and snowfalls that covered completely the solar panels.

For the same reason, data has only been collected in one scenario, in which we did not have any of the previously defined loads connected, only the laboratory lightning and heating loads. Since the generation was low, to force the system to work in this mode, first we had to charge the batteries to the maximum and then disconnect all the loads in order to make the generation greater than the consumption and thus be able to inject energy into the network.

So, as we have done in the previous operating modes, we will comment on the results of each parameter separately

<u>Frequency</u>

We start with the frequency, as this graphic shows, the values are within the limits and the variation around the nominal value is quite low.

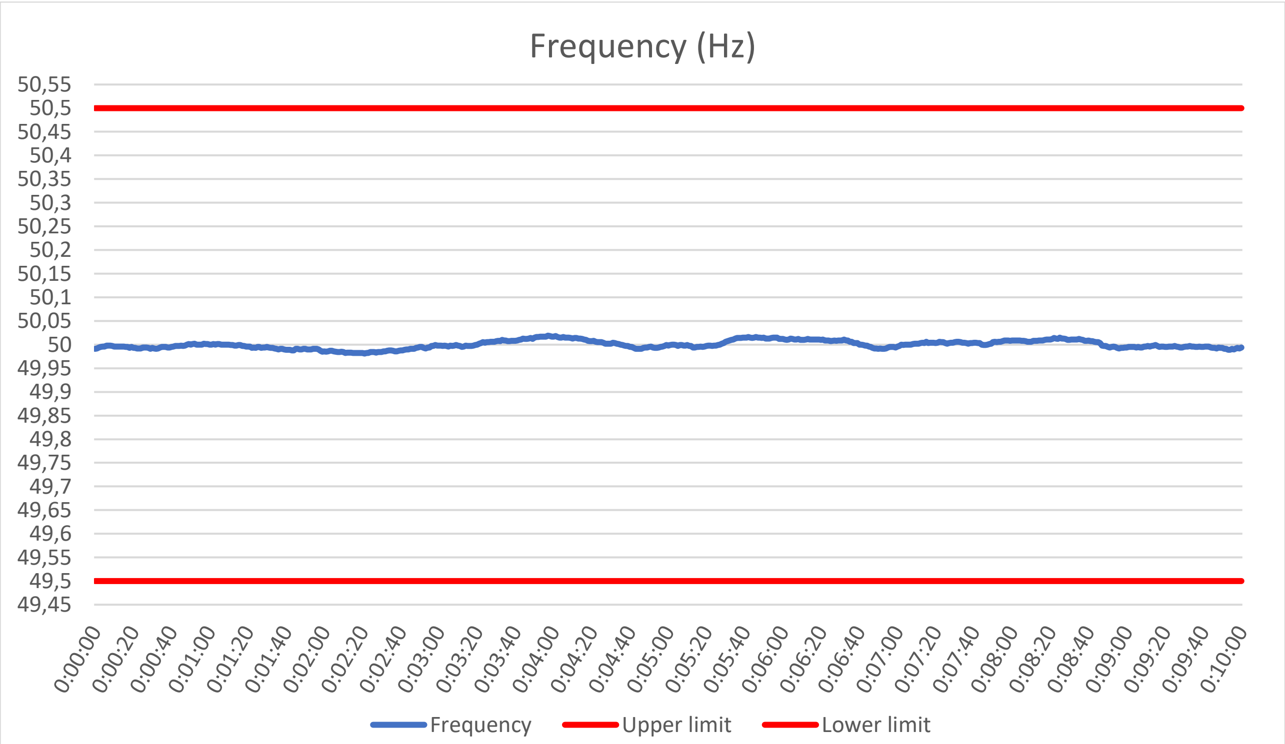

Figure 41:Frequency in the Distribution network measurement point. Mode 3

Voltage

The voltage is more or less the same that in the first mode that we have analysed (Consuming / On-grid) because when the microgrid is connected to the DN, it is the latter who imposes the voltage on the microgrid and therefore responsible of this variation around the nominal value of 220 V and always the values between the defined limits.

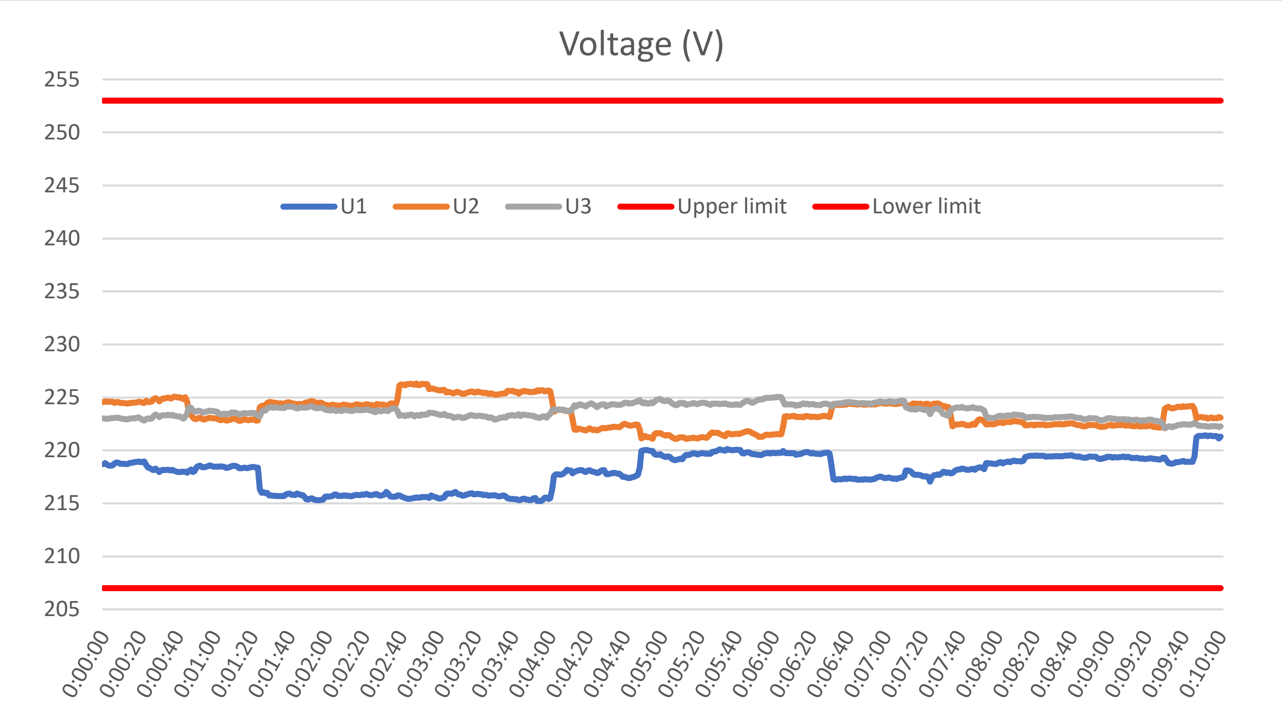

Figure 42: Voltage of the 3 phases in the Distribution network measurement point. Mode 3

THD Voltage

The harmonic content in the voltage waveform is very low, as the other on-grid analysed mode, and the distortion indicator is quite far of the maximum permitted, as we can check in the following figure:

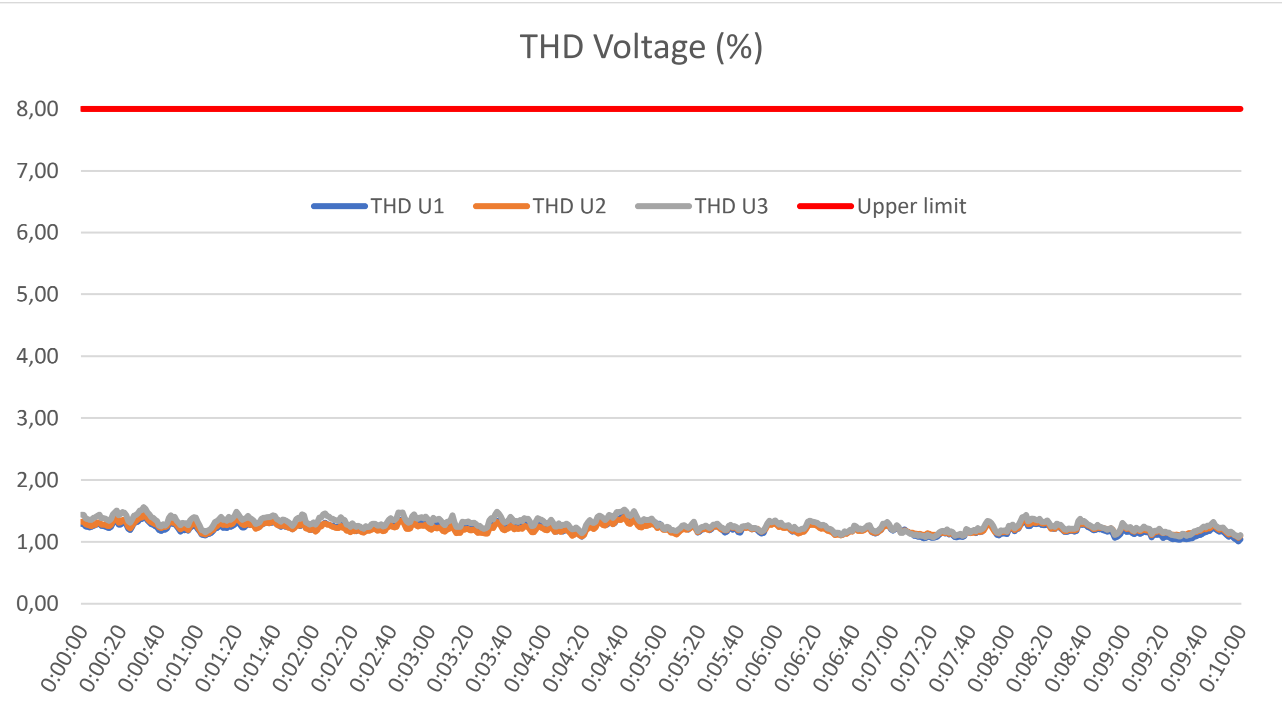

Figure 43: Voltage THD of the 3 phases in the Distribution network measurement point. Mode 3

THD Current

Regarding the quality parameters of the current, we can see in this graphic that there are two phases that have more harmonic content than the third one, which has more or less the same THD values as the previous on-grid mode.

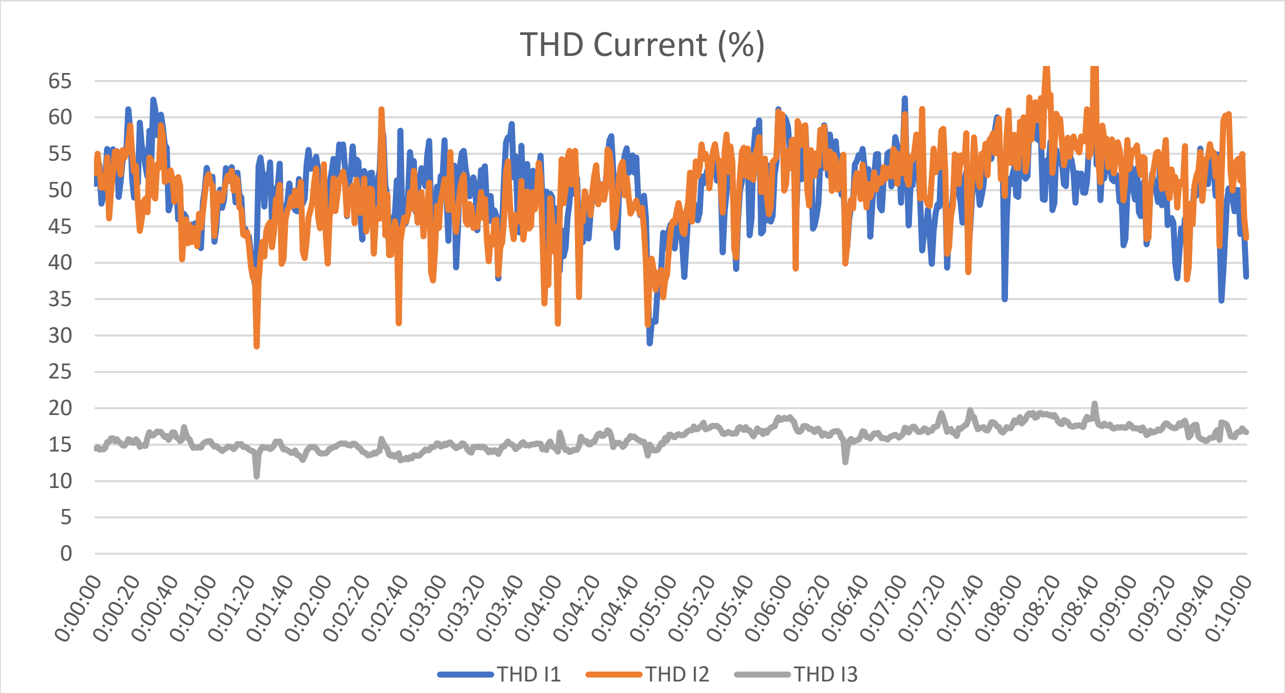

Figure 44: Current THD of the 3 phases in the Distribution network measurement point. Mode 3

TDD Current

Here we can check that these two phases don't comply the recommended limits of current distortion, but as we have very little data, we cannot draw a conclusion that explains this behaviour.

