Technical report for

The Experimental investigation on the performance characteristics of anti-islanding techniques in the prospect of high PV penetration level

Project acronym: Multi-island

USER PROJECT	
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USER GROUP	
Name (Leader)	Prof. Nikolaos Papanikolaou
Organization (Leader)	Democritus University of Thrace
Country (Leader)	Greece
Name	Konstantinos Bampouras
Organization	Democritus University of Thrace
Country	Greece
Name	Alexandros Boumparis
Organization	Democritus University of Thrace
Country	Greece
Name	Syllas Frantzeskakis
Organization	Democritus University of Thrace
Country	Greece

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1. Introduction

1.1 State of the art

Over the recent years, solar energy production has been moved to alternative sources (solar, wind, etc.). The milestone of 500 GW will be certainly met by 2020 as the global cumulative capacity of PV installation is growing almost exponentially. Exploitation of solar energy is not only applicable in large energy parks but also in small-scale residential installation connected to low voltage distribution network with the introduction of micro-inverters (MICs). A major issue of MICs is the facilitation of unintentional islanding detection of the PV-system. Low voltage distribution network applications are characterized by low penetration levels (PL ≤ 20%) in order to efficiently detect and prevent self-supplying islands without disturbed power quality arrangements. One variable that sets the PL boundary is the method that PV identifies the network condition, specifically if the MICs operate in island or grid-tied. Towards this prospect, in order to exceed the predetermined boundary and reach greater PL values (e.g. 50%-60%) an effective anti-islanding method must be used.

Anti-islanding methods can be simply distinguished as passive and active. Passive methods measure grid frequency and/or voltage. If the values above differ from predetermined limits, the PV control recognizes an island condition and halts power production. Yet in greater PL the cumulative production of the island may meet the load demand, thus neither frequency nor voltage may be affected by switching from grid-tied to island operation. As a result, passive methods for anti-islanding detection should be rejected for surmounting the PL limitation and more sophisticated active based anti-islanding techniques are required to meet the standards. Some active methods of anti-islanding detection introduce major disturbances on the output current in order to gain information whether or not the PV is grid-tied. In high PL networks, where many MICs operate simultaneously, those disturbances may accumulate affecting the THDi% and THDv% over the predetermined limit of ≤3% and ≤8% respectively, rendering the distribution networks unacceptable as that approach is resulting in the reduction of power quality of the utility.

In order to achieve higher PL, new anti-islanding method must be introduced. Yet first, we need to comprehend the cooperation of different type of inverter topologies using different methods of anti-islanding detection, for various PL values and load conditions. For that a large number of measurements are required for all the aforementioned combination. By acquiring those measurements, it is possible to understand the effects on the active anti-islanding protection by introducing many independent PV inverters and to analyze and understand the coordination of harmonics injection active method with other passive or active methods. Positive results may lead a new generation of PV-inverters that are able to detect network conditions in a short time, without disturbing the power quality. Over the time new, greater PL arrangements will be set and a greener, more environmental-friendly network will be a reality with power generated mostly (and some day solely) from alternative sources.

1.2 Detailed description of proposed project

The main target of the proposed activity is acquiring measurements that will further our understanding, and by extension the knowledge of the scientific community about the incorporation of different PV-inverters on a grid and the reaction between them in comparison with different PLs. Those measurements may lead in developing a new strategy that the MICs should follow in order to surmount the difficulties that bound the PL to ≤20%, paving the way for a network that produces energy from alternative sources, protecting the environment by reducing harmful oxides as less energy is required by burning fossil fuels.

In order to acquire those measurements, we require a test bench with different types of PV-inverter units (single-phase, three-phase) and with different topologies. That is essential as it is important to understand the response of the output characteristics of PV-inverters during the switching of operation between grid-tied and island conditions and the amount of time it requires for each of the aforementioned -inverter to detect and disconnect. Of course, disconnection time is mainly affected by the different anti-islanding methods that each PV-inverter is supporting (and in many cases the condition of the grid and the load as in passive anti-islanding methods). Disconnection time is also affected by the PL of the system as the cumulative energy production of PV may suffice the power demand of the load. It must be mentioned that the maximum time set by arrangements for the detection and disconnection of PV-inverters is 2s. The apparent power provided by the network according to the real power that the PV and MICs provide is a major factor of our set-up as it regulates the PL in every measurement. In contemplation of the above, our true goal is to increase the real power production of the PVs and reduce the apparent power provided by the network (resulting to the incretion of PL drastically), without reducing the power quality of the low voltage grid. All that achieved in detection and disconnection of the individual MIC in less than 2s. In order to succeed is necessary to accurately measure and regulate the amount of energy the network is conveying. Different values of apparent power are expected to alter the individual time response of the MICs and the overall power quality that is dispensed to the load.

1.3 Originality, innovation and impact

The importance of implementing a quick and effective method for anti-islanding detection is in critical value for the safety operation of the network in case of a condition that resorts to failure, i.e. the need for disconnection of the PV-inverters from the load and the grid. PVs should disconnect without create self-sustained power island. In the prospect of producing more energy from alternative power sources it is expected those failures that lead to island conditions to present more often. Due to the constant decrease of PV-inverter cost and with research that increases the power density of inverter for residential applications, there has been a rise in power production in the low voltage distribution network resulting in higher occurrences of islands. Although the importance of the anti-islanding detection there has been little to none publications that leads to the understanding and the correlation of the anti-islanding methods on multiple PV-inverters in the prospect of higher PL levels. It is of fundamental interest the incorporation of multiple PV-inverters in a complete set-up for experimenting in order to understand the technical issue that may present now or in the future during an occurrence of failure. In other words, the impact to the grid from the introduction of different anti-islanding schemes, i.e. if the cumulative production of PV-inverters that incorporates passive or active methods produces power evenly or one from the aforementioned methods is dominant.

By introducing the active and passive schemes with different ratios of incorporation, we expect a different time response and different power quality levels of the grid. By completing the experiment and my acquiring data for the different anti-islanding methods and their correlation with PL levels, we can present the results to conferences and generally on electronic libraries in order for the scientific community to understand the impact of the methods above on the grid.

In the prospect of reaching higher PL levels, a new efficient anti-islanding method is critical. Harmonic injection is a candidate that may lead to surmounting that arrangement, paving the way for the day that the majority of power will be produced from alternative sources, protecting the environment from harmful oxides.

2. Experimental procedure

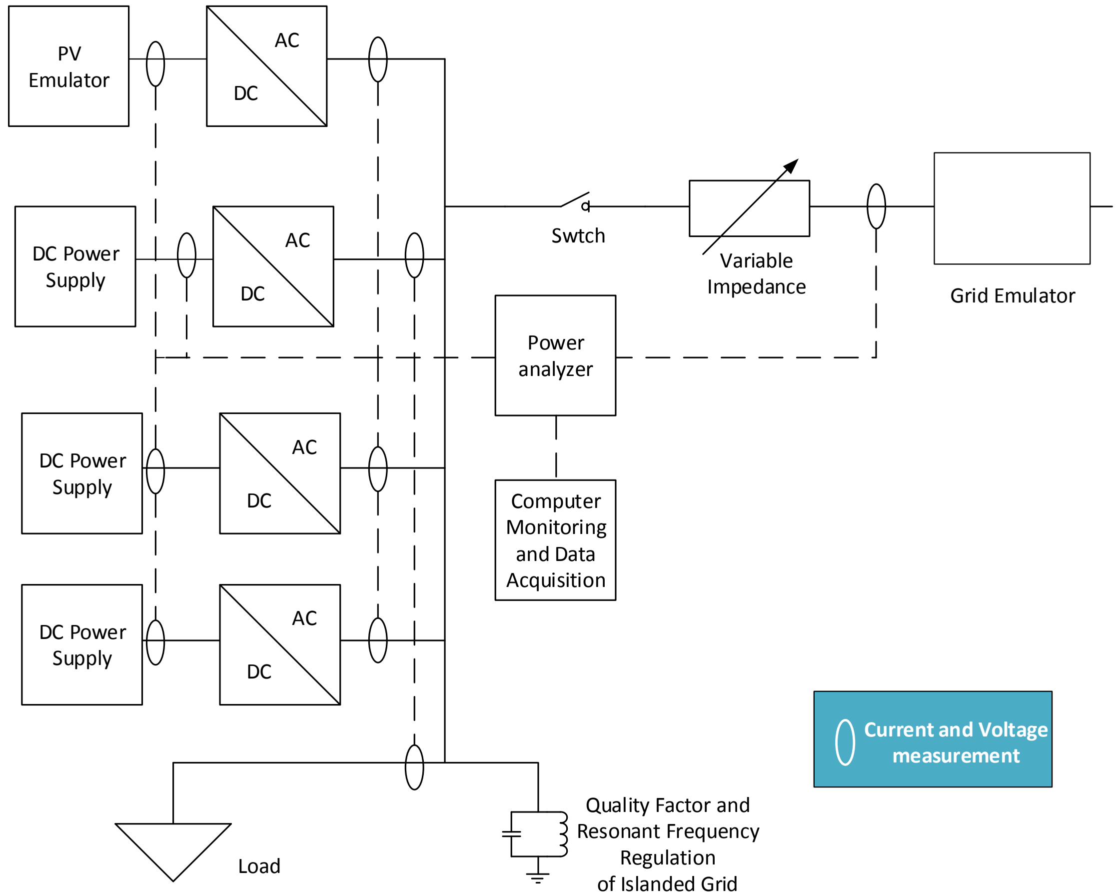


Figure 1: Setup of the experimental procedure

For our experimental procedure for anti-islanding detection we will use three inverters

	POWER	Phase
Inv. 1	4.5 kW	3
Inv. 2	2X300 W	1
Inv. 3	1 kW	1
Inv. 4	1 kW	1

Table 1: Inverters available for our experimental procedure.

For the experimental procedure, we incorporated different combinations of inverters in order to capture their response, first during steady state and second during an island event. In every test the load power consumption will meet the PV power production (load matching conditions). This will push the anti-islanding methods to the limits as it increases the possibility of creating self-sustained islands. We will examine the response of the anti-islanding detection of the following combinations:

	Z1		Z2		Z3		Z4	
inv	Steady state	Island event	Steady state	Island event	Steady state	Island event	Steady state	Island event
1	X	X	X	X	X	X	X	X
2	X	X	X	X	X	X	X	X
3	X	X	X	X	X	X	X	X
1,2	X	X	X	X	X	X	X	X
1,3	X	X	X	X	X	X	X	X
2,3	X	X	X	X	X	X	X	X
1,2,3,4	X	X	X	X	X	X	X	X

Table 2: Measuring table for every combination of inverters for steady state and islanding condition with different impedances

The measurements above will be obtained for different grid impedance values in order to emulate strong and weak grid conditions, as shown in table 2. In order to reach different impedances

The different combinations are shown in table 3.

	R(Ohm)	X(mH)	Z(Ohm)
Z1	2.2+0.5+0.25+0.11+0.05=4.51	1.47+0.98+0.67+0.49=1.13354	3.31
Z2	2.2	1.47+0.98+0.67+0.49=1.13354	2.475
Z3	0.25+0.11=0.36	1.47+0.98+0.67=0.97968	1.04373
Z4	0.05	0.49	0.16178

Table 3: Combination of different impedances.

The measurements above were taken for linear load. In the last scenario when all the inverters were connected, we repeated the procedure with non-linear load. The quality factor (QF) during all measurements were between 2 and 2.5 according to our resonant frequency capacitors and inductors.

For the non-linear load, we introduced a diode rectifier with a resistor, approximately 10% of the total load.

We examine also the response of the anti-islanding detection during Normal and Faulty conditions.

The faulty conditions incorporate two distinct fault categories:

F1) Under/Over voltage and under/over frequency conditions (+10% -15% Voltage deviation and ±0.5 Hz, symmetrical).

F2) The rms value of the negative phase sequence component of the supply voltage is 2 % of the positive phase sequence component (asymmetrical).

Note that:

1. “Normal conditions” means Symmetrical 400V phase to phase voltage supply, 50 Hz.
2. For F1 we will take measurements as shown in table 4.
3. We will experiment with F2 only when the 3-phase inverter is on-line.

Voltage	49.5 Hz	50 Hz	50.5 Hz
+10%	High Voltage-Low Frequency (HVLF)	High Voltage-Normal Frequency (HVNF)	High Voltage-High Frequency (HVHF)
+0%	Normal Voltage-Low Frequency (NVLF)		Normal Voltage-High Frequency (NVHF)
-15%	Low Voltage-Low Frequency (LVLF)	Low Voltage-Normal Frequency (LVNF)	Low Voltage-High Frequency (LVHF)

Frequency

Table 4: "Window" of under/over voltage and under/over frequency conditions.

Finally, the last round of measurements will be taken for different conditions of the grid, when higher order harmonics are present. Measurements will be taken for three distinct grid conditions.