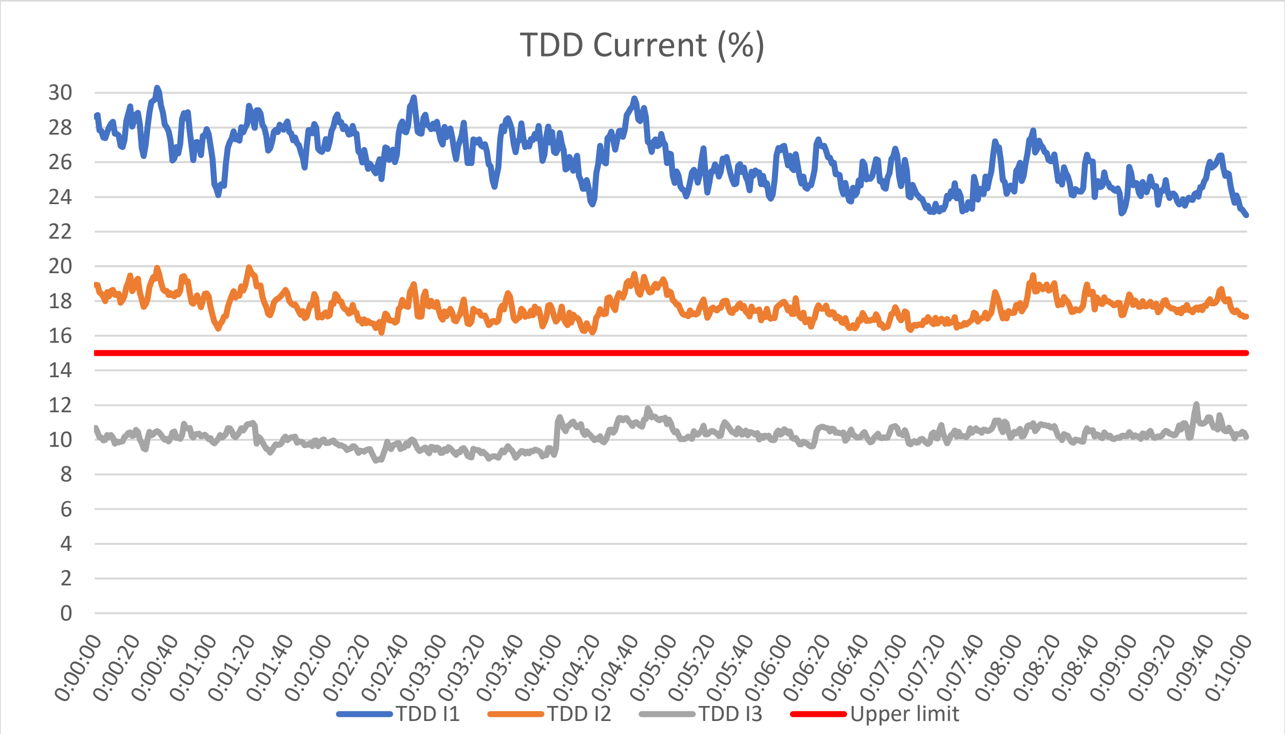

Figure 45: Current TDD of the 3 phases in the Distribution network measurement point. Mode 3

And here we would finish the analysis of the 3 operating modes of the microgrid, not without first reviewing the most relevant conclusion of this analysis:

- Off grid modes have a much more stable and constant voltage and frequency than when the microgrid is connected to the grid.
- The nominal value of the voltage in the microgrid depends on whether it is connected to the distribution network or not, in on-grid mode it is 220 V and in island mode is 230 V.
- The harmonic content in the voltage is quite low in any operating mode.
- The single-phase Ginlong inverter generates a lot of reactive power and quite a few harmonics in the current of the phase where it is connected (phase nº2), causing the current distortion indicators to increase only in that phase.
- This anomalous operation of the Ginlong inverter may be due to the fact that the operation point that has been analysed is very far from its design conditions, but in the next section we will analyse its operation in more depth.
- The bidirectional Sunny Island inverters are able to stop the transmission of the harmonics generated inside the microgrid and thus comply with the regulations to be able to connect to the DN.
- In the generating / on-grid mode, when energy is injected into the DN, the recommended standards of harmonic content in the current are not met, but due to the little data that we have been able to obtain from this mode, we cannot conclude that the system does not be able to work within established limits.

3.4.4. Inverter analysis

In this section, the intention is to analyse the behaviour of all the different inverters of the installation, observing the main electrical parameters and the efficiency of the conversion in order to draw conclusion about their operation.

<u>Sunny tripower inverter</u>

We start with the three-phases Sunny tripower inverter, and the first parameter that we are going to analyse is the active power generated:

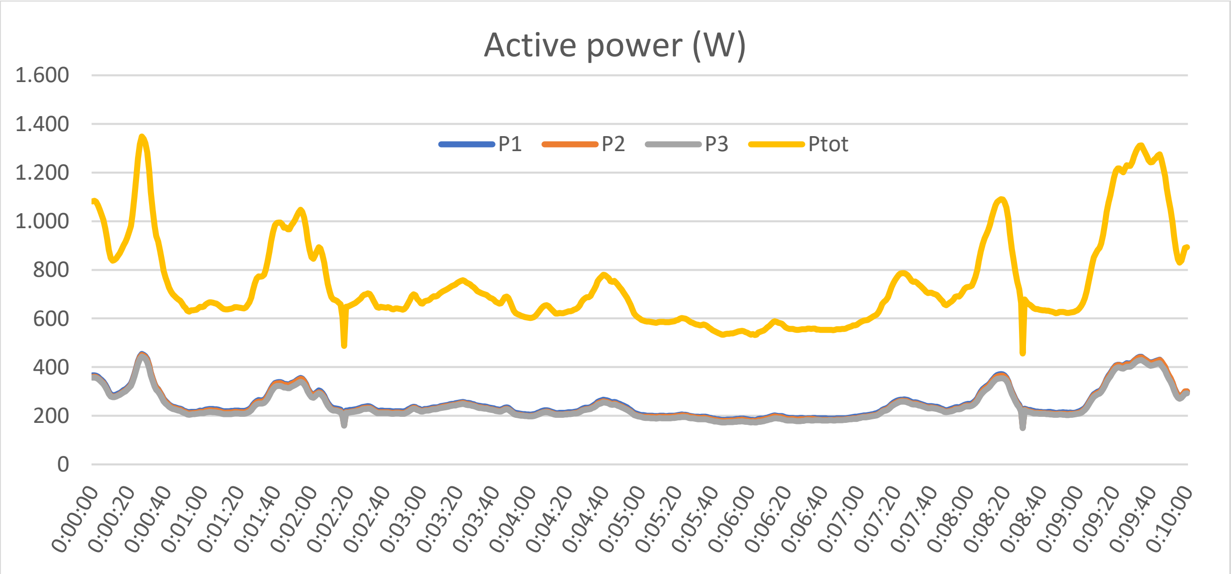

Figure 46: Active power generated in the 3 phases of the Sunny tripower inverter

We can see that the three phases are producing the same active power and the variation of the power generated is due to on the day the measurements were made, there were some clouds and this causes the irradiance received by the solar panels to vary and with it the energy produced.

The next relevant parameter is the reactive power, important to analyse the cause of the problem that we have with the generation of current harmonics.

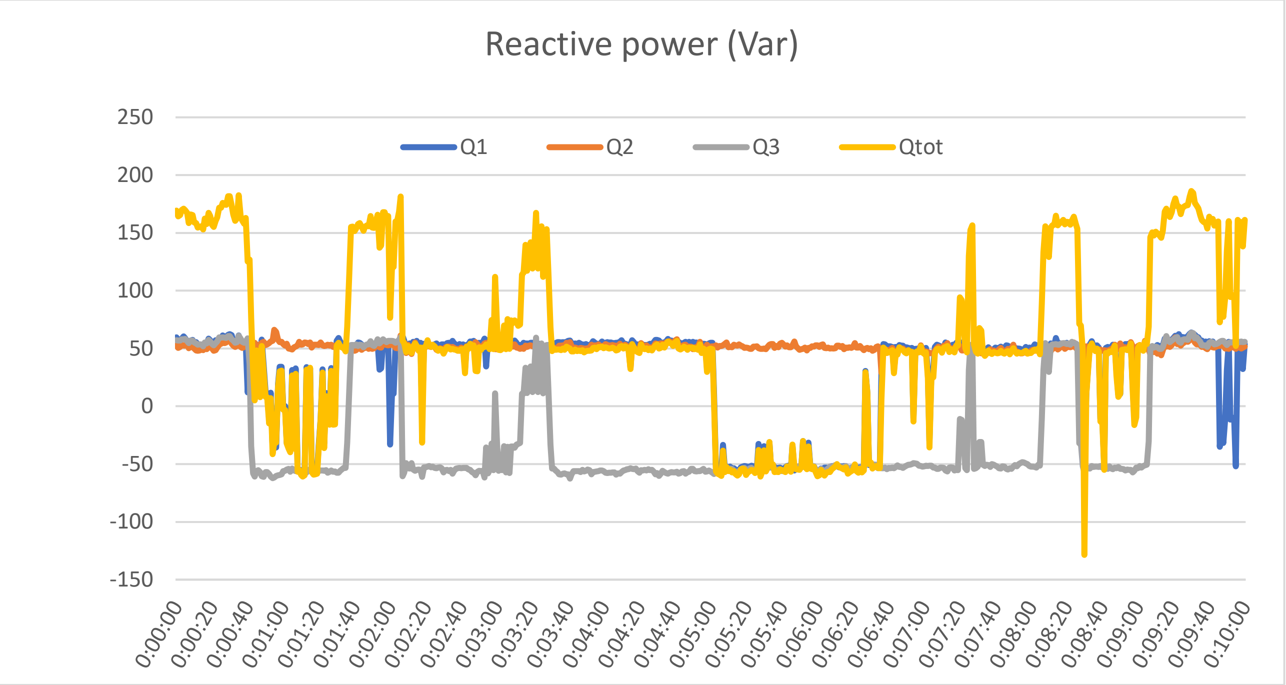

Figure 47: Reactive power generated in the 3 phases of the Sunny tripower inverter

We can observe that seems that there is a maximum of reactive power per phase, both consumed and generated in 50 Var, since all the values of the three phases are between -50 and 50. It can be also noted that the total reactive power is quite low with respect to the total active power generated.

We are also going to analyse the harmonic content of the voltage of the AC part of the inverter:

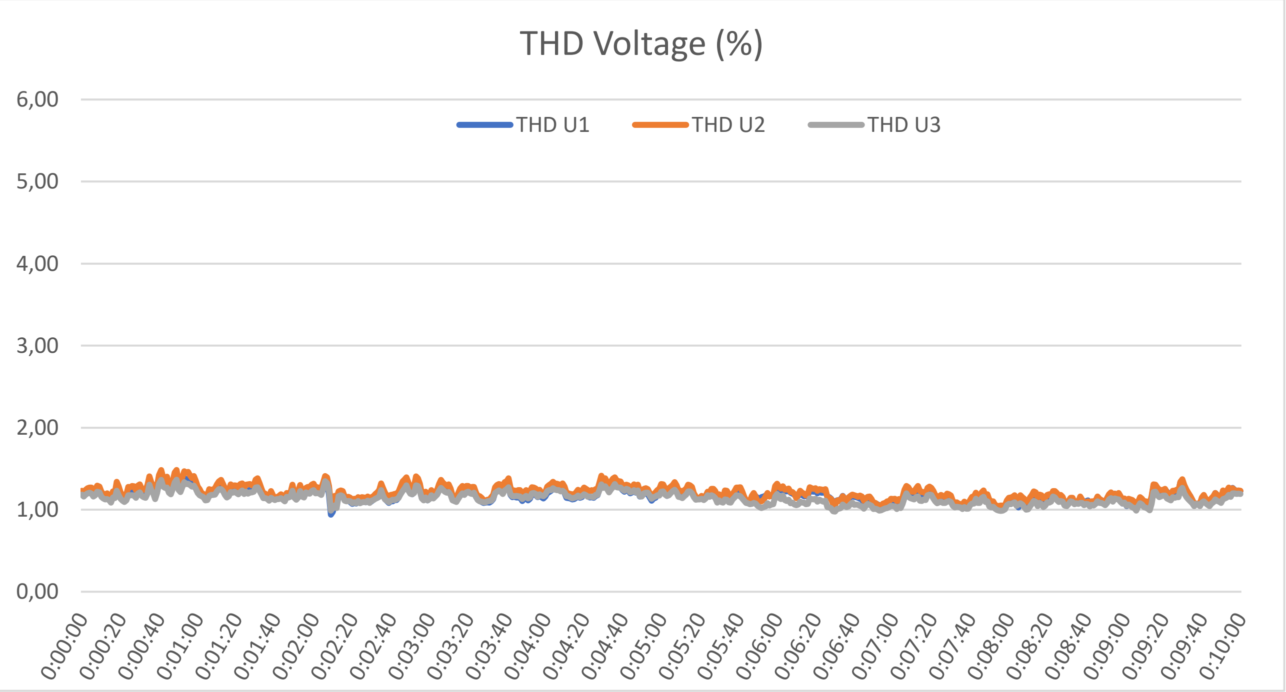

Figure 48: Voltage THD of the 3 phases of the Sunny tripower inverter

From this graphic we extract that the level of harmonics in the voltage is quite low, slightly grater than 1% in the entire sample.

The last parameter that we are going to analyse is the current TDD to see how important is the presence of harmonics in the current

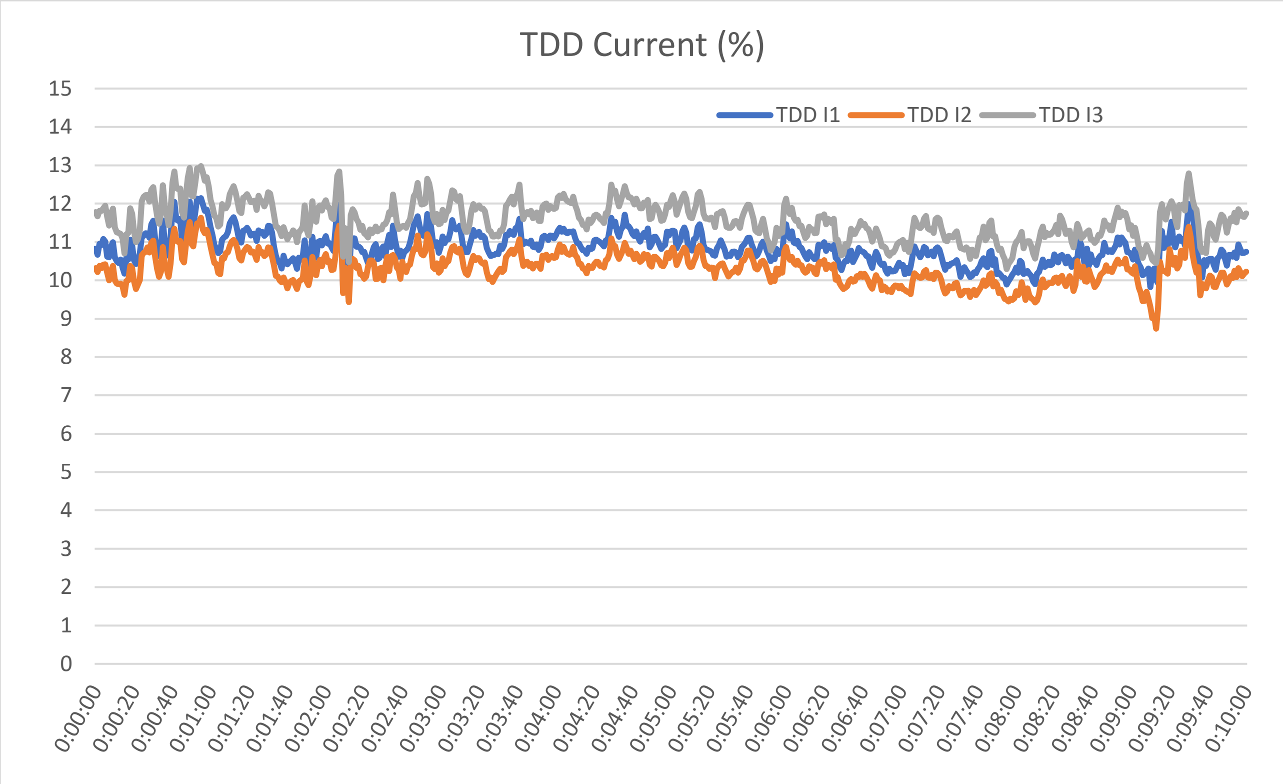

Figure 49: Current TDD of the 3 phases of the Sunny tripower inverter

We see that all the values of the three phases are below 15%, which is the recommended limit value, therefore we can conclude that this inverter doesn't generate almost distortion in current or voltage and with fairly low reactive power levels.

Finally, we are going to calculate the efficiency of the conversion, measuring the active power in both DC and AC part. We have taken measurements at different operating points and from there we have calculated the efficiency at each point and the global average:

	P dc part (W)	P ac part (W)	Efficiency
Measure 1	1360,8	1084,8	79,72%
Measure 2	565,75	532,8	94,18%
Measure 3	559,5	547,8	97,91%
		Average	**90,60%**

Table 6: Efficiency of the Sunny tripower inverter

We can see that it has better efficiency at low power, but we would have to carry out a study with more data to confirm this trend, but with this data we can see that the efficiency of this inverter is quite high.

Single-phase Ginlong Inverter

It is the turn to the single-phase Ginlong inverter, we are going to follow the same analysis dynamics as with the previous inverter, therefore we begin by analysing the active power generated:

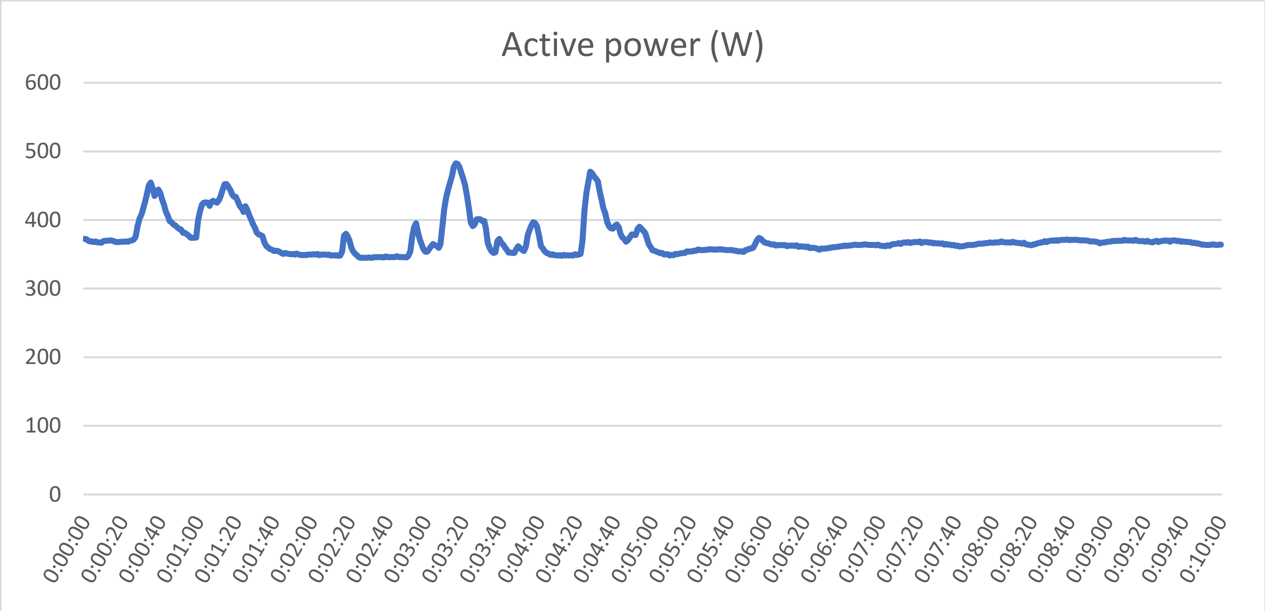

Figure 50: Active power generated in the 3 phases of the single-phase Ginlong inverter

The figure 50 shows that the active power is more or less constant and its variations are due to changes in wing speed or gusts.

Now we can see in picture 51, that the data of the reactive power generated are quite constant, but the most interesting is that this reactive power is always higher than the active one. This denotes inefficient operation and outside of design conditions, and it is the cause of the problems that we have previously encountered.

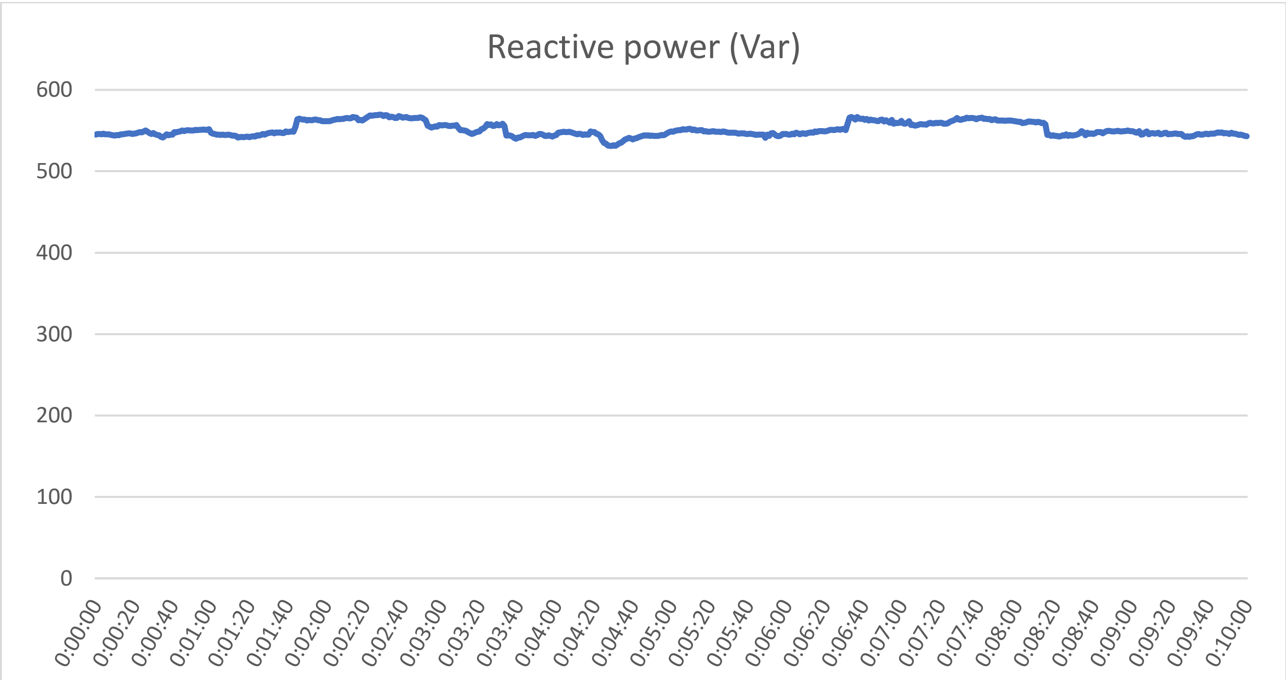

Figure 51: Reactive power generated in the 3 phases of the single-phase Ginlong inverter

Here we can see that the levels of Total Harmonic Distortion of the voltage are very low, as in almost all the cases we have analysed before.

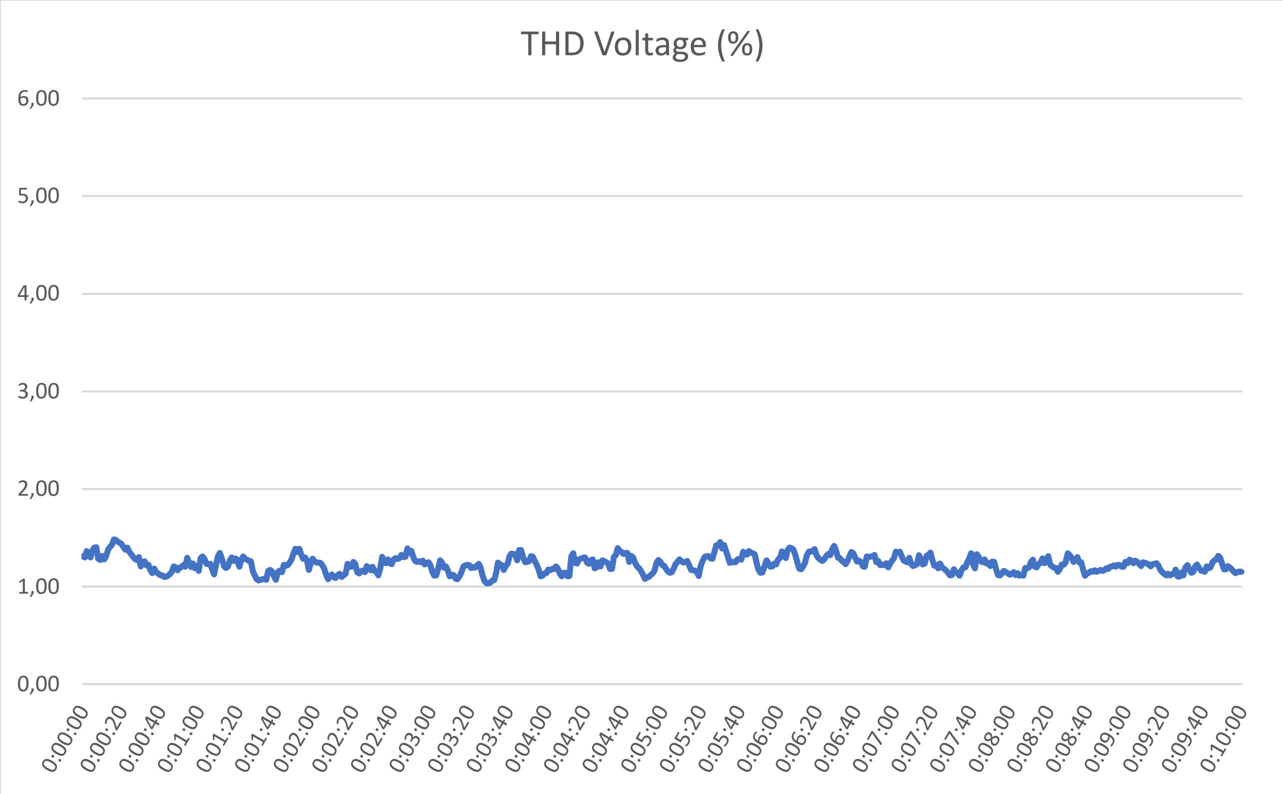

Figure 52: Voltage THD of the 3 phases of the single-phase Ginlong inverter

And the last graphic is for the current distortion indicator, where we can check that the current generated by the inverter doesn't have much harmonic content, less than 8%, and is within the recommended values (< 15%).