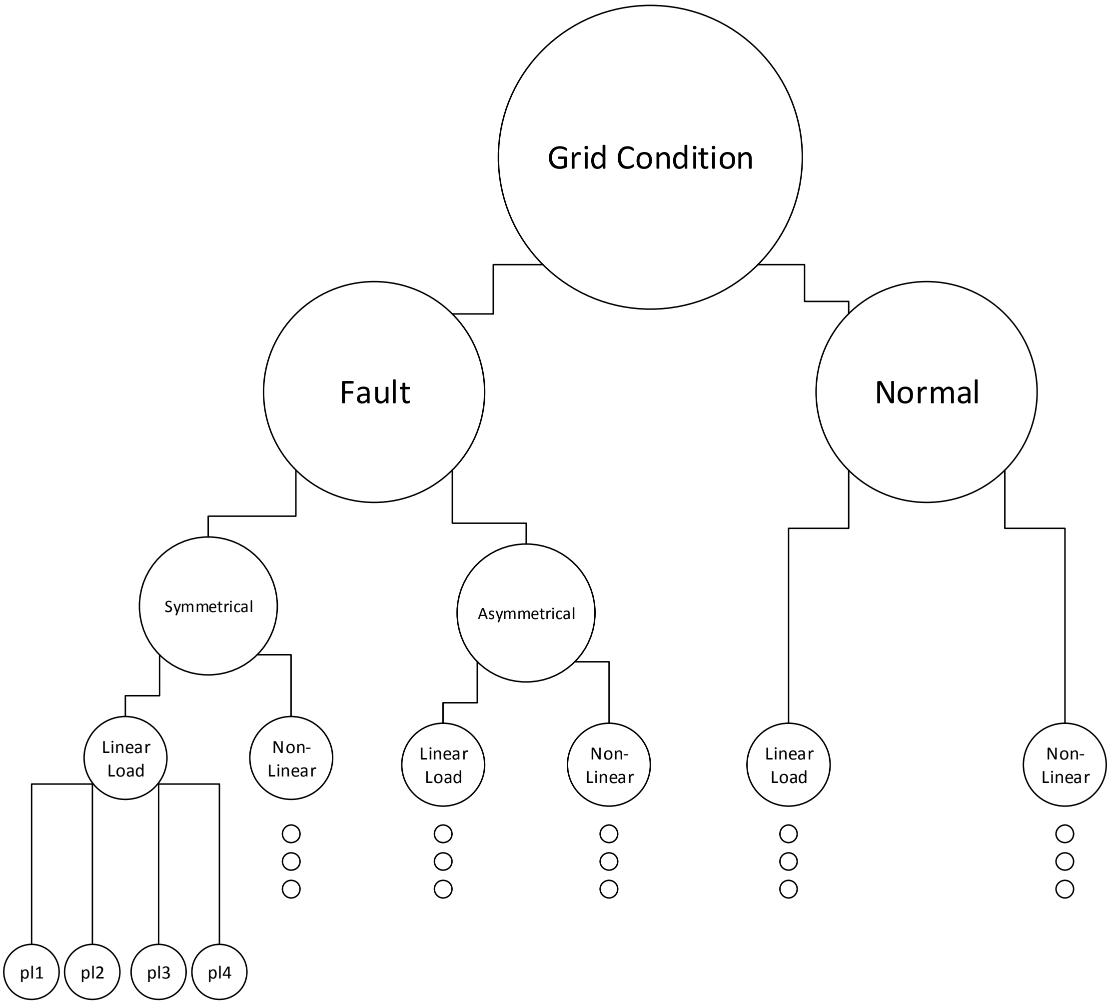
a) HD1: Pure sine wave
b) HD2: Mildly distorted
c) HD3: Highly distorted

The percentage of each individual harmonic component is shown in table 5. Note that we also used Mildly Distorted 2 and Highly distorted 2 conditions, as in some cases when inverter 3 was connected it failed to start, especially in low line impedances.

	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	THD%
Pure sine wave	0	0	0	0	0	0	0	0	0	0	0
Mildly distorted	0	2.5%	0	3%	0	2.5%	0	0	0	2%	5.05%
Highly distorted	1.5%	2.5%	0	5%	0	4%	0	0	0	2%	7.31%
Mildly Distorted 2	0	0.5%	0	1.5%	0	1.5%	0	0	0	2%	2.96%
Highly distorted 2	1%	1%	0	3%	0	0.25%	0	0	0	2%	4.61%

Table 5: Distinct harmonic components as a percentage of fundamental harmonic component.

Graphical tree of the experimental procedure



3. Implemented method for anti-islanding protection

The condition of ''islanding'' in distributed generators is an electrical phenomenon that occurs when the energy injected to the power grid is interrupted due to various factors and the distributed generators continue to supply some or the entire load. Thus, the power grid stops controlling this isolated part of the distribution system. This situation may compromise security, restoration of service and the reliability of the equipment. It is important to explore the cooperation of different anti-islanding methods in order to verify that each technique performs well both for an individual inverter and for multiple inverter with different anti-islanding detection methods. Thus, in order to carry out our experiment we need to understand the anti-island technic that each inverter respect.

The 3ph-inverter incorporates both an active and a passive method. For the passive method, when an island occurs, voltage and frequency exceed normal conditions with high probability. When that abnormal condition occurs, the inverter measures and analyzes the voltage and frequency and reacts accordingly. The islanding detection tripping matrix respects the IEEE 1547 standard. For the active anti-islanding method, the inverter injects a reactive current component that changes periodically (inductive or capacitive current component). The average reactive power is zero in total, respecting the IEEE 1547 standard. The reaction of the frequency on this reactive current pattern is measured and analyzed. In case of grid connection, the grid frequency will not be influenced by the change in the reactive current. In case of an island operation the reactive current causes a change in frequency. The measurement and analysis of the frequency indicates the island condition and the inverter trips.

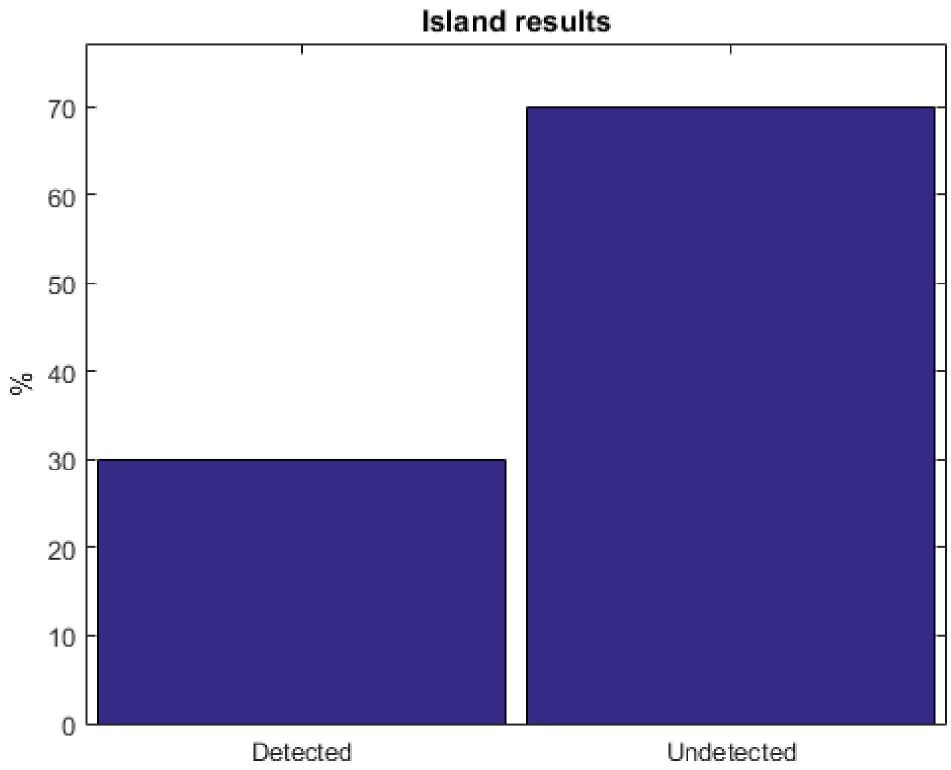
The 1ph-inverer incorporates both an active and a passive method. For the passive method, when an island occurs, voltage and frequency exceed normal conditions with high probability. When that abnormal condition occurs, the inverter measures and analyzes the voltage and frequency and reacts accordingly. In addition, the inverter measures the voltage and frequency rate of change. During grid tied operation, these values are expected to stay within limits. When an island occurs, a sudden change is probable. The active method of the 1ph-inverter injects a higher order harmonic current component in order to measure and analyze the grid impedance. When an island occurs, the inverter measures a sharp rise in grid impedance. As a result, the inverter trips.

The 1ph-microinverter implements a passive and an active method for anti-islanding detection. It measures and analyzes the grid voltage and frequency. When an abnormal condition occurs, the inverter measures and analyzes the voltage and frequency and reacts accordingly. In addition, the inverter measures the voltage and frequency rate of change in order to trip. For the active method, the micro-inverter changes the active power injection periodically. During grid-tied operation, the voltage measurement is not expected to fluctuate. If an island condition occurs, the power fluctuation is expected to influence the grid voltage by changing its amplitude. That change is measured and analyzed, thus, the microinverter trips.

4. Results and analysis

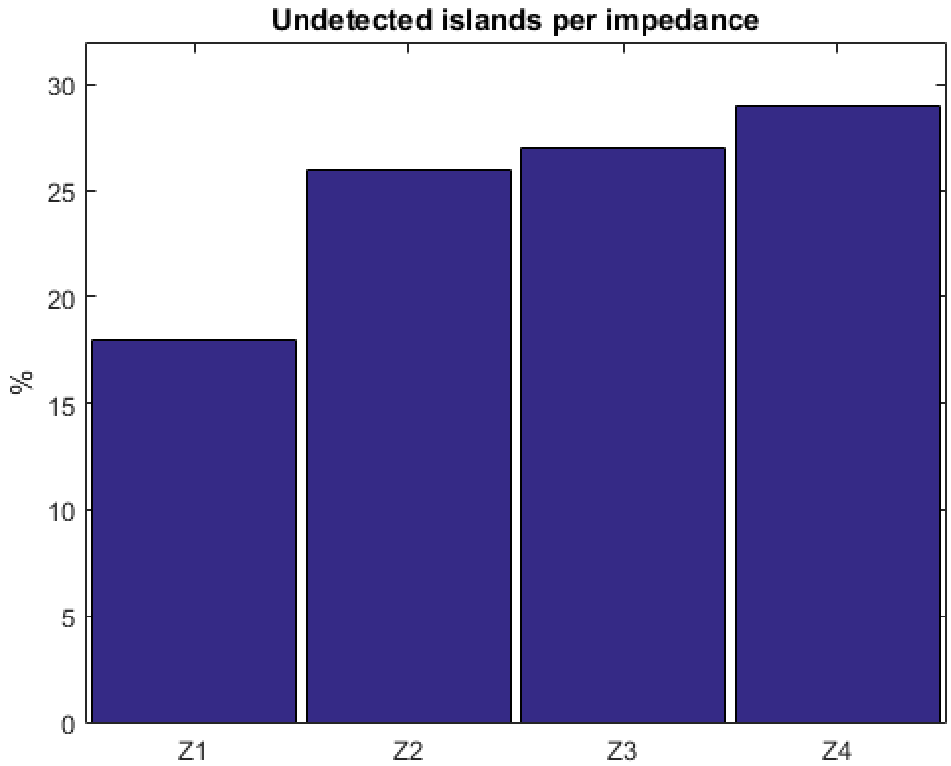
4.1 3ph Inverter (Linear Load)

The experiment with the 3ph inverter resulted to the detection of the island condition at 30% of the cases. 70% of the cases couldn't be detected by the inverter (Graph 1).



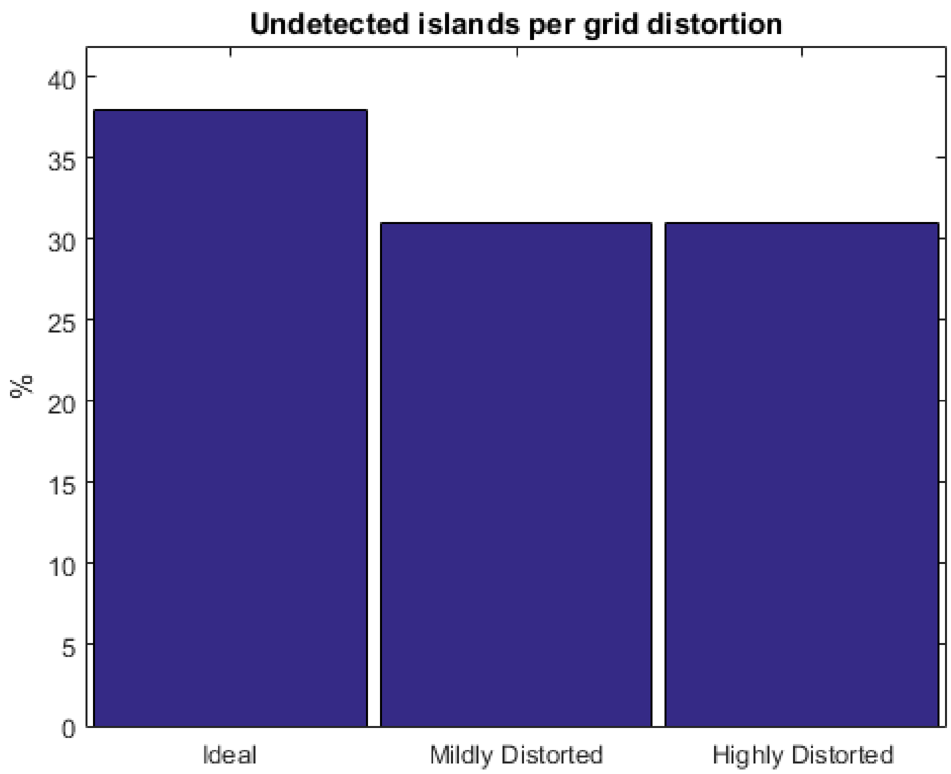
Graph 1

Most of unsuccessful island detection cases regarding to the 3 ph-inverter occurred with a strong grid (Graph 2).