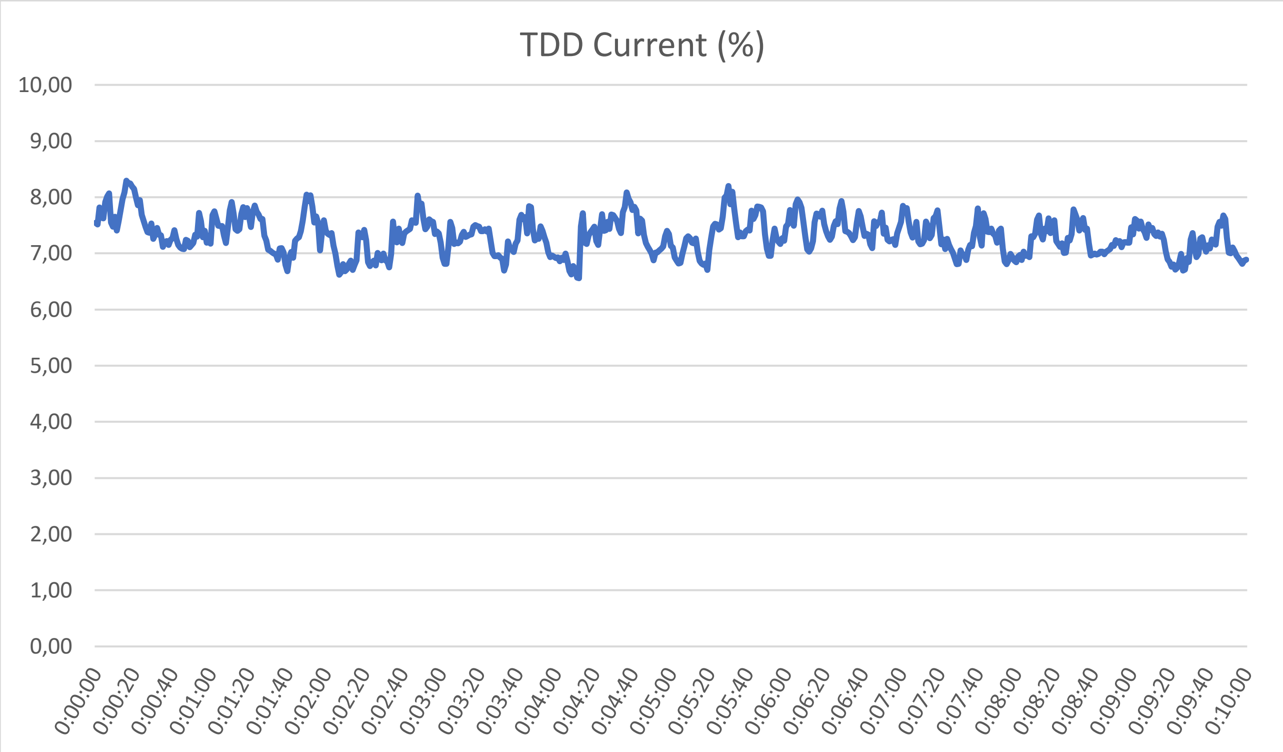

Figure 53: Current TDD of the 3 phases of the single-phase Ginlong inverter

And finally, with the active power data of both parts of the inverter, we calculate the efficiency of the conversion from direct current to alternating current for different operating points and the global average:

	P dc part (W)	P ac part (W)	Efficiency
Measure 1	427,93	368	86,00%
Measure 2	452,24	390	86,24%
Measure 3	527,1	450	85,37%
		Average	**85,87%**

Table 7: Efficiency of single-phase Ginlong inverter

The three points are quite close, but we see that the efficiency does not vary much, in the three cases around 86 %. It is a high efficiency, but normally the inverters tend to have efficiencies above 90 %, and in the specification sheet it ensures that the efficiency of the Ginlong inverter is always greater than 96 %, therefore it seems that it is not working at all well this device. [7]

Bidirectional Sunny Island inverters

The last remaining inverters are the bidirectional Sunny Island inverters. Since we have already analysed all electrical parameters on different cases on one side and the other of the inverters, we will limit ourselves to calculating the efficiencies of the three inverters, differentiating the two modes in which they can work.
We start with the mode of charging batteries, that they convert alternating current into direct current, working as a rectifier, and these are the results:

Charging mode	P dc part (W)	P ac part (W)	Efficiency
Sunny Island 1 (master)	271,99	398,2	68,30%
Sunny Island 2	410,7	532,97	77,06%
Sunny Island 3	368,41	507,94	72,53%

Table 8: Efficiency of the three bidirrectional Sunny Island inverters. Charging mode

We see that the efficiency is around 73 % and there is a trend that indicates that the higher the power, the greater the efficiency. [10]

We continue with the normal mode of an inverter, when the batteries are discharging, and they convert direct current into alternating current:

Discharging mode	P dc part (W)	P ac part (W)	Efficiency
Sunny Island 1 (master)	57,584	54,285	94,27%
Sunny Island 2	1180,14	1023,5	86,73%
Sunny Island 3	74,358	69,3	93,20%

Table 9: Efficiency of the three bidirrectional Sunny Island inverters. Discharging mode

We observe that the efficiency is higher with this mode than the previous one, all around 90 %. We can conclude that are high enough values to say that these inverters work quite well, but as always, a more detailed study would be needed to confirm it, but this objective is beyond the limits of this project.

4. Matlab model

In this section we are going to address the other main topic of this thesis, the development of a virtual model of the installation under study with the simulation software Matlab-Simulink.

4.1.Description and hypothesis of the model

First of all, we will begin by describing the main parts of the model separately and explaining the assumptions that have been made in order to simplify the simulation of each part. The following illustration shows the complete model:

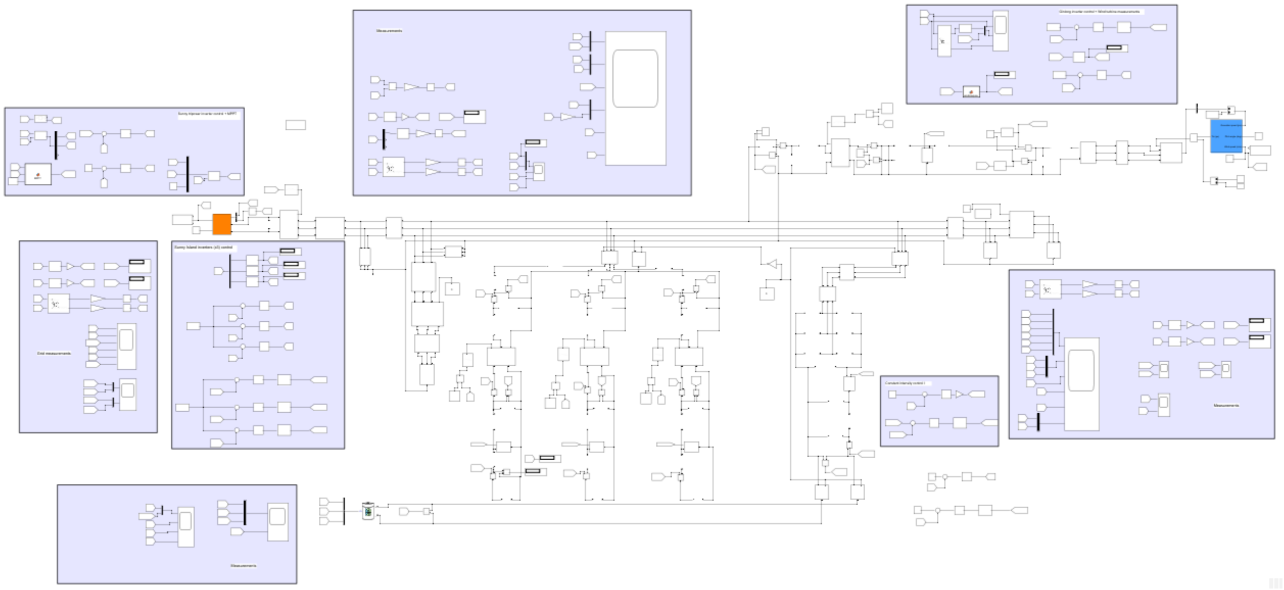

Figure 54: Complete virtual model of the microgrid in Matlab-Simulink simulation software

We can see in this diagram, in the upper left corner, the solar power plants and the three-phase inverter with all its controllers, next to we find the connection to the DN. In the upper right corner is the wind turbine with the one phase inverter connected with its controllers. In the lower left corner, we can find the battery connected to the DC current bus through a charger controller, and finally all the components that are between DC and AC bus are the simulation of the three bidirectional inverters. The rest of the components are to generate the visualization of the results or the control of any of the previous systems.

In the following lines we are going to explain more deeply the strategies that have been followed to simulate each component:

- **Solar panels + control (MPPT) + Sunny tripower inverter**
  We model both type of solar power plants (static and solar tracker) with a Matlab block with 24 modules with the parameters of the real solar panels, all of them connected in one string to reach the same maximum power that both power plants: 6000 W. Then we have implemented a control through the Maximum Power Point Track (MPPT), that with the instant measurements of current and voltage of the solar panels, calculate and control the optimum current and reach the maximum power point.

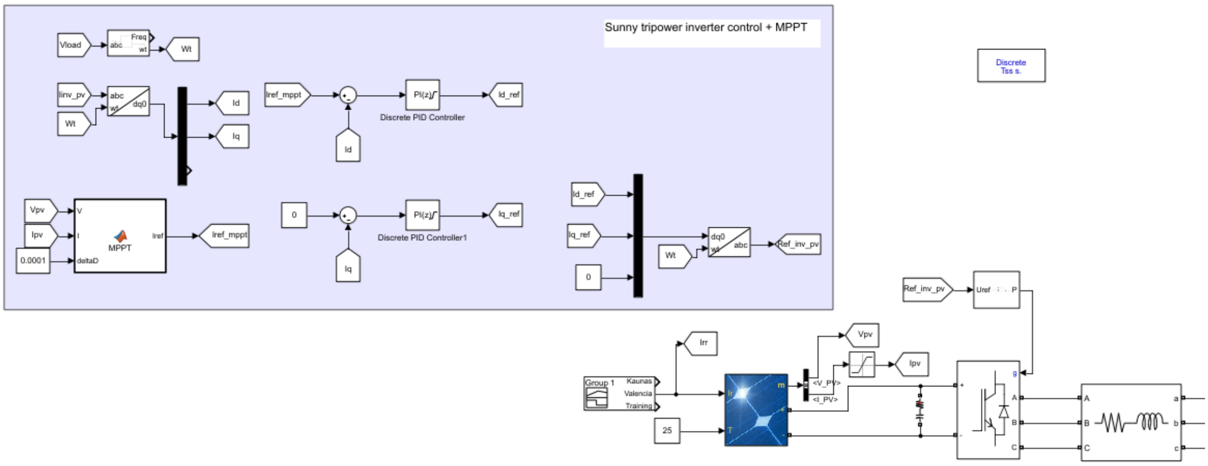

Figure 55: Simularion of the solar panels, its controllers and the Sunny tripower inverter

This control has been implemented using a PID controller and the Matlab programming block where the scheme that MPPTs usually use (Figure 57) has been implemented. In the picture number 56 we can see part of the code to implement the logic of the control scheme.

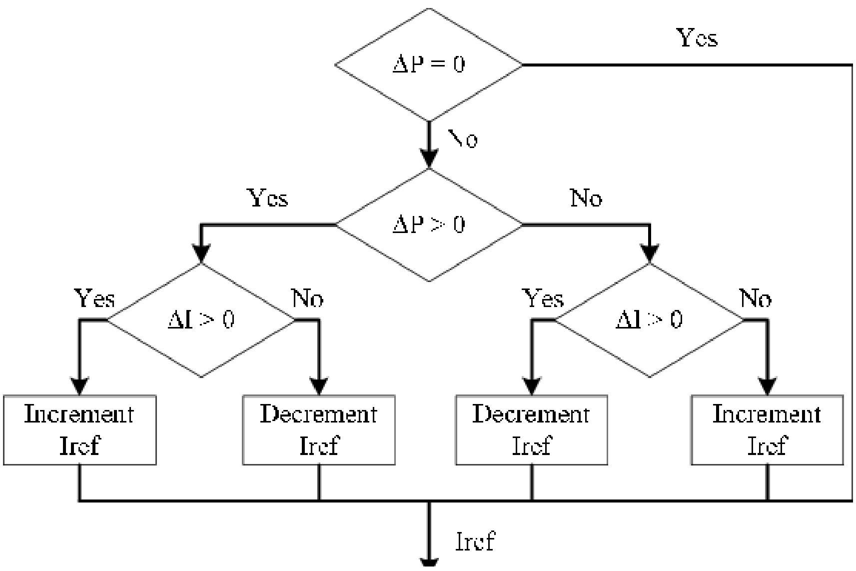

Figure 57: Tipical logical control scheme of a MPPT [12]

```
if isempty(Vold)
    Vold=0;
    Pold=0;
    Iref_old=Iref_init;
end
P=V*I;
dV=V-Vold;
dP=P-Pold;
Iref=Iref_old;

if dP~=0 && V>400
    if dP<0
        if dV<0
            Iref= Iref_old - deltaD;
        else
            Iref= Iref_old + deltaD;
        end
    else
        if dV<0
            Iref= Iref_old + deltaD;
        else
            Iref= Iref_old - deltaD;
        end
    end
end

if Iref>= I_max
    Iref=I_max;
end
if Iref<Imin
    Iref=Imin;
end

Iref_old=Iref;
Vold=V;
Pold=P;
```

Figure 56: Part of the code of the MPPT

And finally, we have the three-phase Sunny Tripower inverter that converts the DC power of solar panels, into AC to inject to the microgrid. This inverter is simulated with a IGBT transistor bridge, which is controlled by PWM technique.

- **Grid connection**

  The DN was modelled with a three-phase alternant current source and the connection is a circuit breaker that cuts the electricity flow of the three phases to disconnect the microgrid from the DN. This circuit braker is controlled by the state of the batteries and the consume of the loads.

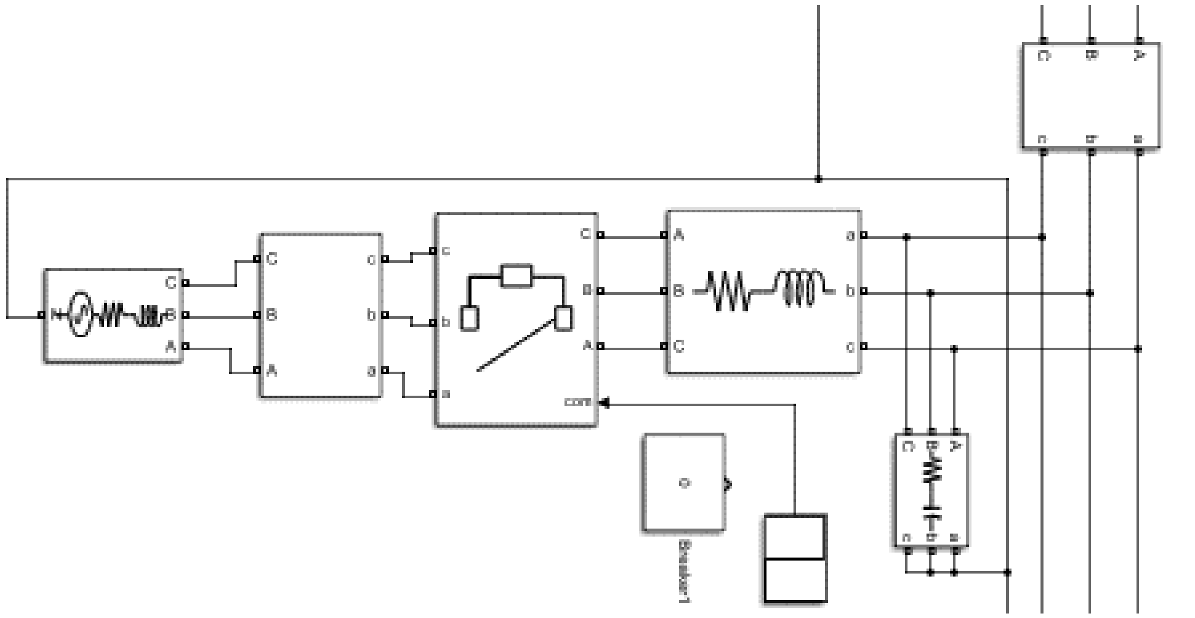

Figure 58: Simulation of the distribution network and the connection with the microgrid

- **Wind turbine + control + Ginlong inverter**
  The wind turbine has been modelled through a permanent magnet synchronous machine and with a matlab block of wind turbine that integrate the control to generate the maximum power from the wind. But, as the Ginlong inverter converts DC into one-phase AC, and the synchronous machine generates three-phases AC, we need three-phase rectifier that its output is 48V of DC (the same output that the real wind turbine), and then we need a combination of a converter boost DC-DC to increase the voltage and one-phase inverter to transform the DC power into AC, that is the real output of the Ginlong inverter.

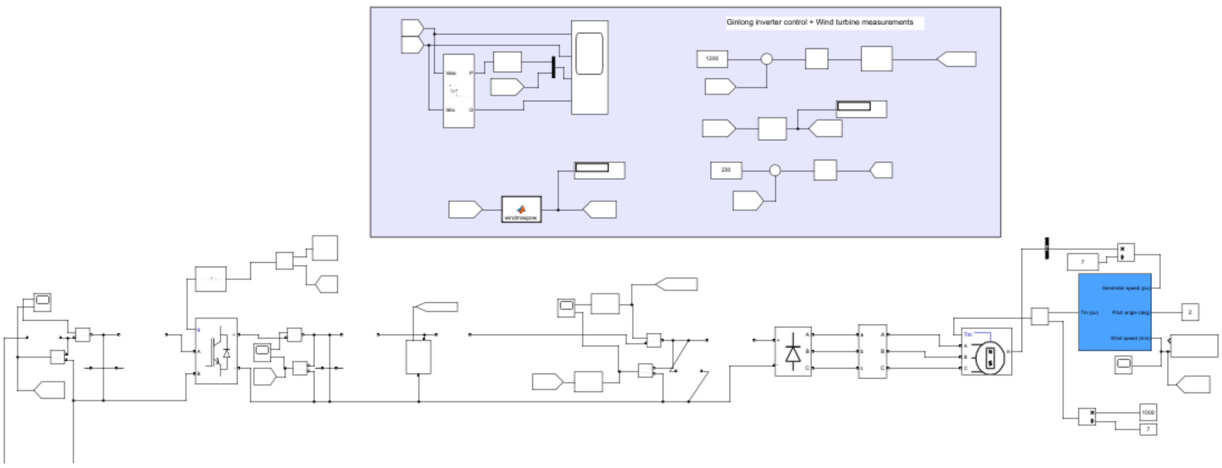

Figure 59: Simulation of the wind turbine, its controllers and the Ginlong inverter

The three stages of conversion are controlled by PID controllers, the first step, the rectifier is simulated with a diode bridge, the second step is the boost converter to increase the voltage formed by an inductor, a capacitor, a diode and a IGBT transistor. And the third step, the one phase inverter is simulated by a IGBT transistor bridge.
To ensure that the simulated wind turbine works as indicated in the characteristics sheet of the real one, the control has implemented the power – wind speed curve, given by the company, as a reference.

- **Battery + control**
  We model the 24 batteries of 2V with only one battery of 48 V and the same capacity of all of the real ones (190Ah). The control of charging is a constant current control that modify the voltage of de DC bus to charge the battery with constant current of 15 A, a value recommended by the producer.

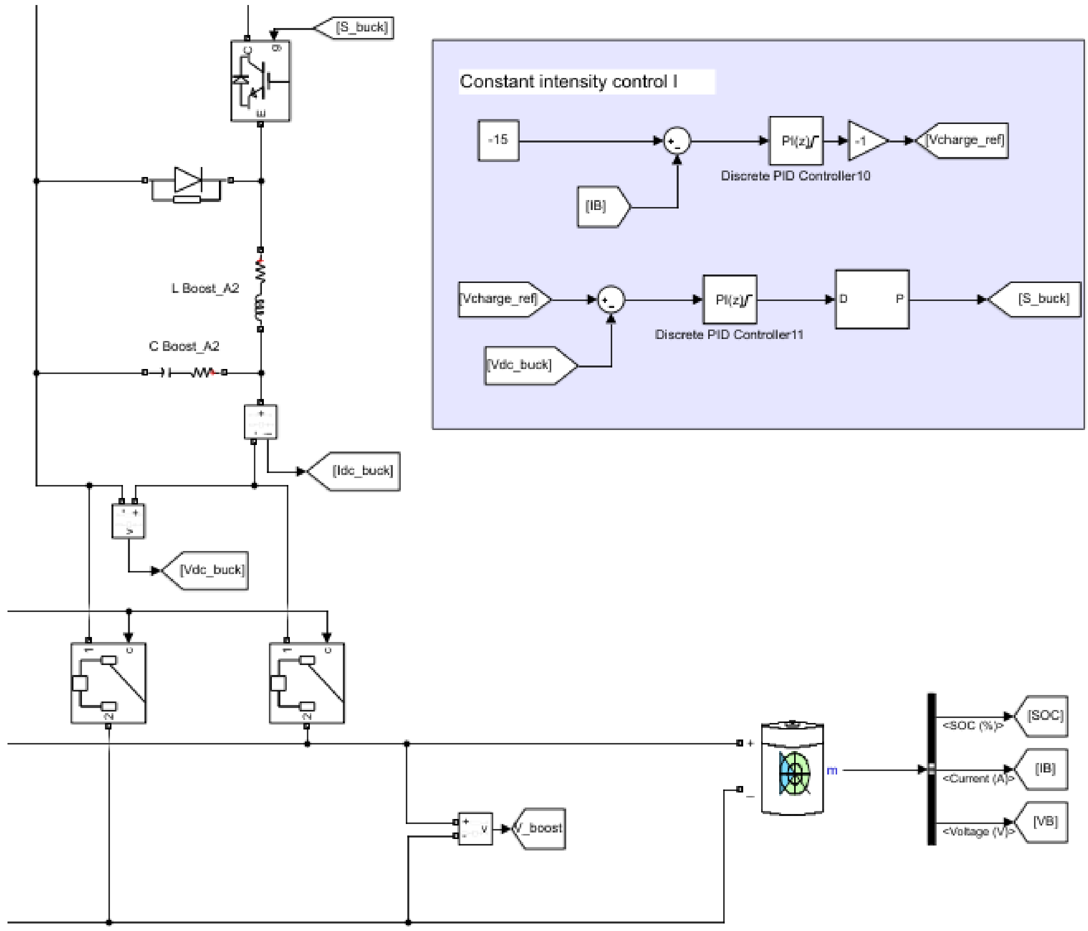

Figure 60: Simulation of the battery and its constant current controller

- **Sunny Island bidirectional inverters**
  To model these three bidirectional inverters, we have assumed some simplifications in order to simplify the simulation. The strategy that we have followed to implement the two modes of operation has been to separate them so that they work completely independent.
  This means that we have a part that works as a three-phases inverter transforming the direct current from the batteries into alternating current to inject into the microgrid, and another part that acts as a three-phases rectifier, converting the alternating current from the microgrid into direct current to charge the batteries.

  The part of the discharging mode (left part of figure 61) is modelled with a boost converter DC-DC to increase the voltage from 48 V of the DC bus to 1250 V and then a IGBT transistor bridge to convert the DC power into AC and inject this power into the microgrid, and this for each phase.

  The right part of figure 61 is the changing mode model, that is made with a three-phases transformer to decrease the voltage from 380 V to 70 V and then there is a three-phase diode bridge that acts as a rectifier, transforming three-phase alternating current into direct current.
  But to control the charge of the batteries, a buck DC-DC converter is connecter before the batteries, to decrease the voltage to the setpoint level, where this converter is controlled by the battery charge control system, which modifies the value of the DC bus voltage so that the batteries are charged at constant current.
  Switching between one mode and another is done using circuit brakers that depends from different variables such the level of charge of batteries, consumption of loads, if the generators are producing energy, if the microgrid is connected to the DN, etc. But the two modes can never be working at the same time.

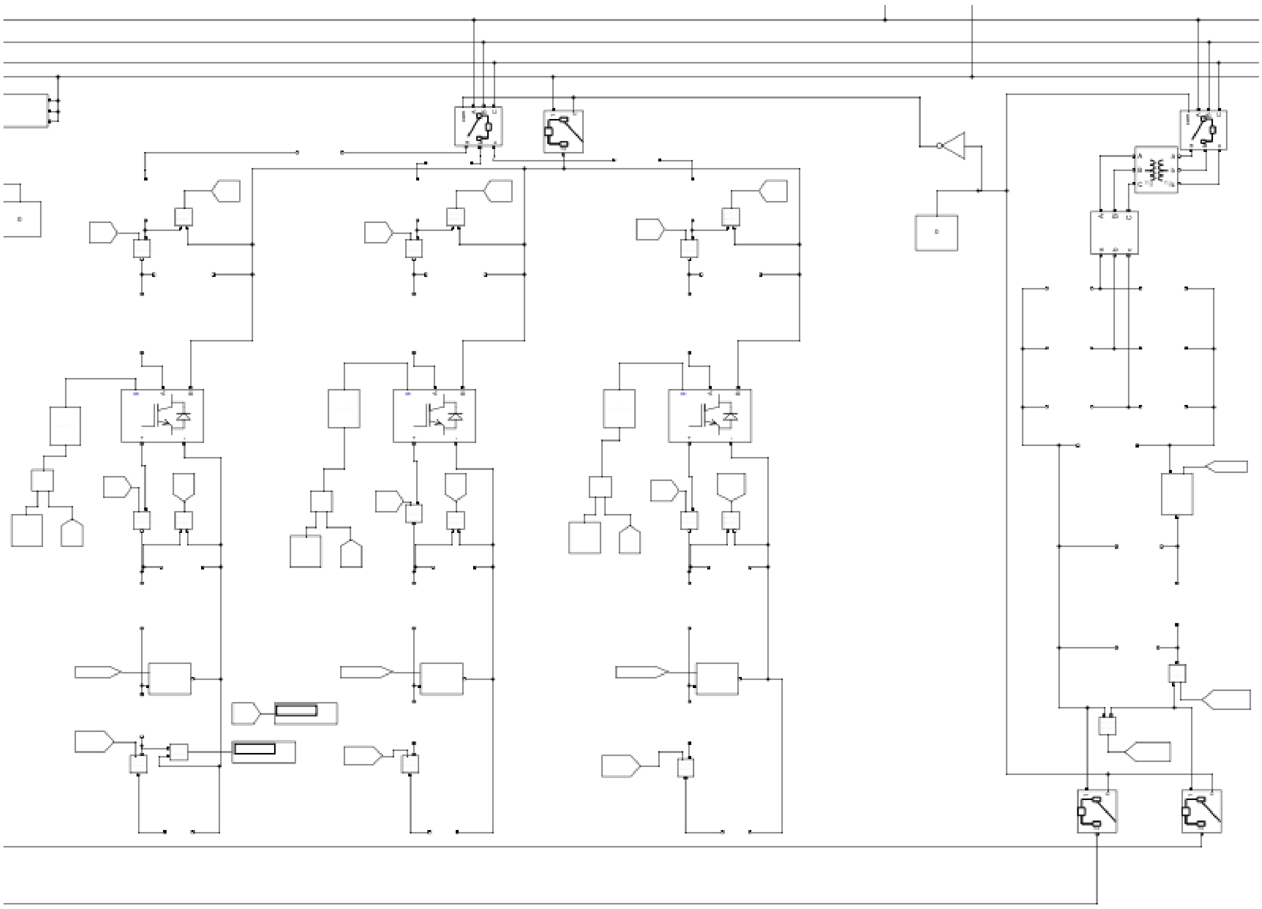

Figure 61: Simulation of bidirectional Sunny Island inverters. Discharging mode left side. Charging mode right side.