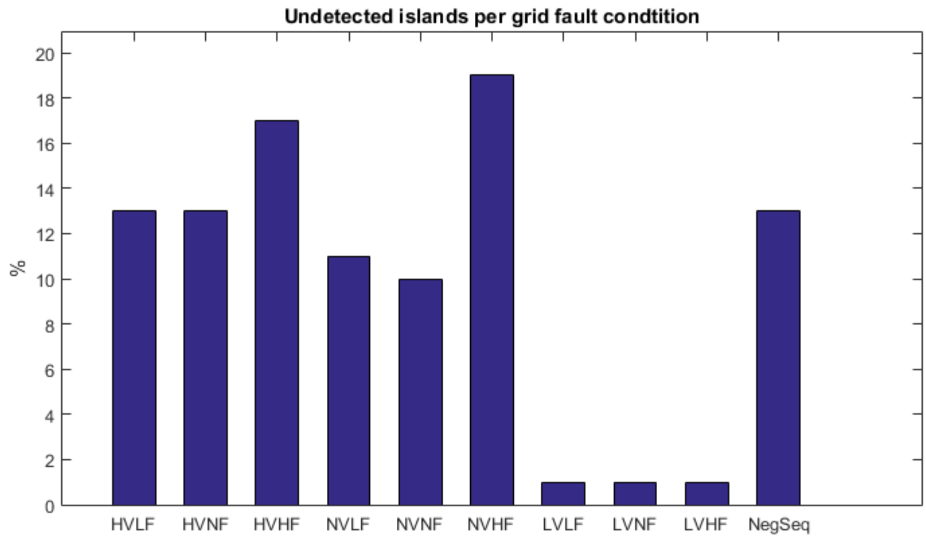
Graph 2

Graph 3 presents the number of undetected cases (%) in respect to the grid distortion.



Graph 3

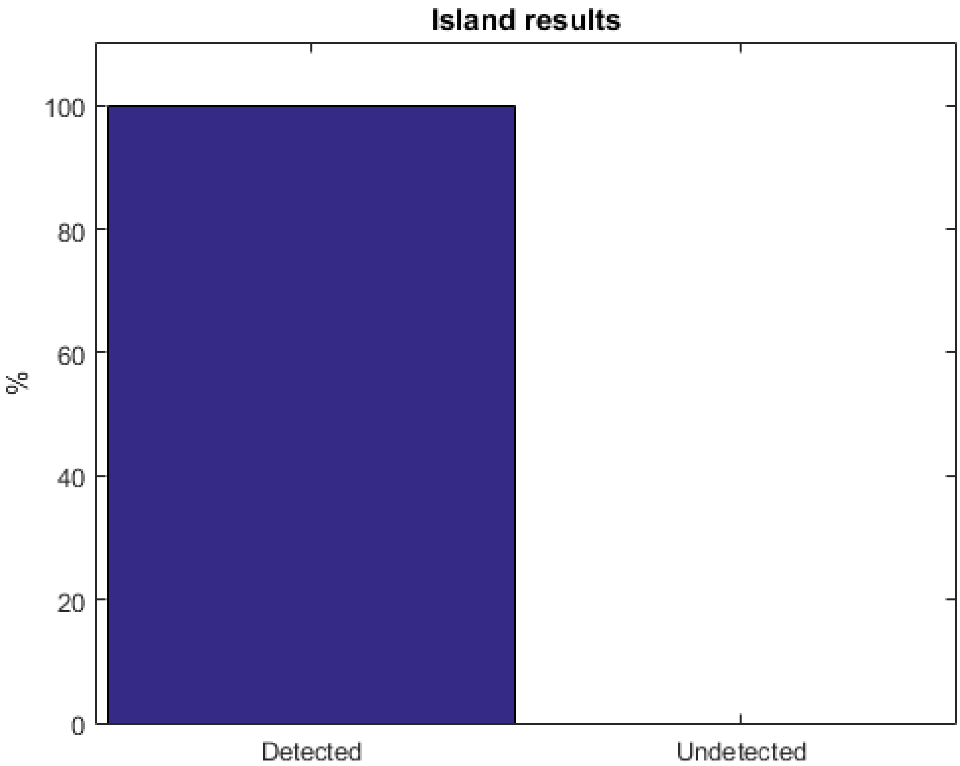
Graph 4 presents the number of undetected cases (%) regarding each fault condition of the grid.



Graph 4

4.2 1ph Inverter (Linear Load)

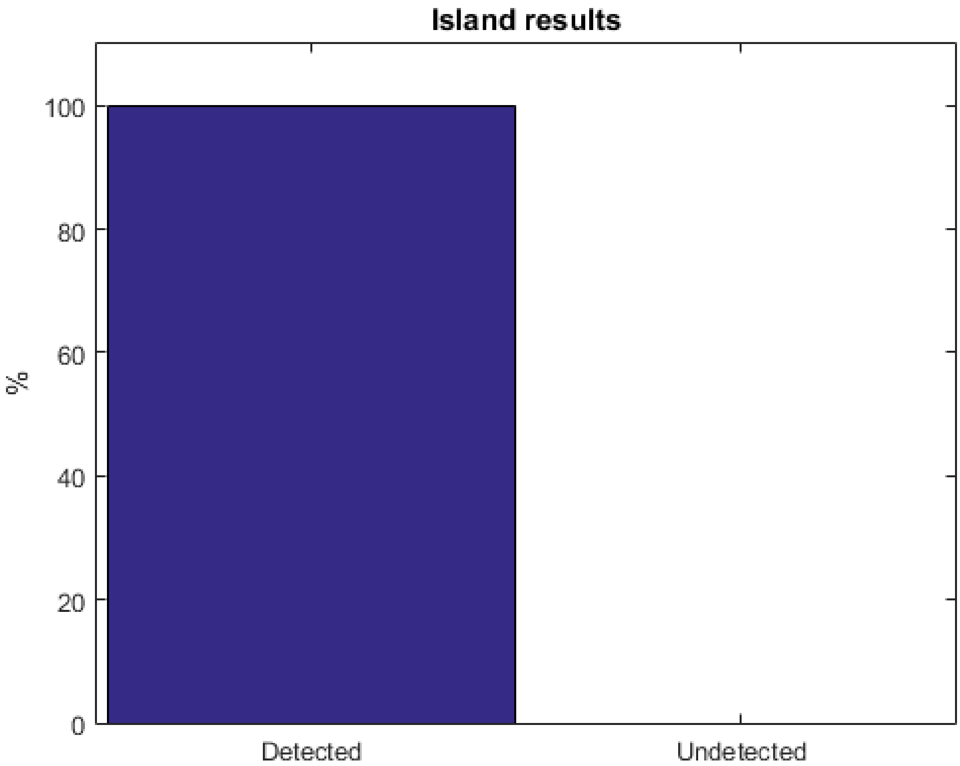
The experiment with the 1ph inverter resulted the detection of the island condition at 100% of the cases (Graph 5).



Graph 5

4.3 Micro-Inverter (Linear Load)

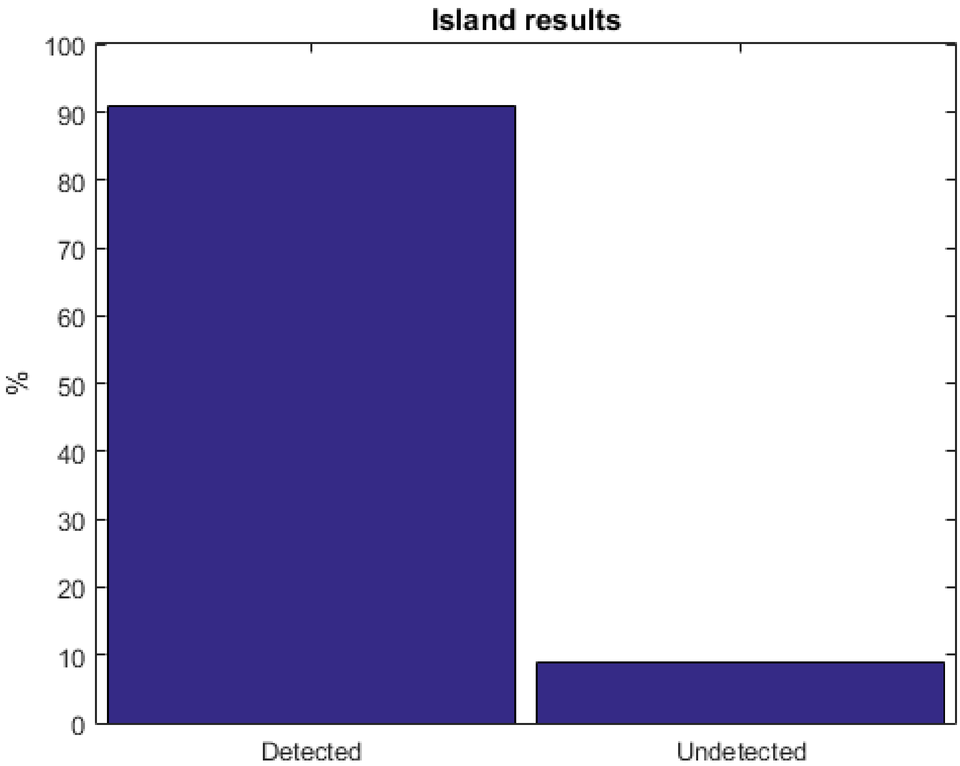
The experiment with the Micro-inverter resulted the detection of the island condition at 100% of the cases (Graph 6).



Graph 6

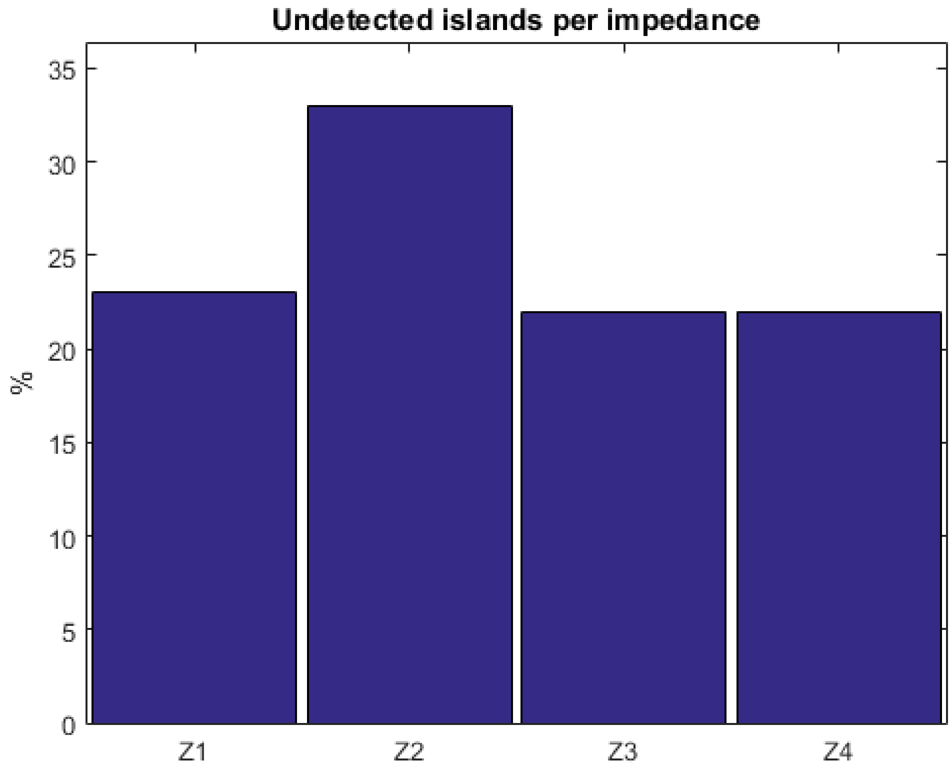
4.4 3ph Inverter - Micro-Inverter (Linear Load)

The experiment with the inverter set (3ph Inverter, Micro-Inverter) resulted the detection of the island condition at 90% of the cases. 10% of the cases couldn't be detected by the inverter set (Graph 7).



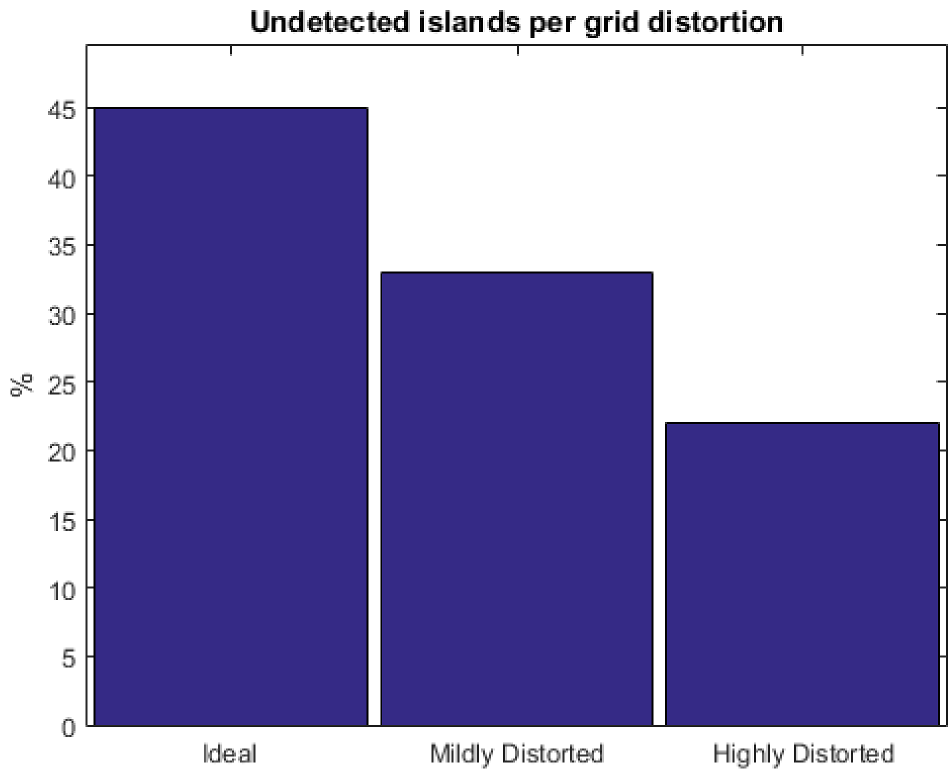
Graph 7

Most of unsuccessful island detection cases regarding to the inverter set (3ph-Inverter – Micro-Inverter) occurred when Z2 impedance was used (Graph 8).