Up to here the description of the model, in the next section we will comment on the results of the simulation and the effects of the assumptions that we have just described.

4.2. Simulation results

Now we are going to analyse and comment the results of the simulation, comparing the behaviour of the model in the different operating modes and under different weather conditions.

Note that all the simulations are 24 seconds long, where each second represents one hour of the day, with the aim of simulating the behaviour of the microgrid during a full day.

We start with the solar power plant, where two simulations have been carried out with different radiation values, the first scenario is the hourly average radiation of a day in August in the city of Kaunas (Lithuania) while the second simulation is with the hourly average radiation data for August in the city of Valencia (Spain). Data available in Appendix 1

In the figure 62 we can see the results of the simulation from Kaunas data, where it's the graphic of the alternating current after the inverter of the 3 phases, and in green is the reference current that the MPPT follows. We can see that in the central hours of the day, the current generated increases with the solar radiation.

To the right of this graphic, we can see another that checks the efficiency of the MPPT, where the real active power and the ideal active power are represented, this last parameter is calculated from the irradiance and the conditions of the solar panel. And we can conclude that the control achieved is quite good.

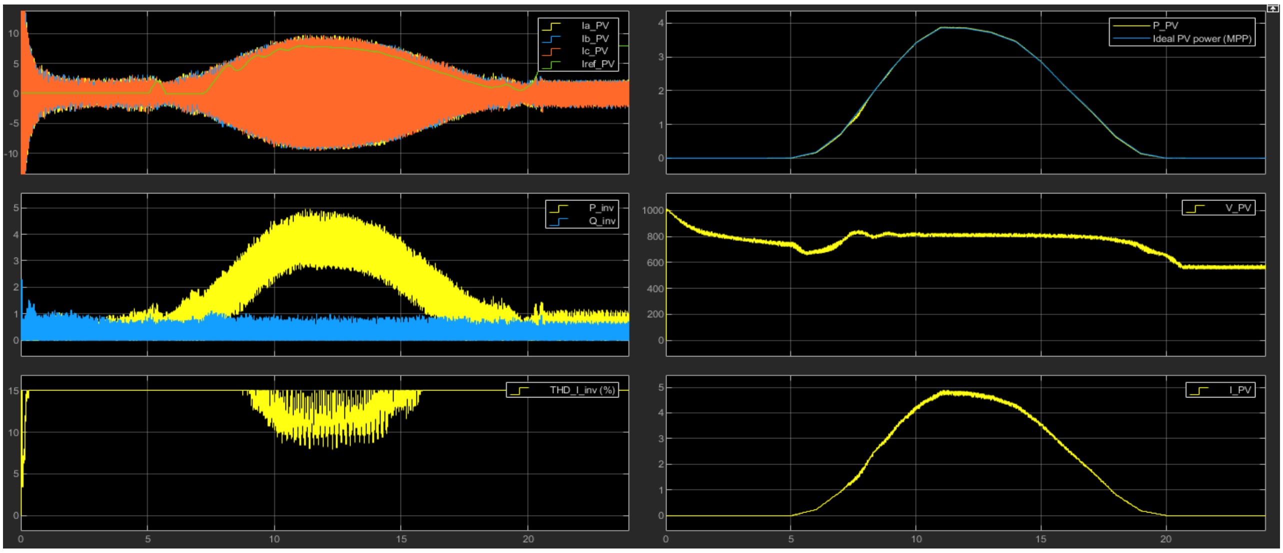

Figure 62: Results of the solar power plant simulation from Kaunas data

In the second row of graphs, we have the production of both active and reactive power, where we can see that we have a residual and constant reactive power due to the operation of the inverter but relatively low compared to the active power that reaches almost 5 kW at the time of most radiation.
Also, we have the voltage and the current generated of the DC part, before the inverter, where the controlled variable is the voltage of the solar panel, to achieve that the current is the same as the reference one and operate at the maximum power point (MPP).
And finally, the last graphic is a quality parameter, the current THD, that we can see that at the moment of maximum power generated, the THD is lower than 15 %.

The next figure represents the same parameters but with the data from Valencia (Spain), where the radiation is higher than in Kaunas, and as we can check the active power generated reaches almost 7 kW, more or less the nominal power of the solar power plant.
The differences are basically the grater current generated and therefore the grater active power, while the reactive power remains constant as the voltage of the solar panel. However, we see that the current THD falls below 10% at the time of greatest radiation, therefore we can conclude that the model works better when it works with powers close to the nominal one, that is why remaining simulations will be made with the radiation of the city of Valencia.

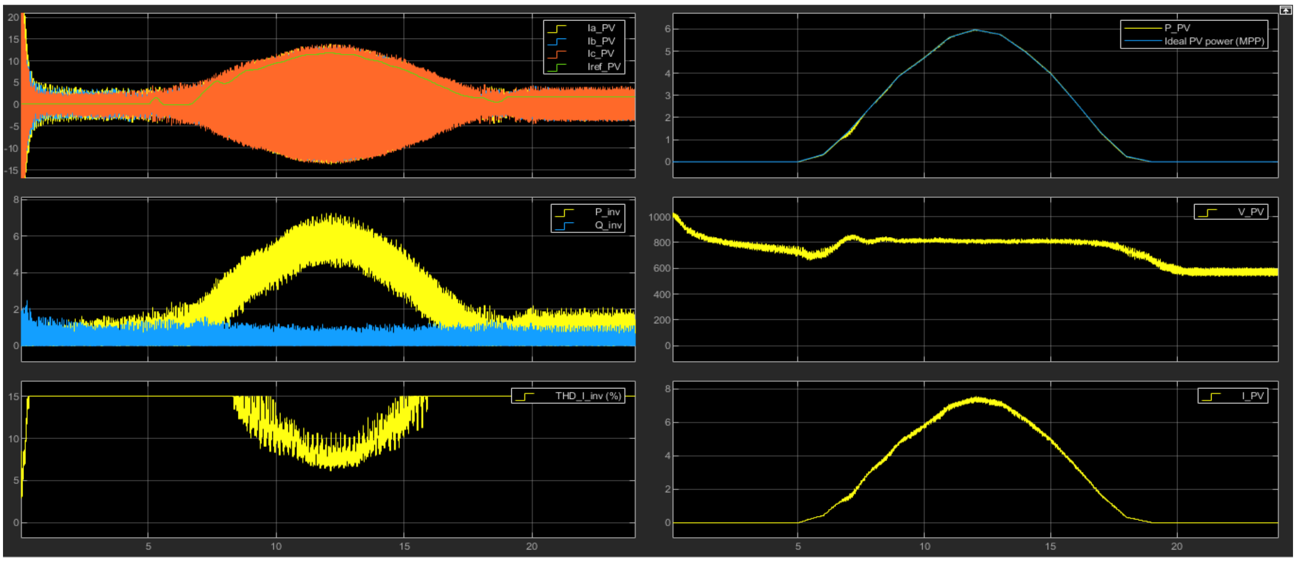

Figure 63: Results of the solar power plant simulation from Valencia data

The next main part of the installation is the other generator, the wind turbine, it has been simulated with wind speed data from an average day of November in Kaunas (data available in Appendix 1). In these graphs we can see the three-phases currents and voltages generated by the permanent magnet synchronous motor, where it is observed that the voltage is kept constant and, depending on the wind speed, more or less current is generated.
We also have a graphic to check the efficiency of the MPPT, comparing the real active power with the ideal, which is calculated based on the wind speed and the parameters of the wind turbine. And it can be seen that a fairly fine control has been achieved for the monitoring of the maximum power point.
And finally, we have also the reactive power generated, as we can see, that is a function of the wind speed and also that the values are almost four times greater than those of the active power, which indicates that the regulation to achieve maximum power at each moment implies the generation of much reactive power, which has been tried to minimize, but is still quite high. As we will see later, this reactive power is reduced in the following conversions so that it does not affect the loads connected to the microgrid.

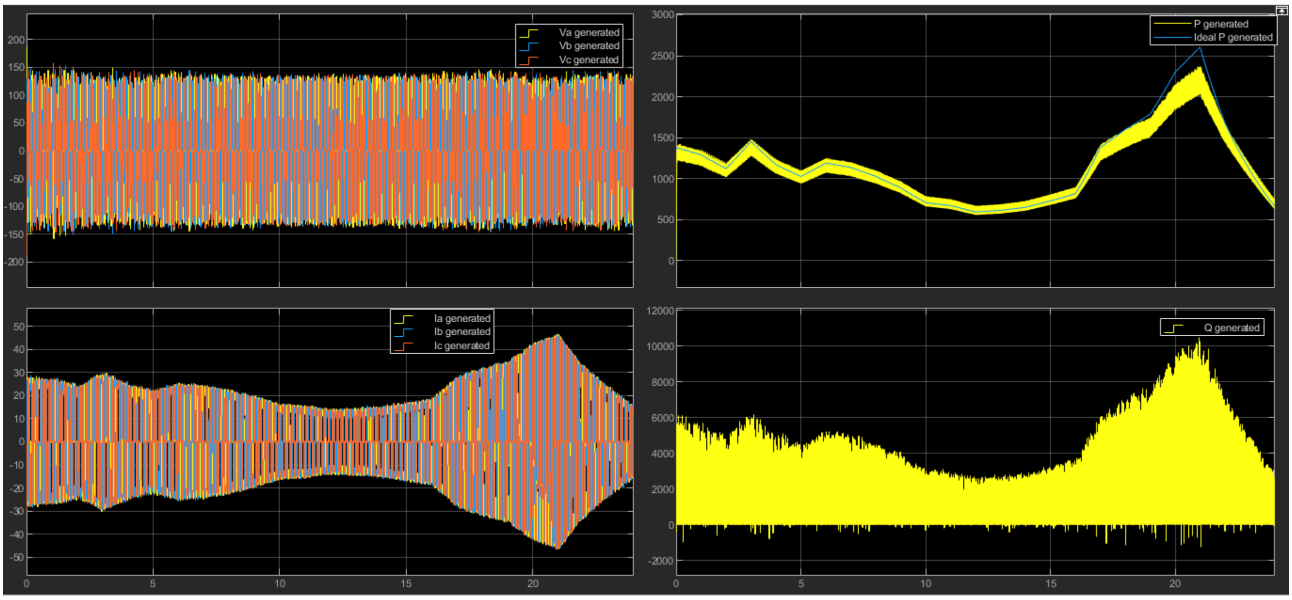

Figure 64: Results of the wind turbine simulation from Kaunas data

Now it's the time to analyse the parameters of the distribution network connection:

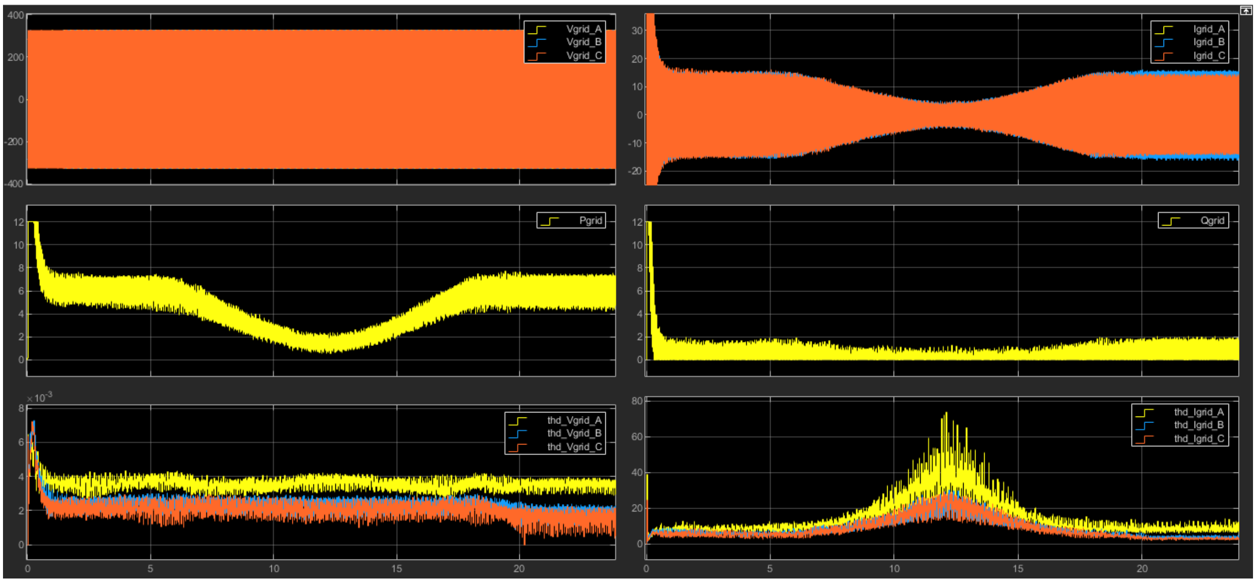

Figure 65: Results of the Distribution network simulation

We have the voltage and current values of the three phases, the power supplied by the network, both active and reactive, and then the quality parameters of current and voltage THD of the three phases.
The influence of solar generation is especially noticeable, as at the central hours of the day the current consumed by the network is lower and therefore the active power. As for the voltage, it remains perfectly constant at the value of 380 V, while the reactive power is also constant and relatively low compared to the active one.
Regarding the quality parameters, we see that the voltage waveform is almost perfect with THD that does not exceed 0.004 %, which denotes that there are practically no harmonics, while the current we see that for current values that exceed 10 A the THD is less than 15%, but when the intensity is lower, the quality indicators is triggered up to 50% at the most critical point.