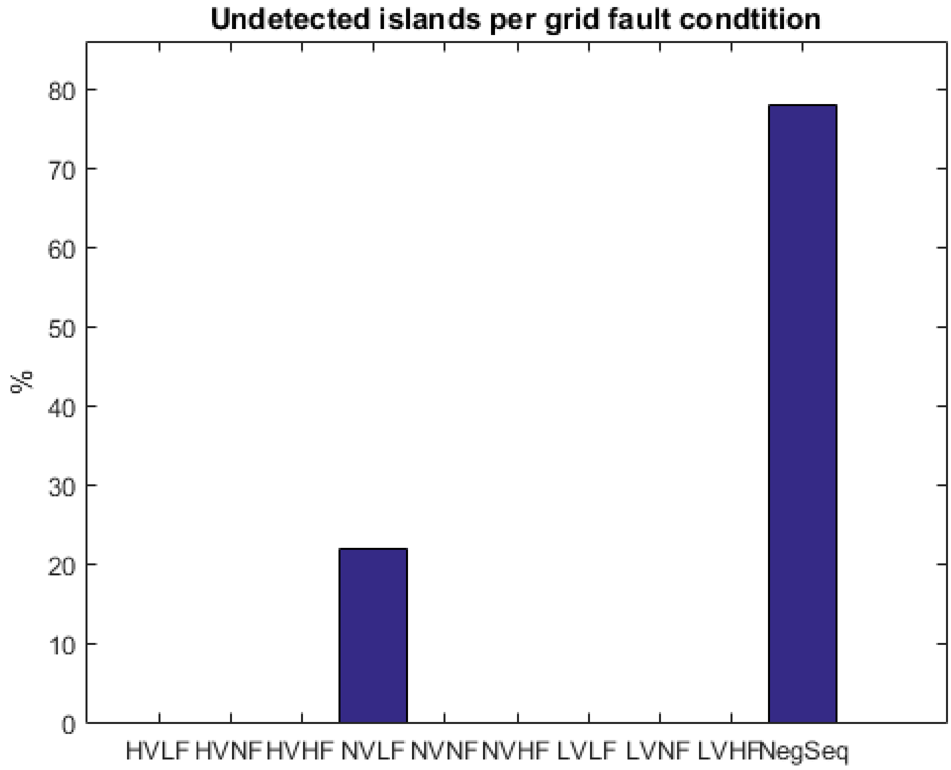
Graph 8

Graph 9 presents the number of undetected cases (%) in respect to the grid distortion.



Graph 9

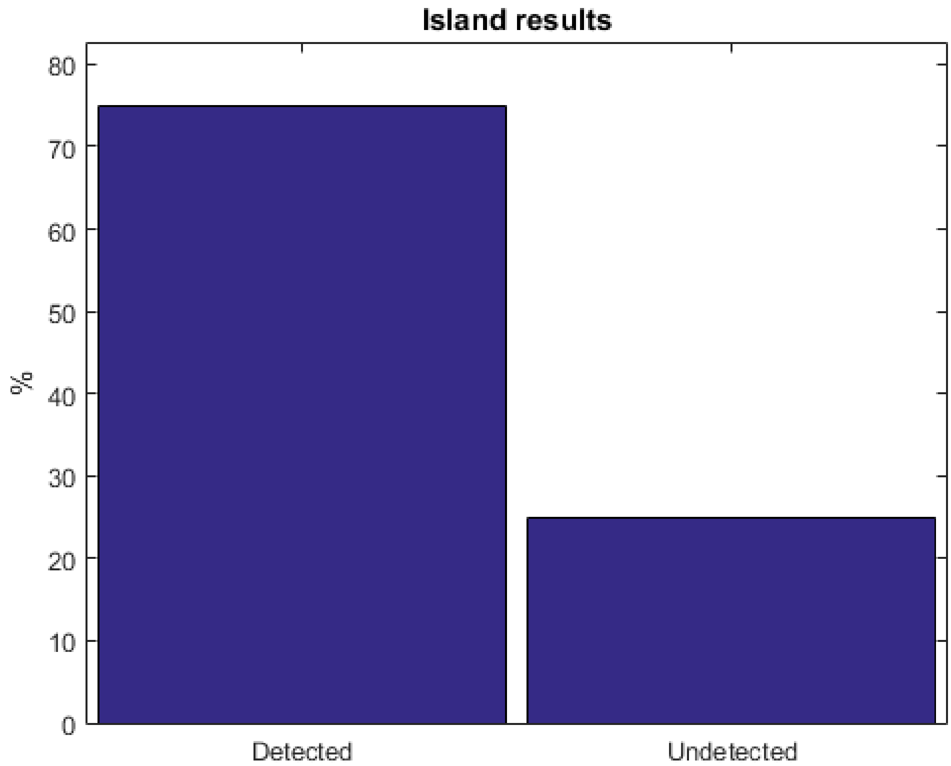
Graph 10 presents the number of undetected cases (%) regarding each fault condition of the grid.



Graph 10

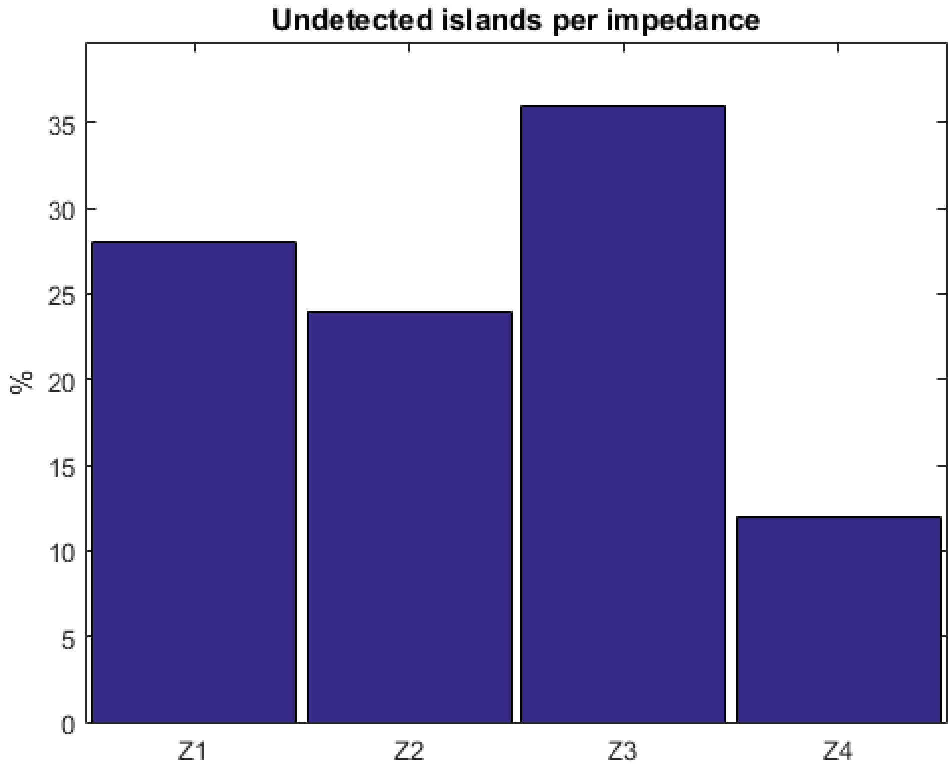
4.5 3ph Inverter - 1ph Inverter (Linear Load)

The experiment with the inverter set (3ph Inverter, 1ph Inverter) resulted the detection of the island condition at 75% of the cases. 25% of the cases couldn’t be detected by the inverter set (Graph 11).



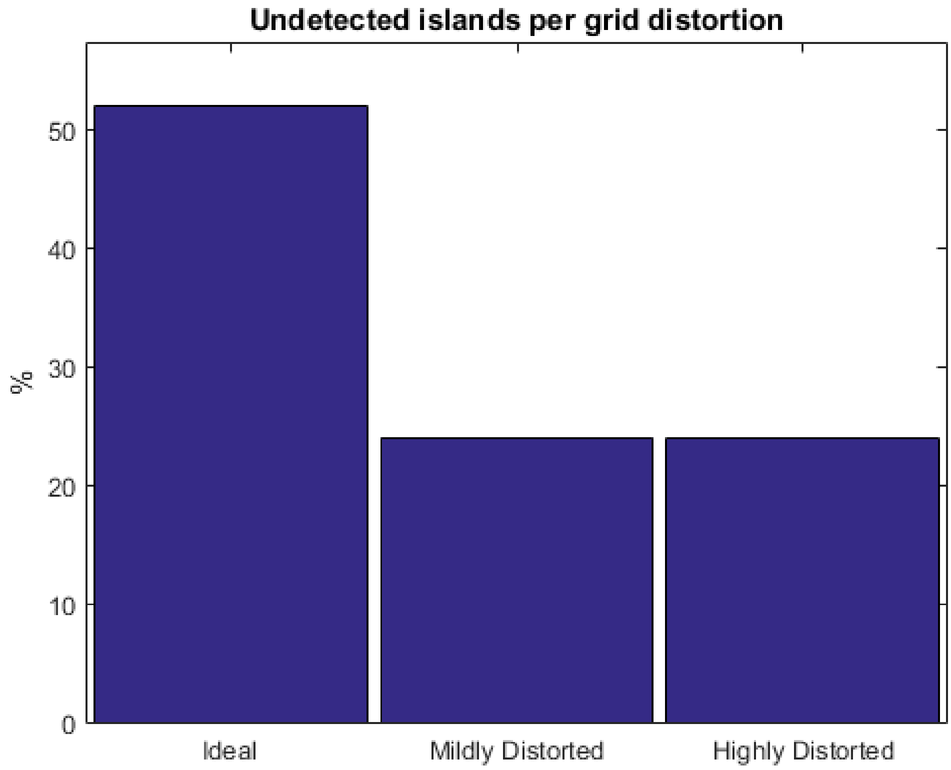
Graph 11

Most of unsuccessful island detection cases regarding to the inverter set (3ph-Inverter – 1ph-Inverter) occurred when Z3 impedance was used (Graph 12).



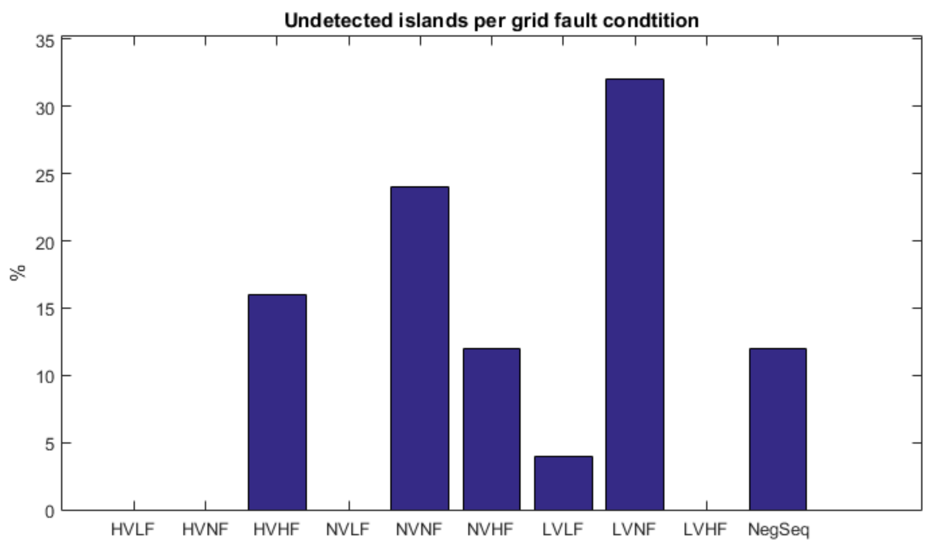
Graph 12

Graph 13 presents the number of undetected cases (%) in respect to the grid distortion.



Graph 13

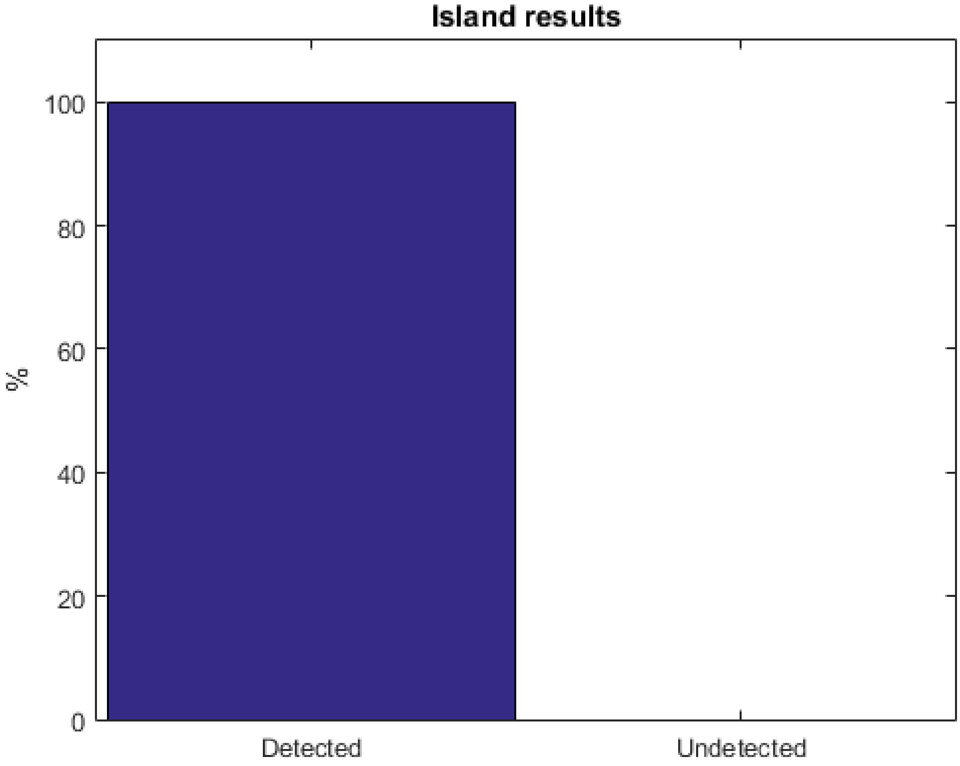
Graph 14 presents the number of undetected cases (%) regarding each fault condition of the grid



Graph 14

4.6 1ph Inverter - Micro Inverter (Linear Load)

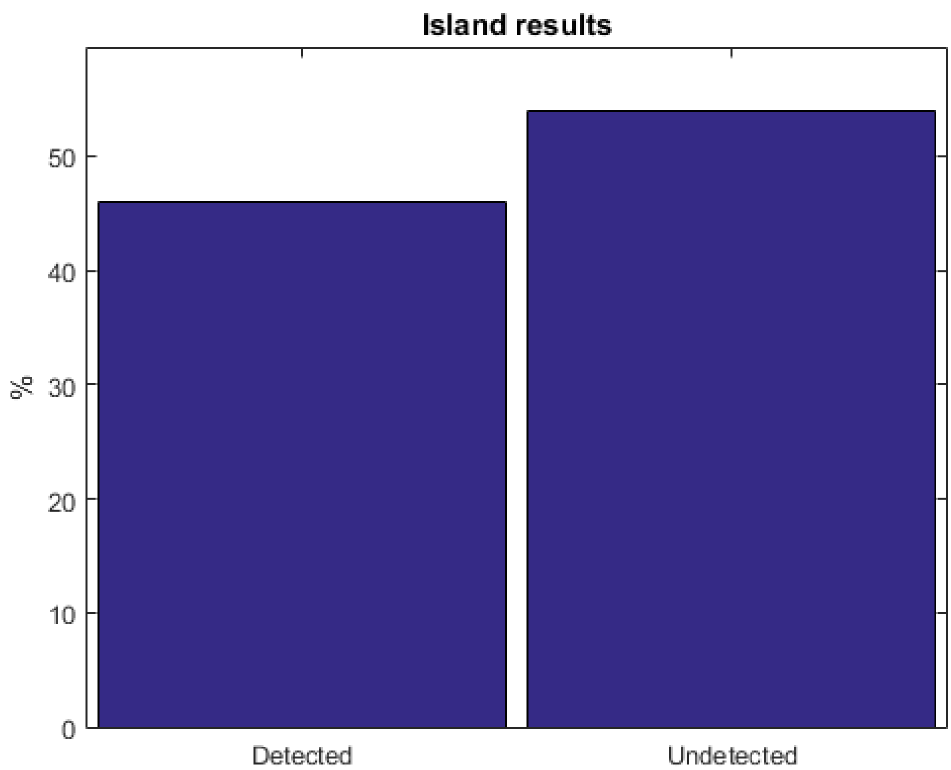
The experiment with the inverter set (1ph-Inverter - Micro-inverter) resulted the detection of the island condition at 100% of the cases.



Graph 15

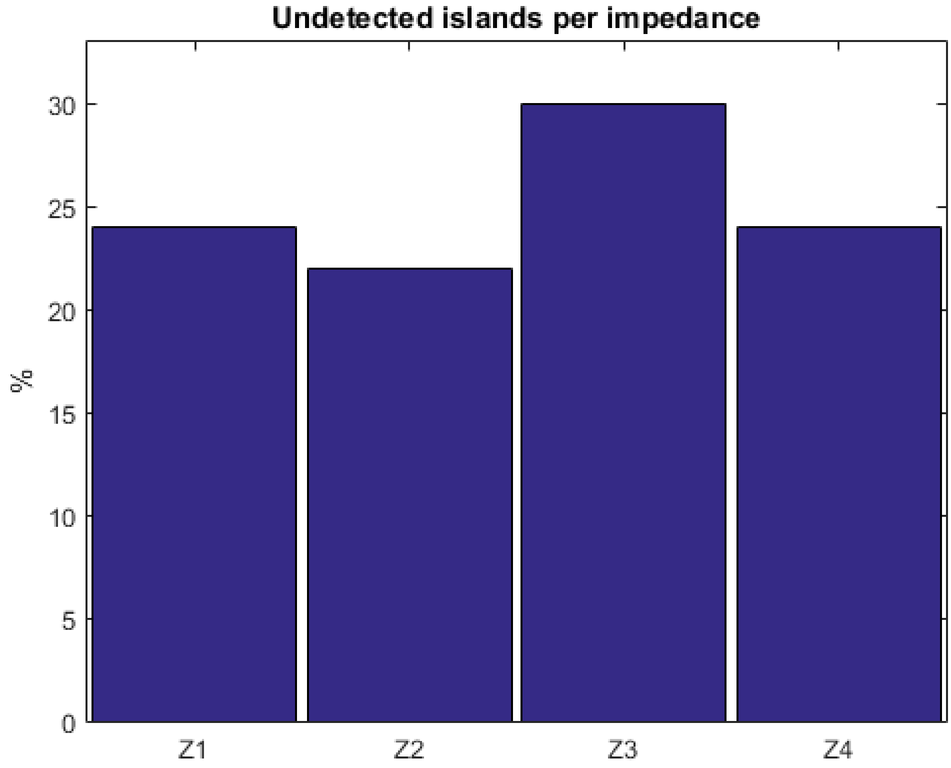
4.7 3ph Inverter - 1ph Inverters - Micro-inverter (Linear Load)

The experiment with the inverter set (3ph Inverter, 1ph Inverter, Micro-Inverter) resulted the detection of the island condition at 45% of the cases. 55% of the cases couldn't be detected by the inverter set (Graph 16).



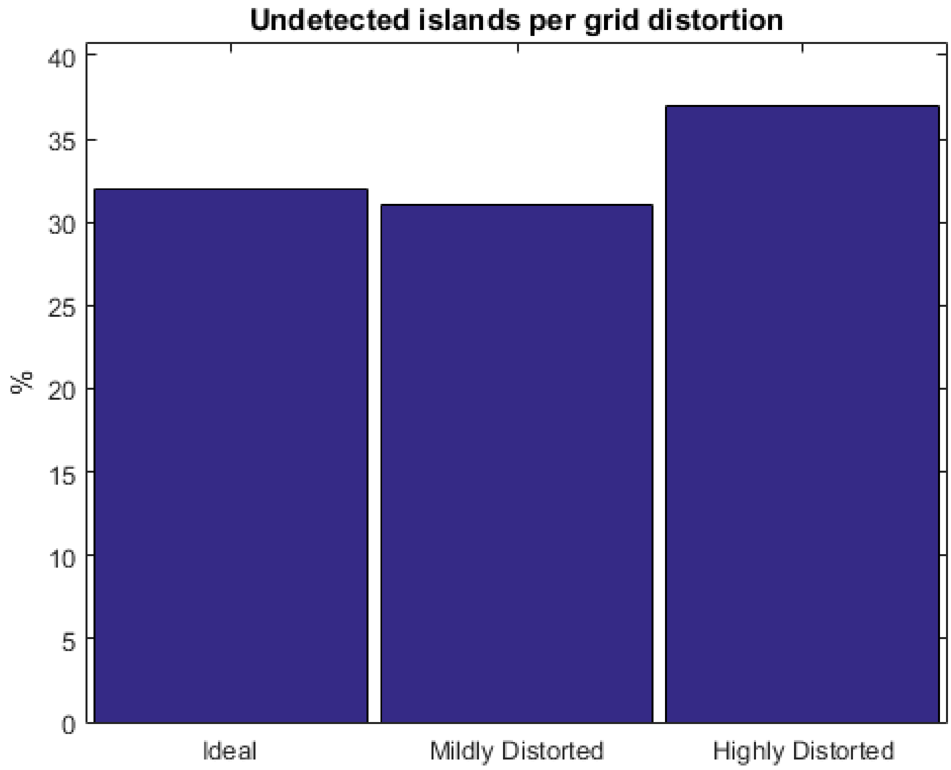
Graph 16

Most of unsuccessful island detection cases regarding to the inverter set (3ph-Inverter – 1ph-Inverter, Micro-Inverter) occurred when Z3 impedance was used (Graph 17).



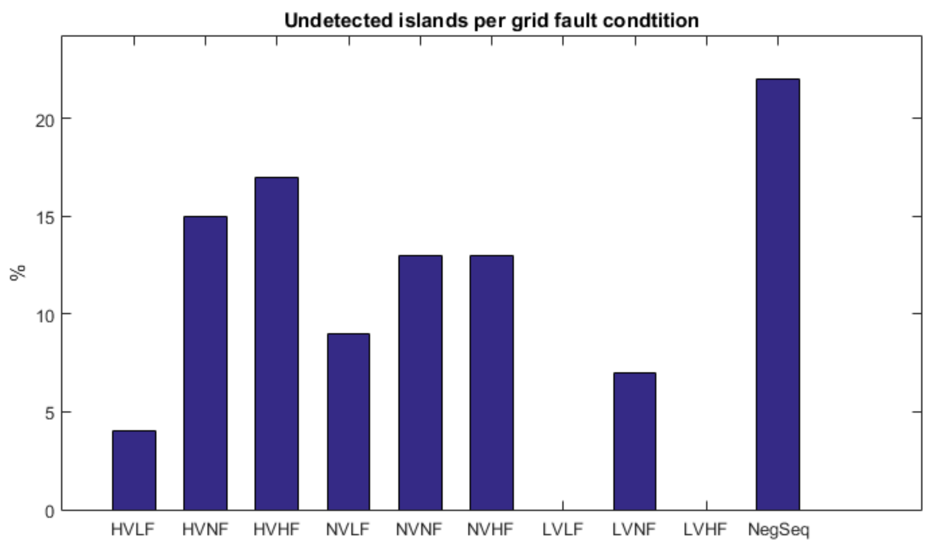
Graph 17

Graph 18 presents the number of undetected cases (%) in respect to the grid distortion.



Graph 18

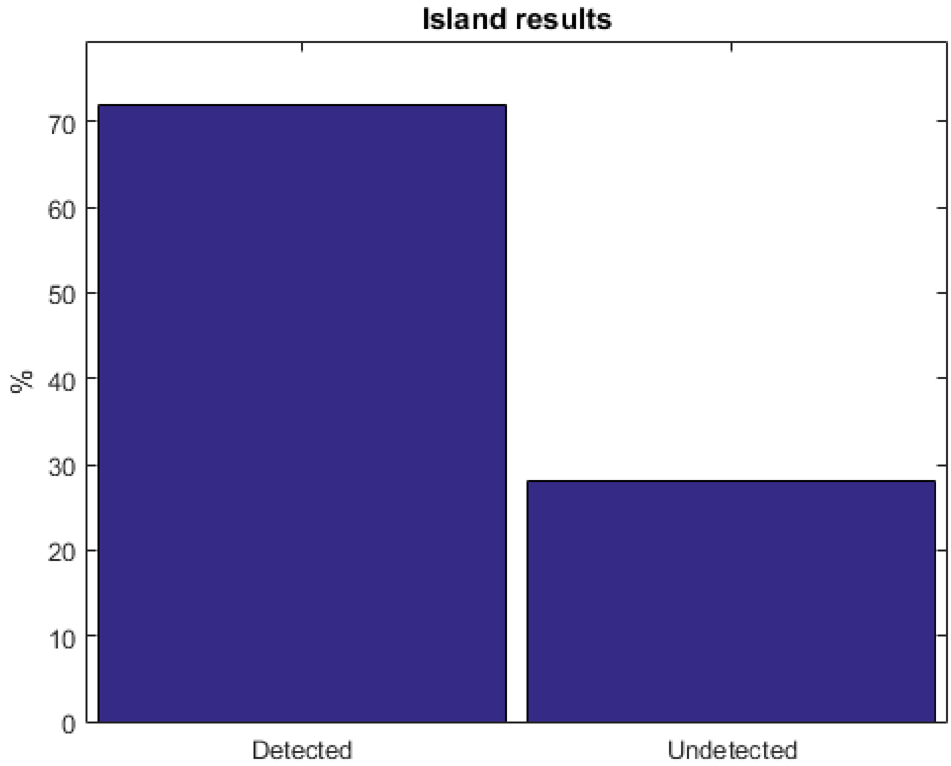
Graph 19 presents the number of undetected cases (%) regarding each fault condition of the grid.