The parameters to analyse are those of the battery operating in charging mode:

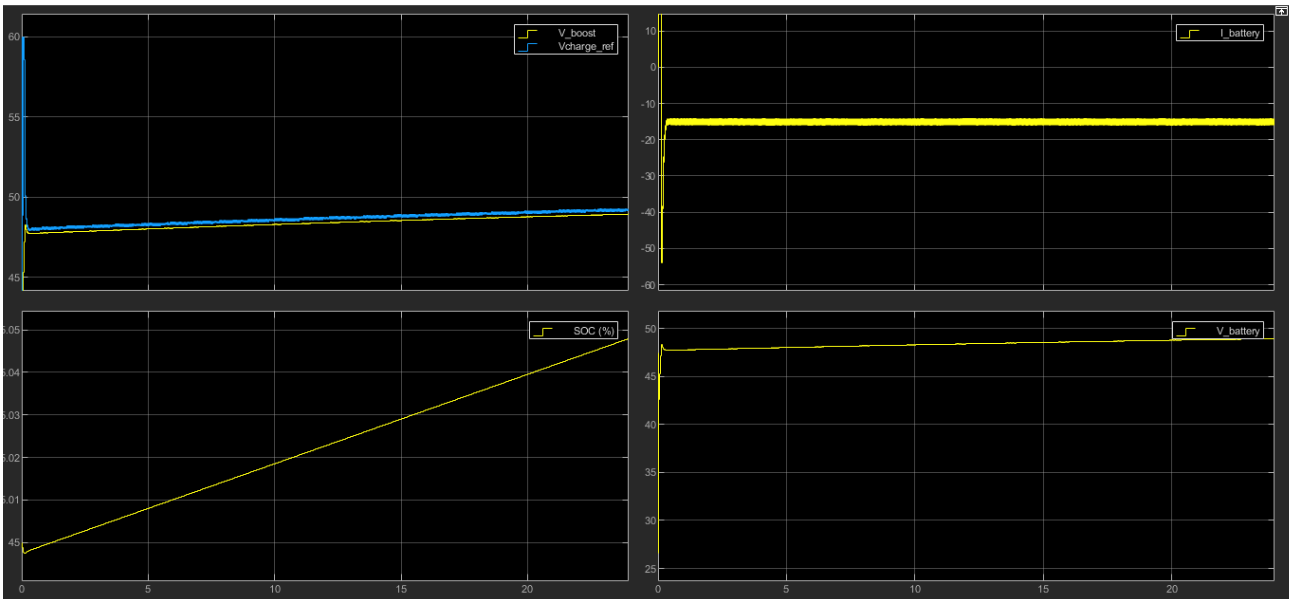

Figure 66: Results of battery parameters operating in charging mode

In this picture is represented the State of Charge (SOC) of the battery, the DC bus voltage and the battery voltage, that must be the same, and finally the battery charging current, negative for charge mode and positive for discharge mode.
In blue colour is the reference DC bus voltage to keep the load current at a constant value of 15 A. And as we can see, the control is quite good since we see that the voltage follows the reference and the charge current remains constant at the quoted value.

Now we are going to comment the parameters of the load in the simulation. Two equal loads of 3 kW fully resistive (reactive power 0) have been simulated to simplify the modelling of the entire installation, and in figure 67 we have the results of the simulation.
We see that both the voltage and the current are quite stable, and therefore the active power, despite the fact that, as we have seen, during the simulation they are supplied by different proportions between the DN and the generators of the system.

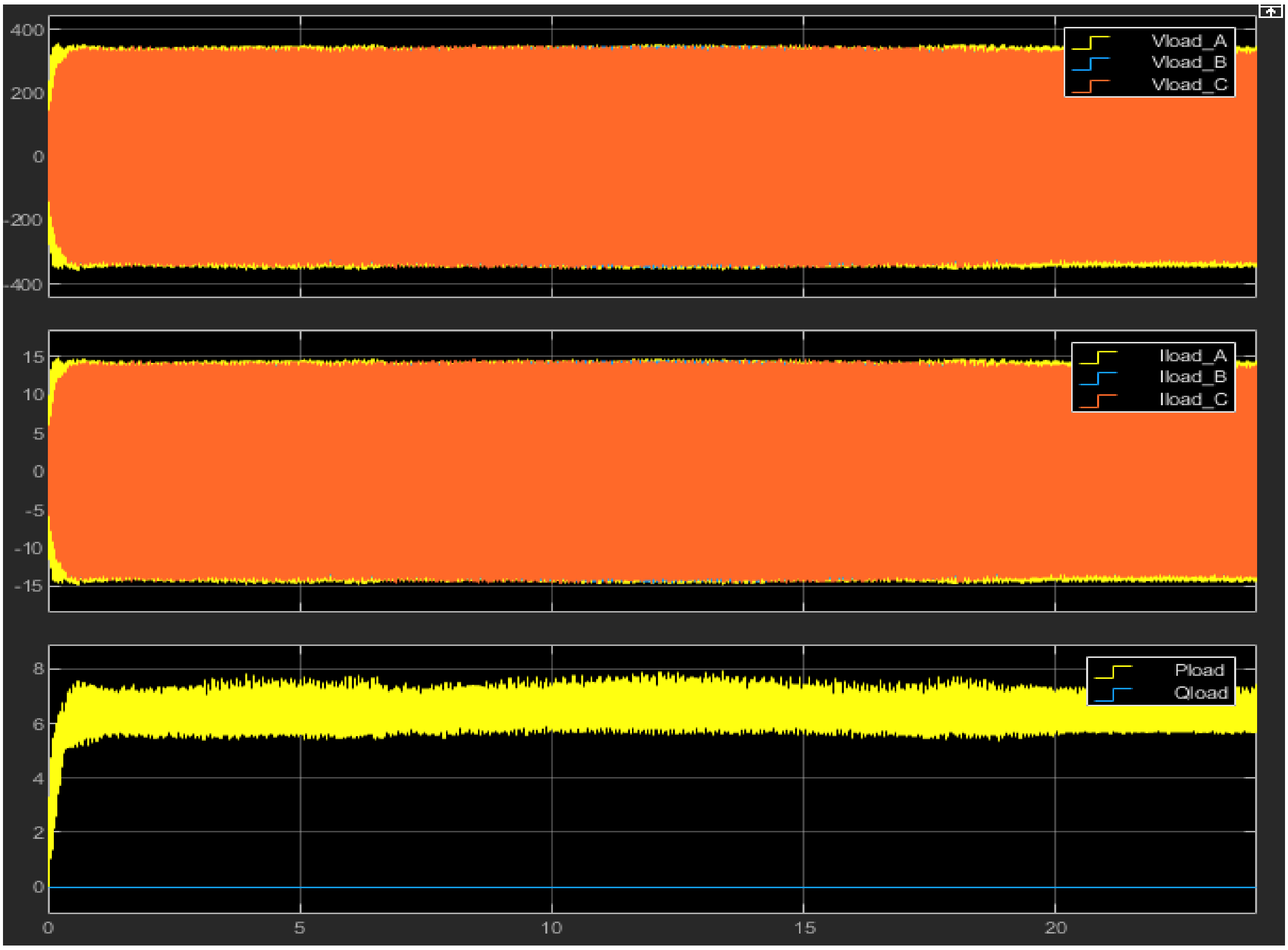

Figure 67: Results of load parameters of the simulation

In the following figure we have the power quality parameters of the microgrid connected to the DN, where we see that the voltage THD is always less than 8% complying with the limits of the regulations, and the current THD does not exceed 7% in any of the phases, which denotes a fairly low harmonic content.

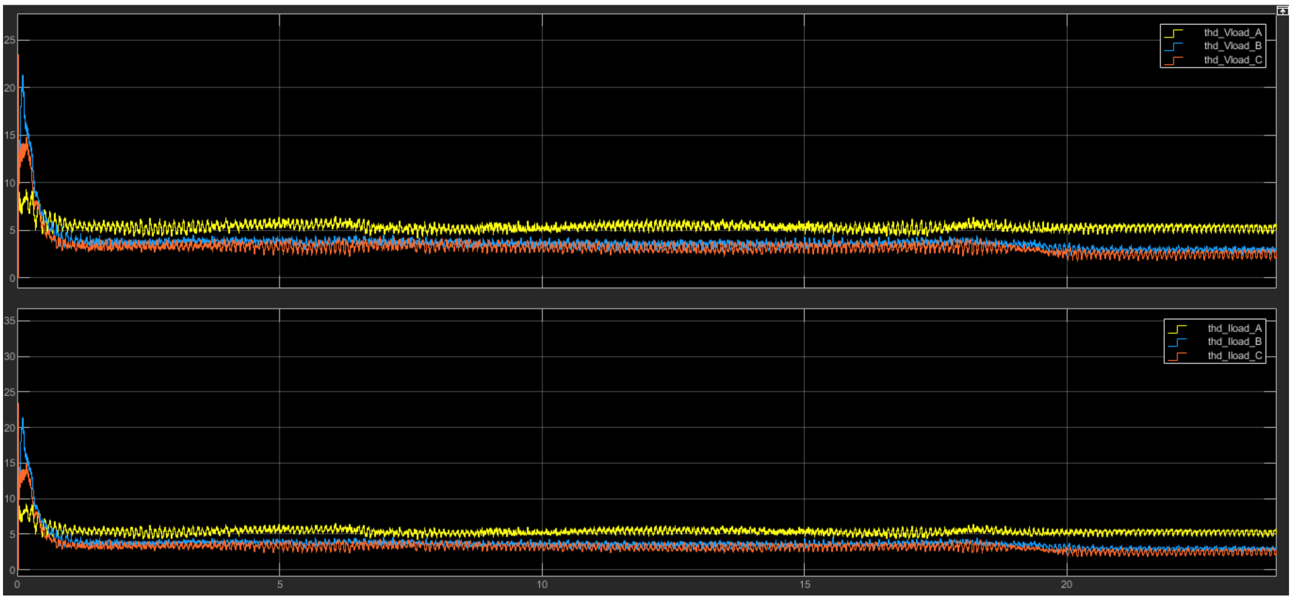

Figure 68: Power quality parameters of the microgrid conected to the distribution network

Now we have to analyse the model when it works in island mode, that is, when it is not connected to the DN and the loads are supplied by the production of the generators and the energy stored in the batteries.

Here we have the results of the energy supplied by the batteries measured in the AC part of the inverter, and the voltage of the DC part:

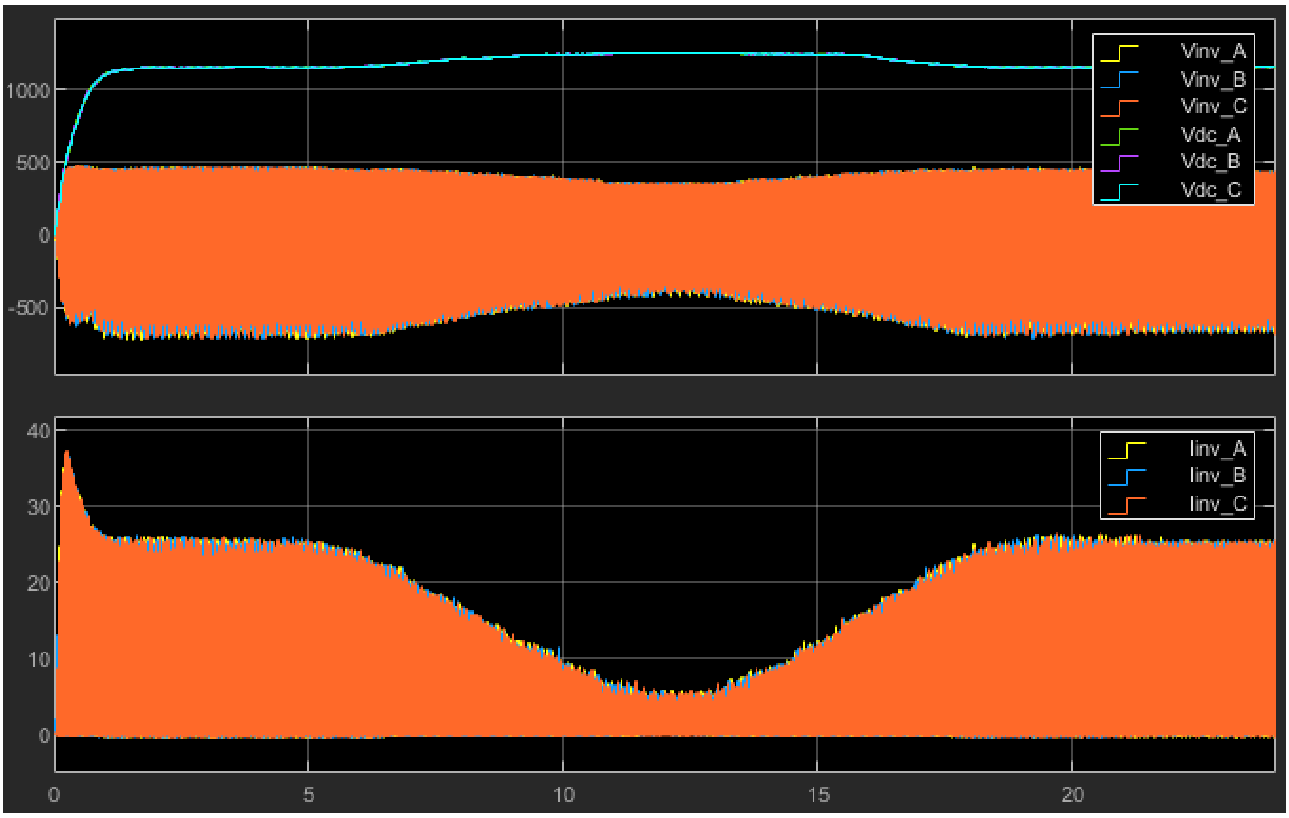

Figure 69: Energy supplied by batteries in island mode

It can be observed how the voltage remains more or less constant throughout the simulation, and the current supplied by the batteries drops in the central hours of the day, mainly due to the production of solar energy, that reduces the energy demand from the batteries.