Graph 19

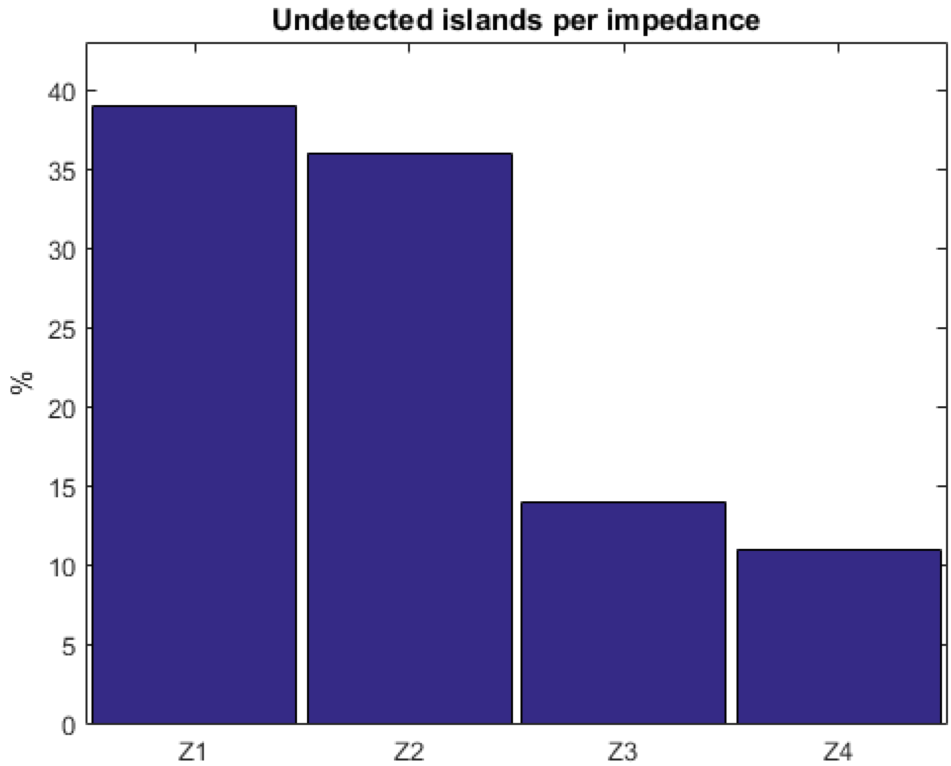
4.8 3ph Inverter - 1ph Inverters - Micro-inverter (Non-Linear Load)

The experiment with the inverter set (3ph Inverter, 1ph Inverter, Micro-Inverter) resulted the detection of the island condition at 72% of the cases. 28% of the cases couldn't be detected by the inverter set (Graph 20).



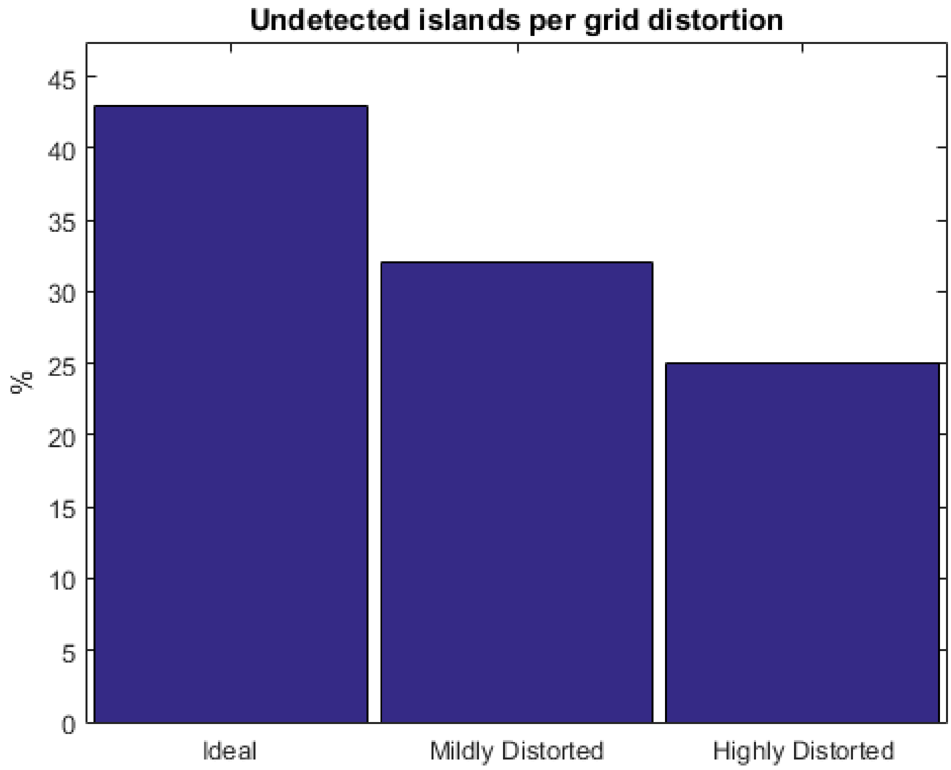
Graph 20

Most of the unsuccessful island detection cases regarding to the inverter set (3ph-Inverter – 1ph-Inverter, Micro-Inverter) occurred with weak grid (Graph 21).



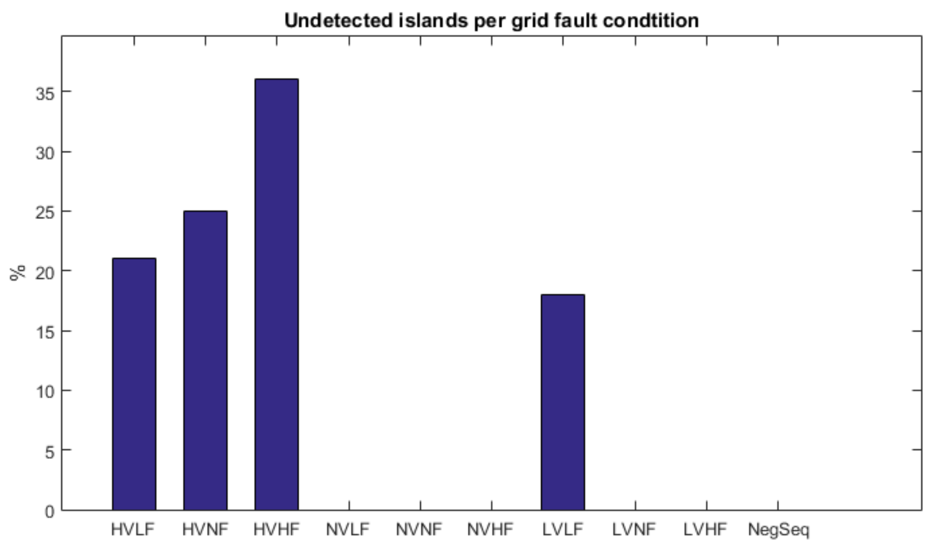
Graph 21

Graph 22 presents the number of undetected cases (%) in respect to the grid distortion.



Graph 22

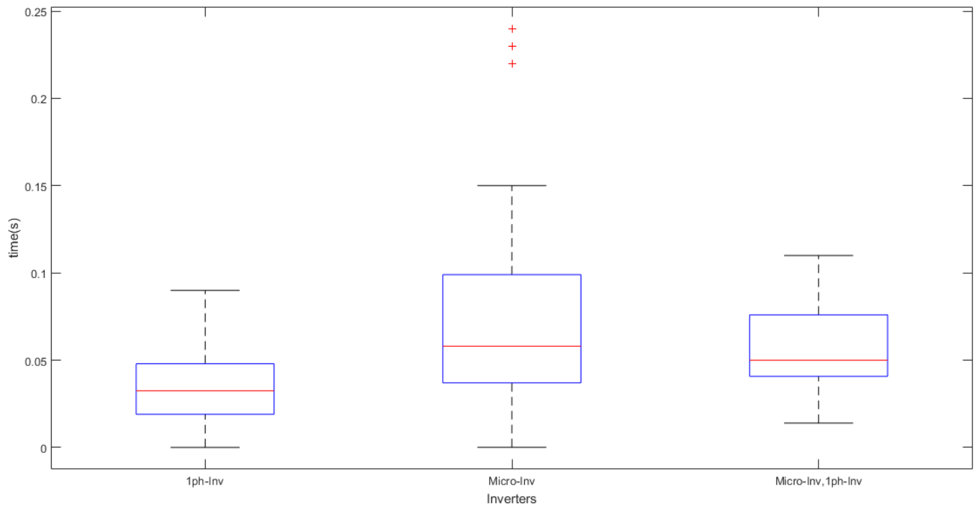
Graph 23 presents the number of undetected cases (%) regarding each fault condition of the grid.



Graph 23

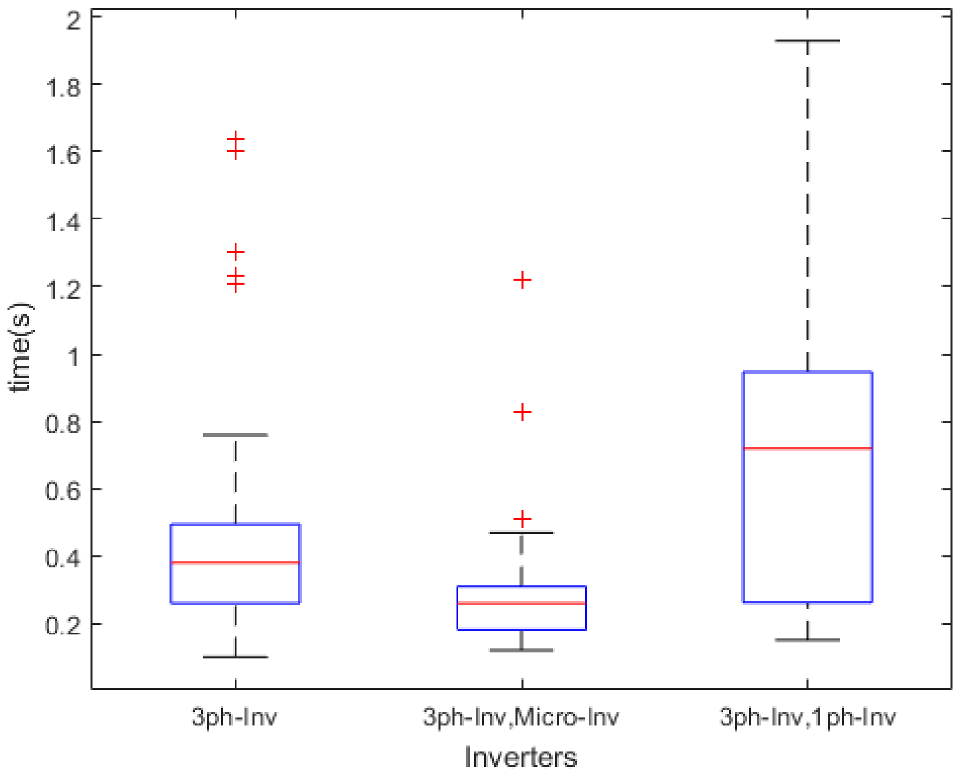
4.9 Comparative analysis

Graph 24 depicts the three combinations of the 1-ph inverter and 1-ph micro-inverter. It is clear that the 1-ph inverter detects the island faster than the micro-inverter. In addition, the distribution between the detection times among those inverters is significantly different, as the 25% mark is closer to the median in the 1ph-inverter round of measurements. Finally, a compromise is noticed when both inverters are connected. In any case, the detection time is within limits.



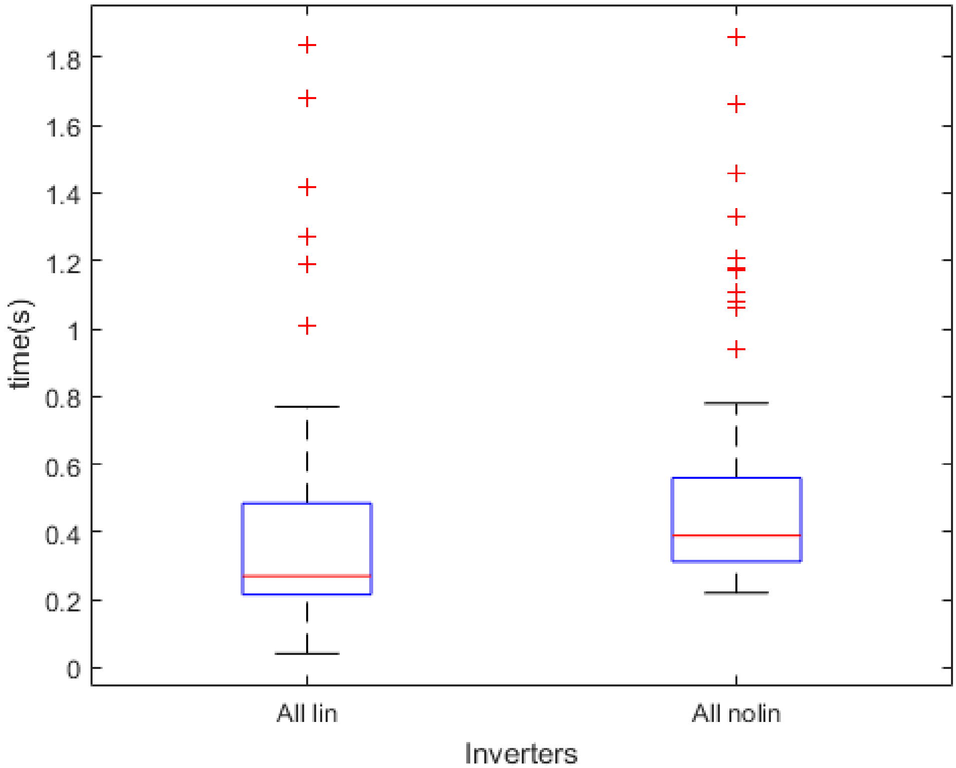
Graph 24

Graph 25 depicts the three rounds of measurements regarding the 3ph-inverter and its combination with 1ph-micro-inverter and 1-ph inverter. It is clear that when the 3ph-inverter and the micro-inverted were combined, the detection time was significantly shorter in comparison to the results for the 3ph-inverter alone. Even though the 1-ph inverter appeared to have the best detection time when it operates solely, each combination with the 3-ph inverter affected its operation.



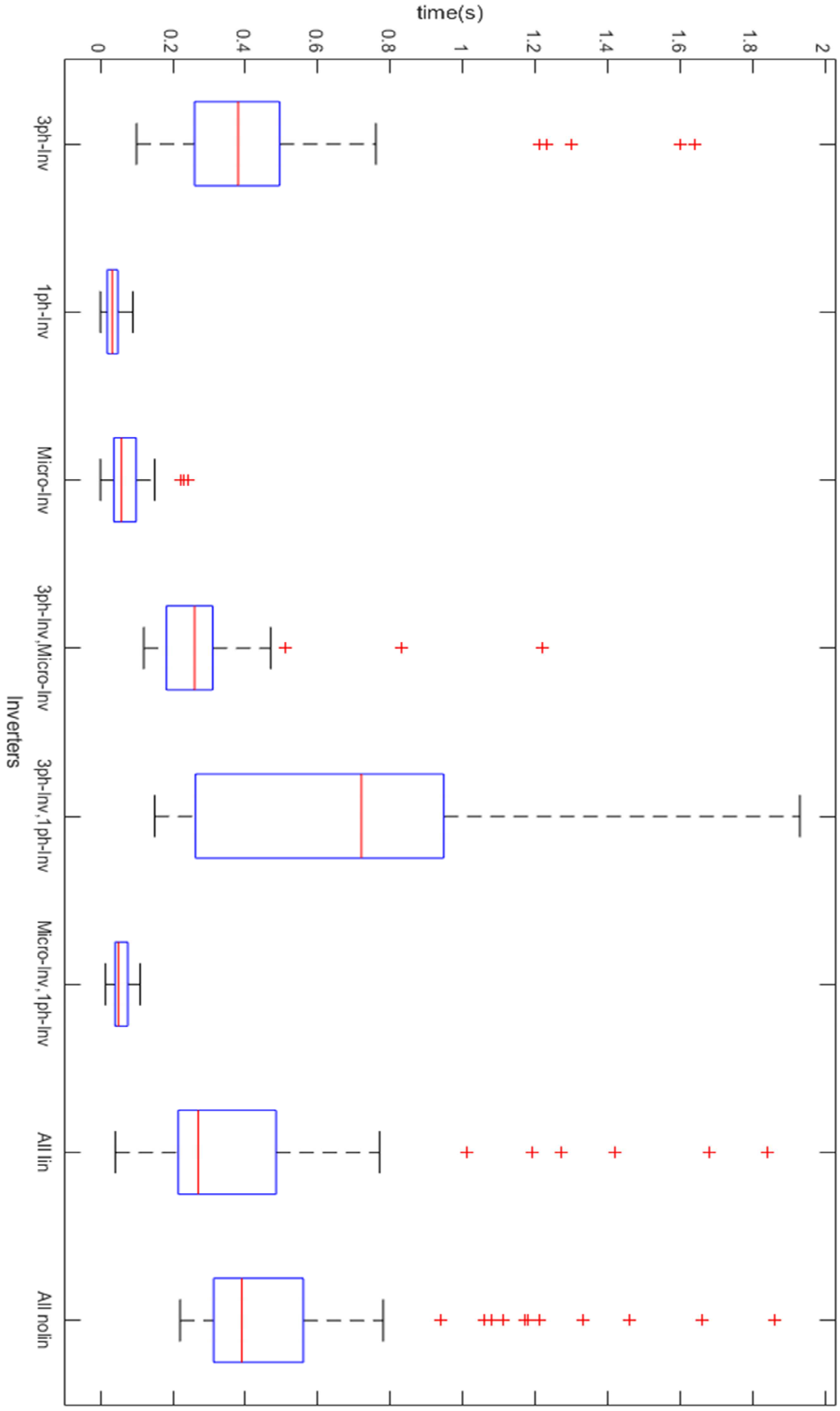
Graph 25

Graph 26 depicts the measurements regarding the linear and non-linear load. It is clear that the detection time of the island when the linear load is connected is shorter compared to the non-linear load. Furthermore, the median value in the case of the non-linear load is more centered in comparison to the linear load.



Graph 26

Graph 27, depicts a comparative analysis of all test cases.


time(s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
3ph-Inv
1ph-Inv
Micro-Inv
3ph-Inv,Micro-Inv
3ph-Inv,1ph-Inv
Micro-Inv,1ph-Inv
All lin
All nolin
Inverters

Graph 27

5. Conclusions

Active methods regarding reactive current components may fail to detect the island when the quality factor is close to 2.5, as the reactive current is limited by power quality standards.

Most of the islands that the 3ph-inverter fails to detect occurred during the high voltage-high frequency conditions and negative sequence conditions.

Most of the measurements that were undetected appeared to occur under strong grid conditions. Apparently, this is due to the anti-islanding algorithm of the inverter and its dependence on the short circuit level at PCC. Yet, this conclusion cannot be generalized, because other inverters presented different dependence on short circuit level.

There are no significant findings about the impact of grid distortion on successful island detection, as regards the 3-ph inverter.

Active methods that employ grid impedance measurement may present connection difficulties when the grid is mildly or highly distorted, especially at low line impedances. In some cases, the inverter failed to reach its nominal power. In other cases when the grid was mildly or highly distorted the inverter could not be connected.

The combination of 3ph inverter with 1ph-microinverter resulted to undetected island mostly under the negative sequence condition. In addition, we can observe a reduction in undetected islands in comparison with the 3ph inverter sole operation.

The combination of 3ph inverter with 1ph-inverter resulted to a reduction in undetected islands in comparison with the 3ph inverter sole operation. In addition, the detection time was significantly increased in comparison with both the 3ph inverter and 1ph inverter sole operation.

The combination of 1ph inverter with micro-inverter resulted to an improvement of the median value of the detection time compared to the micro-inverter sole operation, and a deterioration of the time response in comparison with the 1ph inverter sole operation.

The inverter set (3ph-inverter, 1ph-inverters, Micro-inverter) resulted to a decrease in the median time value of the detected island events in comparison with the 3ph inverter sole operation. On the other hand, the detection time was prolonged.

The presence of non -linear loads, clearly results to fewer unsuccessful island detections. On the other hand, this outcome shows that implementation of strict power quality improvement techniques at load side shall have a negative impact on anti-islanding algorithm performance.

Negative sequence conditions were involved in most of the undetected island occurrences. That condition is probable to exist on distribution networks, so research and standards should be focused on, in order to eliminate the undetected island events.