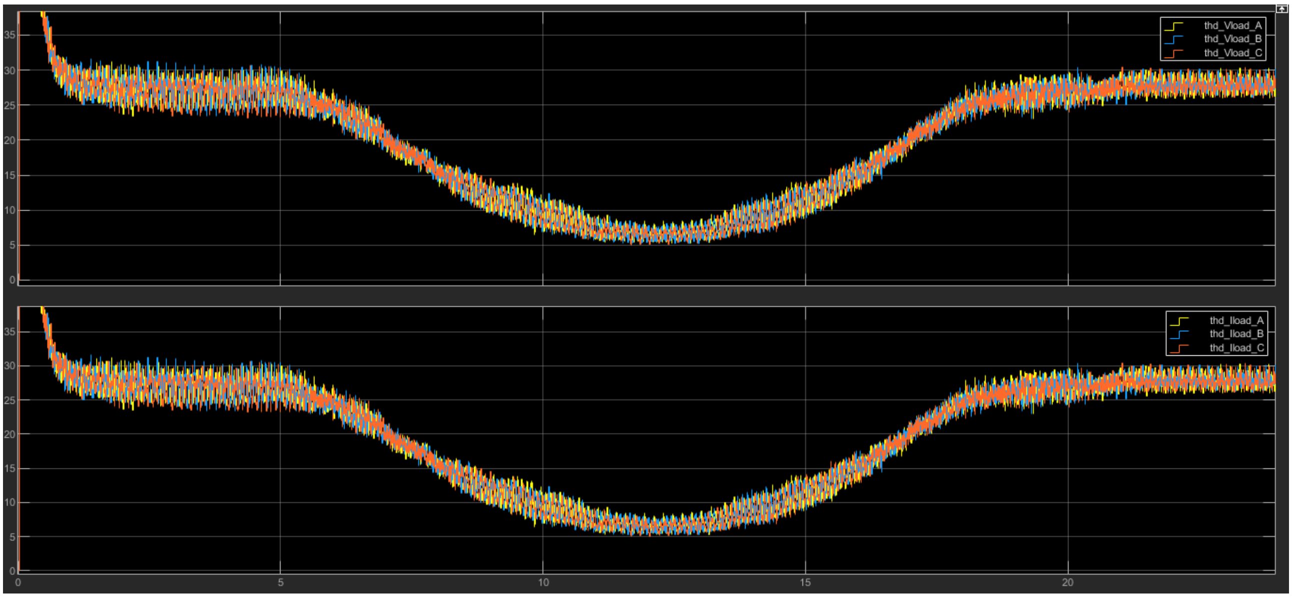

Figure 70: Power quality parameters of the microgrid in island mode

In the figure 70, the power quality parameters of the microgrid operating in island mode are shown, where we see that both, the current and voltage THD have values of 30 % when there is no solar production and drops to 8% when the current injected by the batteries reaches the minimum.

Therefore, we can conclude that the model introduces more harmonics when it works disconnected from the distribution network (discharging mode), than when it works with the on-grid mode. This may be due to the fact that the electronic circuits that we have chosen to simulate this installation are very basic and on reality bidirectional inverters have much more complex and optimized electronic circuits.

And here we end the analysis of the simulation results of the virtual model of the installation under study.

5. Possible improvement measures

In this section, a series of proposals will be suggested, that once the installation has been analysed and the main anomalies detected, it is expected that with their study and application, the operation of the installation will be better and more efficient. And the improvement proposals are the following:

- Change the batteries for new ones: we had many problems in the measurement campaign since many times the system did not measure correctly the state of charge and the charge cycle was slower than expected while when microgrid works in island mode, the discharge cycle was excessively fast, concluding that the batteries have lost a large part of their capacity and a large part of the microgrid reliability failures are due to the state of the batteries. With a complete change of all the batteries, we would improve reliability and avoid the sudden blackout that the installation suffers quite often.

- Set the nominal voltage of the microgrid to 220 V: as we have commented in the analysis of the results of the experimental measurements, depending on the mode in which the microgrid is working, the nominal voltage is different, being 220 V when is connected to the DN, and 230 V when it operates in Island mode. As in the on-grid mode we cannot control the voltage level that reaches the installation, the proposal is to change the nominal voltage of the off-grid mode from 230 to 220 V, which is when the master inverter has control over the voltage, and so on avoid the 10 V step that occurs when changing the operating mode, which can cause malfunction in some sensitive loads.

- Analyse the single-phase Ginlong inverter: carry out a study of the operation of this inverter in order to find the reason why it generates so much reactive power, whether it is a parameter configuration failure, or if it is just a problem that is operating at a power that is very far from its design power, or simply that the inverter is defective, but of course, the measured behaviour should not be normal.

Conclusions

Finally, we come to the chapter of the conclusions, where the main results of this work are summarized:

1. The importance that the microgrid is acquiring in the energy transformation that the electrical system is undergoing and the fundamental nature of controlling the quality of the energy produced in these microgrids.
2. The different parameters that define the electric wave and how to measure harmonics and the harmful effects on loads.
3. The different standards that regulate the quality levels of electricity supplies and their limits.
4. The function and mode of operation of each component of the installation under study.
5. The frequency of the microgrid is within the limits allowed in any operating mode, in island mode the control is more precise if possible.
6. The voltage values have also been within the limits set by standard in all the measured scenarios, but with different nominal values depending on whether it was connected the DN (220 V) or worked independently (230 V), the control in the latter mode much finer.
7. The voltage THD values have been bellow the maximum allowed (8%) in all the cases analysed.
8. We have discovered an abnormal behaviour in a phase of microgrid, due to the generation of a large amount of reactive power by the single-phase Ginlong inverter, which causes a generation of harmonics in the current.
9. Due to this last fact, the current THD values of the phase in question are very high in almost all operating modes.
10. The current TDD parameter is below the recommended limit (15%) when the microgrid is supplied by the DN, but when the energy flow is the opposite it far exceeds this limit, it means, when the microgrid injects the surplus energy produced into the DN does so with a harmonic level in the current that is much higher than recommended. It must also be said that in this mode the number of samples obtained has been very low and these conclusions may not be relevant.
11. The efficiency of the three-phases Sunny tripower inverter is verified to be higher than that of the single-phase Ginlong inverter.
12. Bidirectional Sunny Island inverters are more efficient in battery discharge mode (acts as an inverter) than in charging mode (acts as a rectifier).
13. Each main element has been implemented in the virtual model, describing the strategies followed for their model and analysing the results of the simulation of each element.
14. With the maximum radiation in the city of Kaunas we do not reach the maximum power of the solar power plant, but nevertheless with the radiation of the city of Valencia (Spain), yes.
15. We have verified the proper operating of the MPPT both in the solar panels and in the wind turbine.
16. We have compared the two modes of operation of the virtual model and we have seen that the island mode has a worse power quality, that is, when the microgrid is connected to the DN, it has lower harmonic content.
17. And finally, we have made a few suggestions to improve the operation of the installation, which are, to change the batteries, set the nominal voltage of the island mode at 220 V and analyse the behaviour of the single-phase Ginlong inverter.

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Appendices

Appendix 1. Weather conditions considered for the simulation

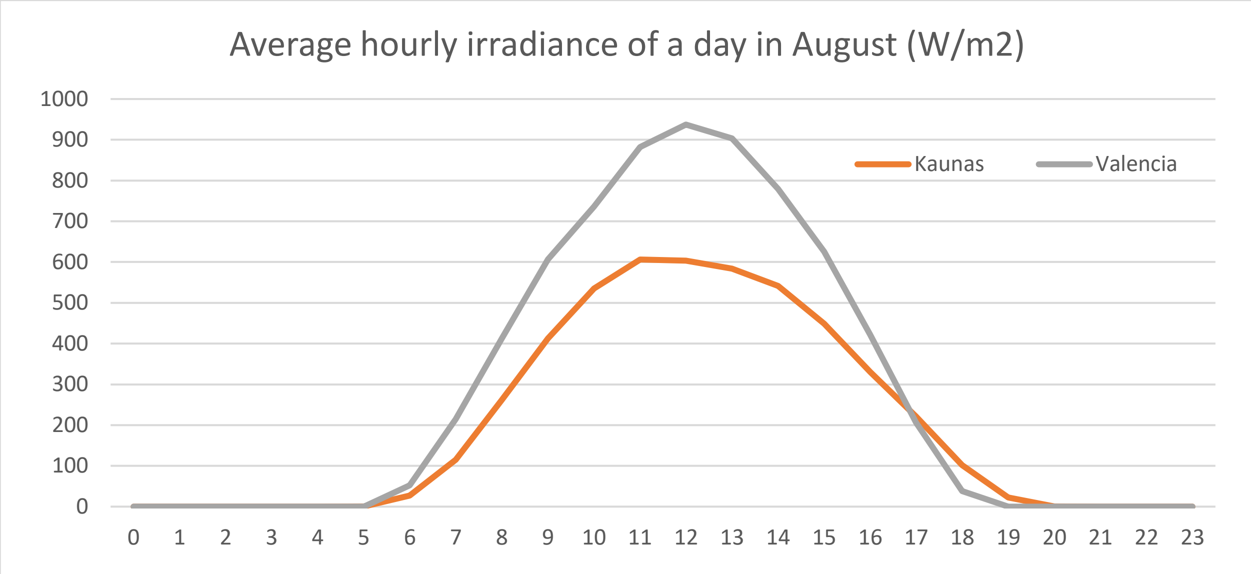

Figure 71: Average hourly irradiance of a day in August in Kaunas and Valencia

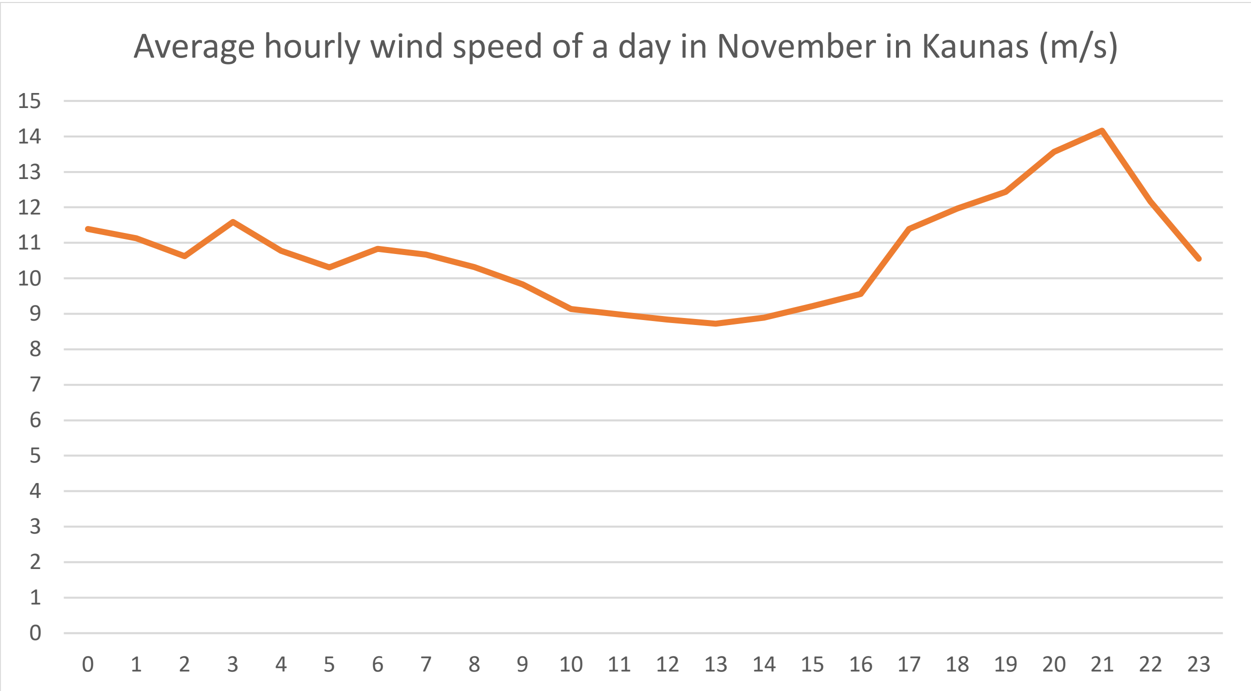

Figure 72: Average hourly wind speed of a day in November in Kaunas