6. Experimental setup

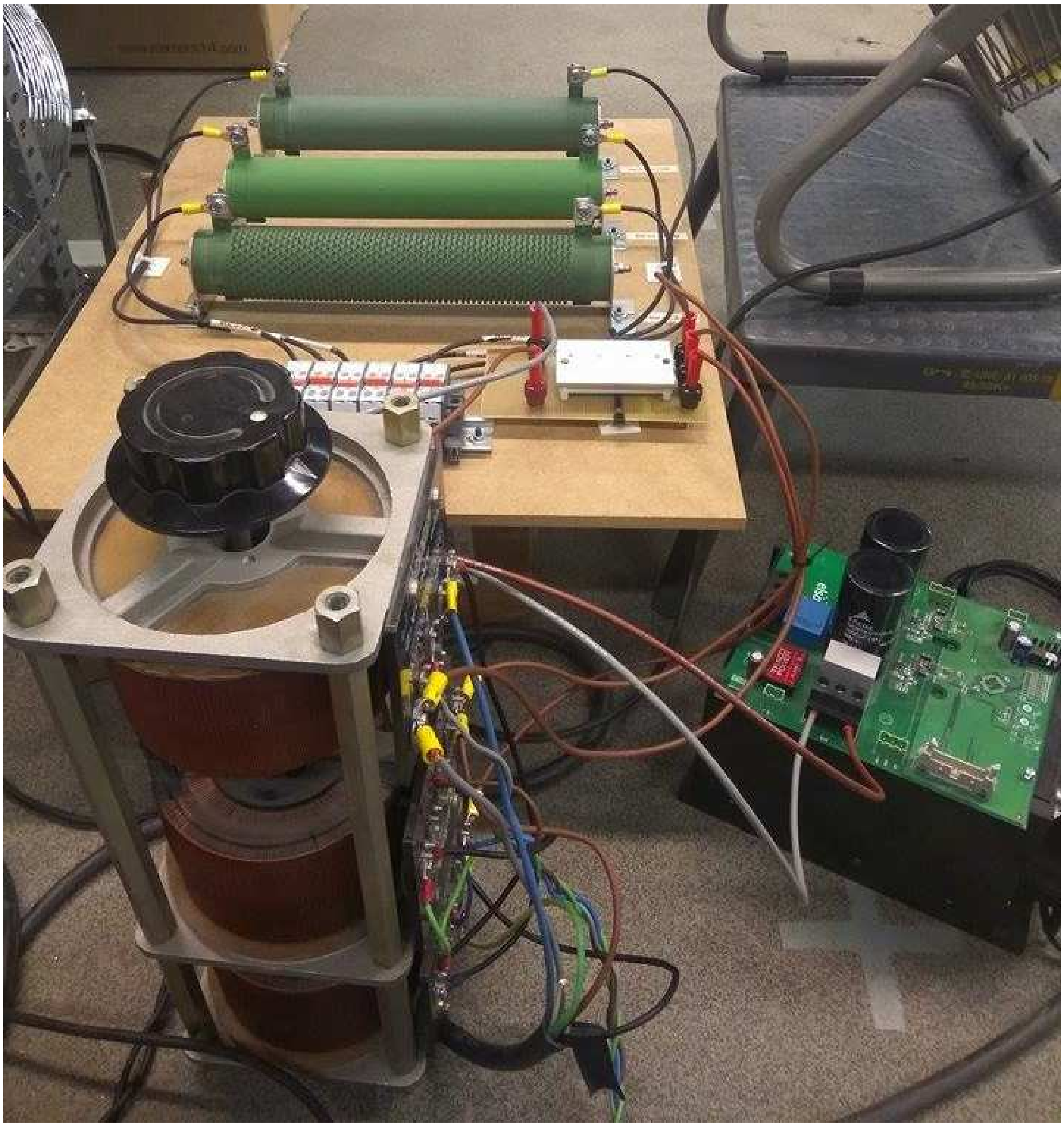


Figure 2: Non-linear load and linear load regulator

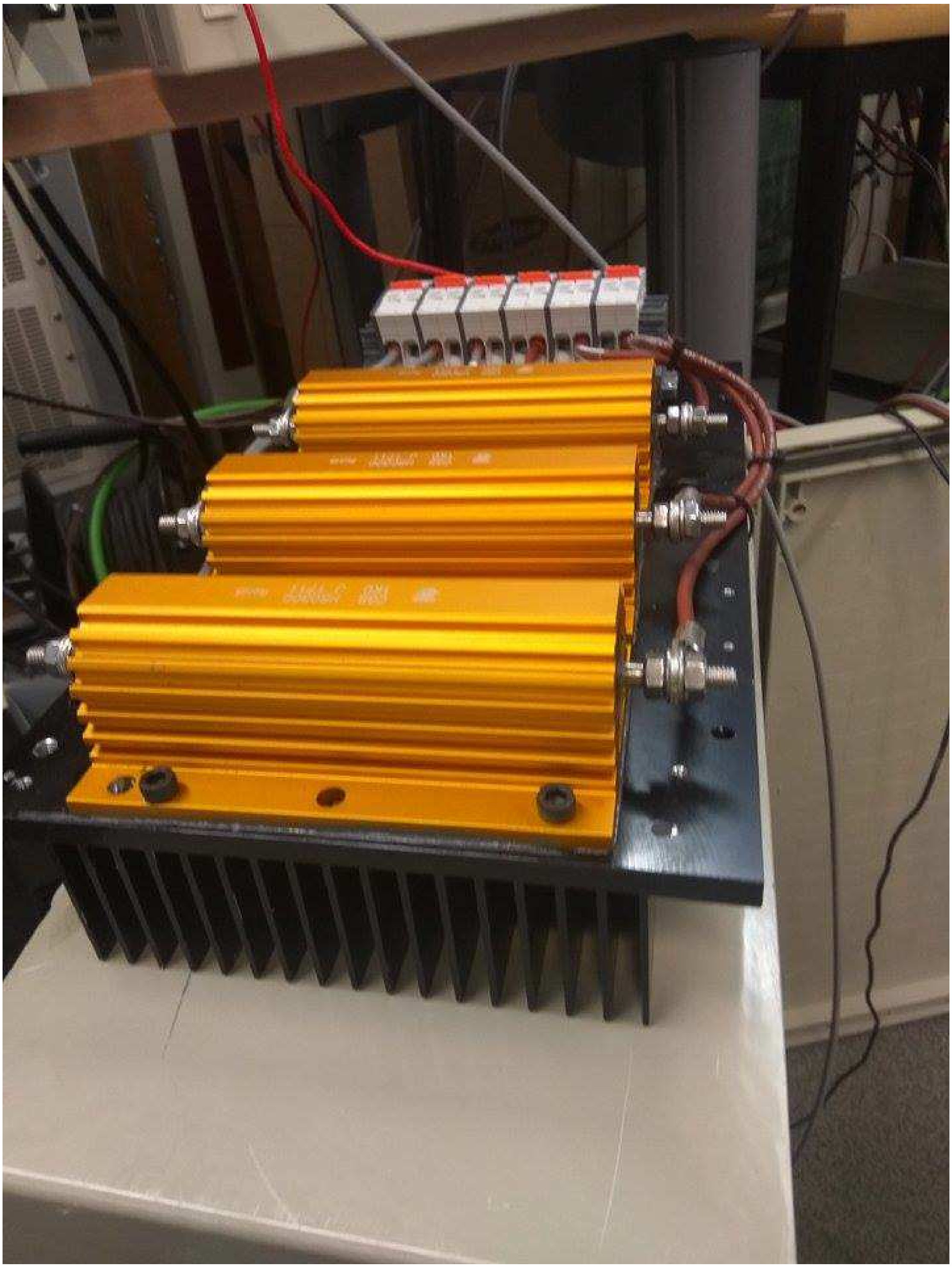


Figure 3: Parallel resistors for the voltage source

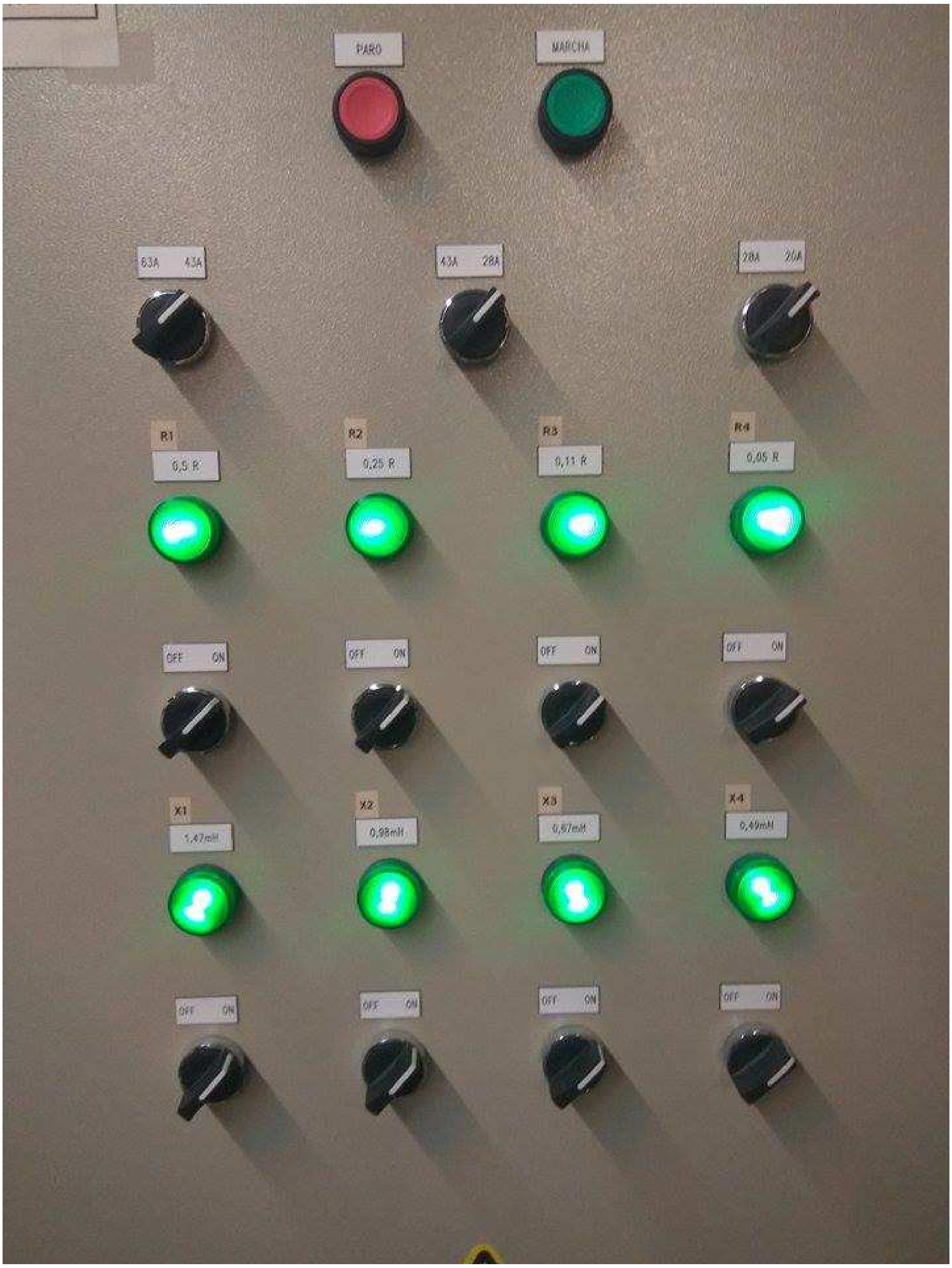


Figure 4: Line impedance

Figure 5: Inverters of the setup

Figure 6: Grid and Inverter switches

Figure 7: Parallel resistors for the PV emulator

Figure 8: Grid emulator

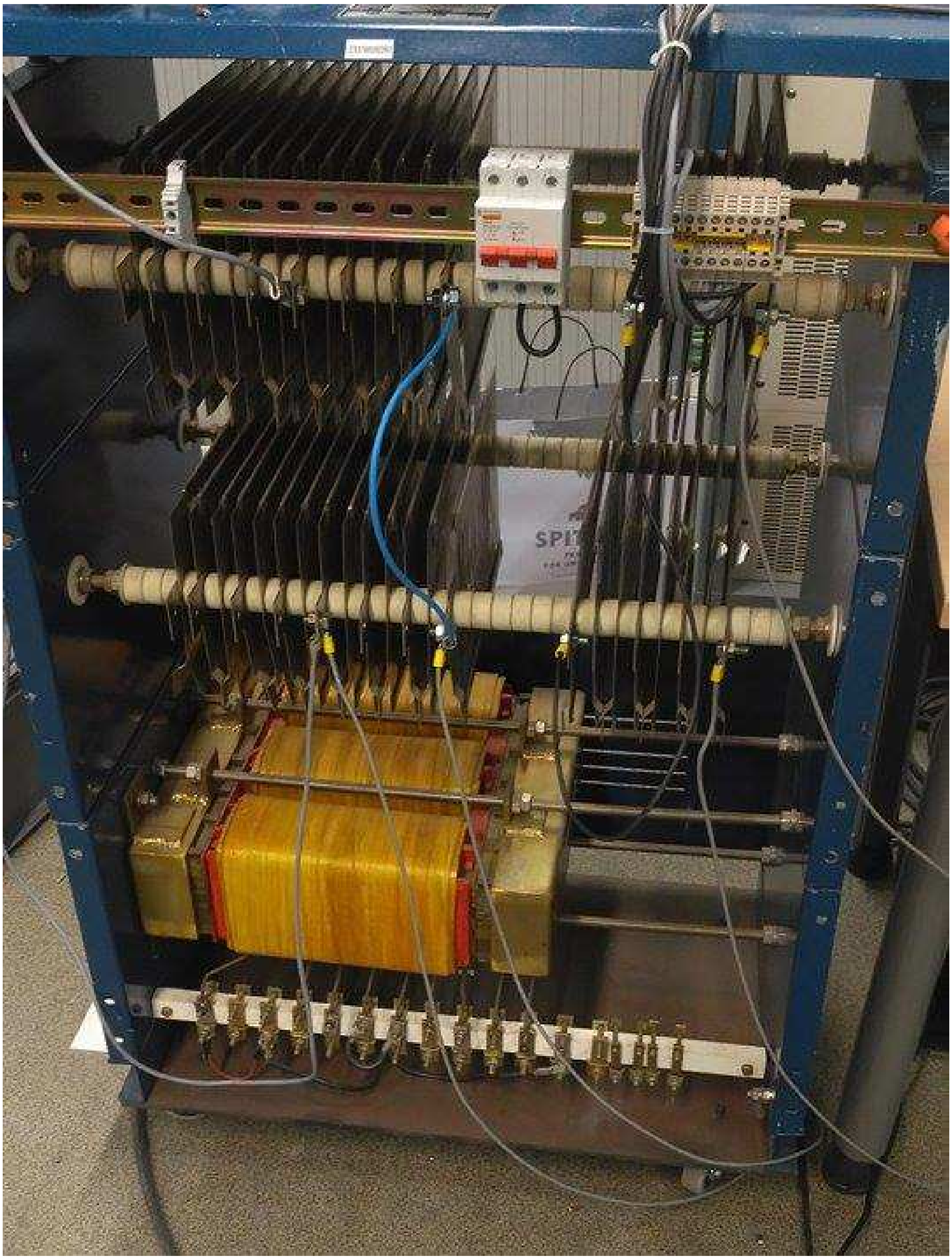


Figure 9: Series resistors for the PV emulator

Figure 10: Line impedances

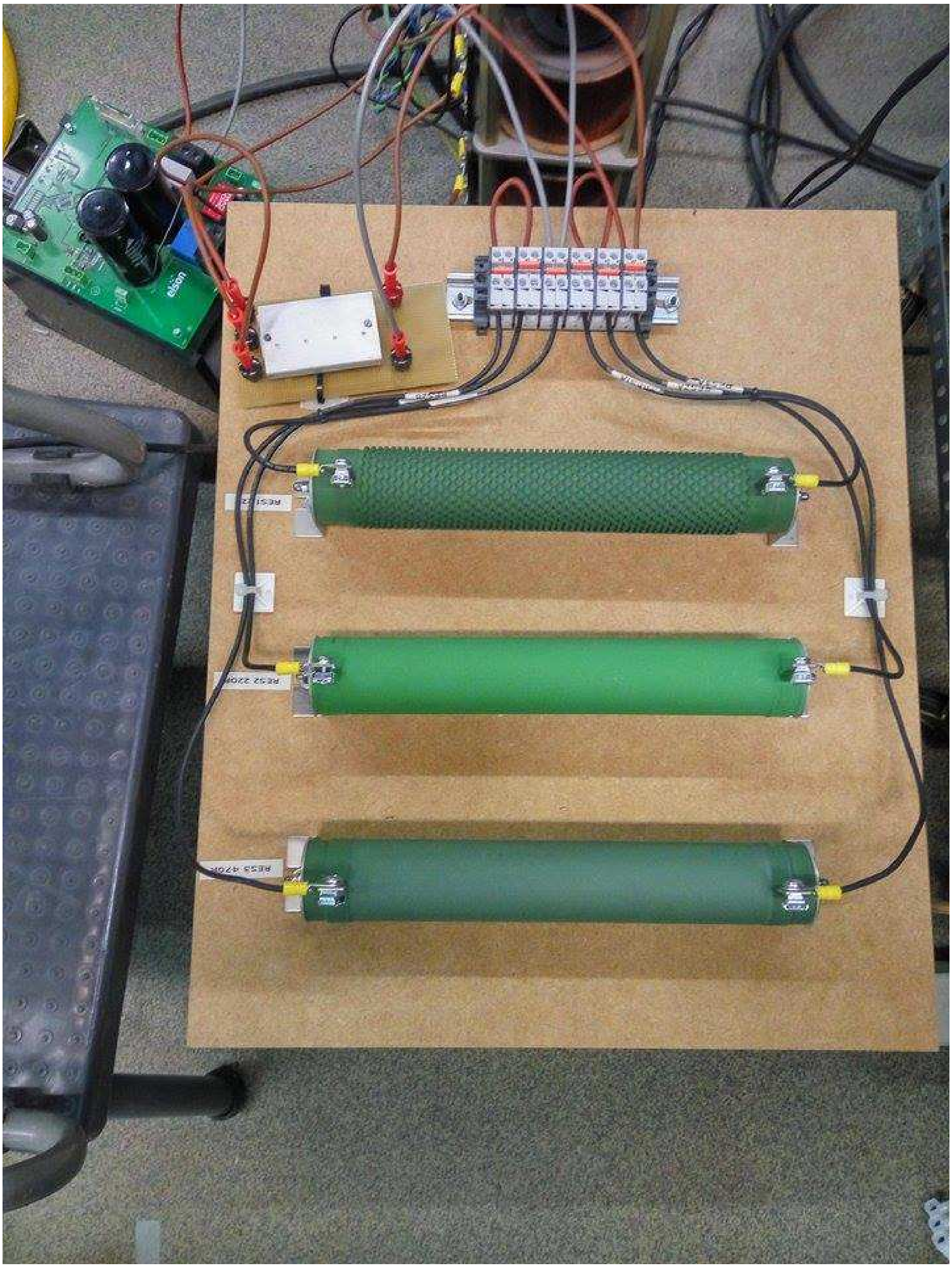


Figure 11: Resistors of the non-linear load

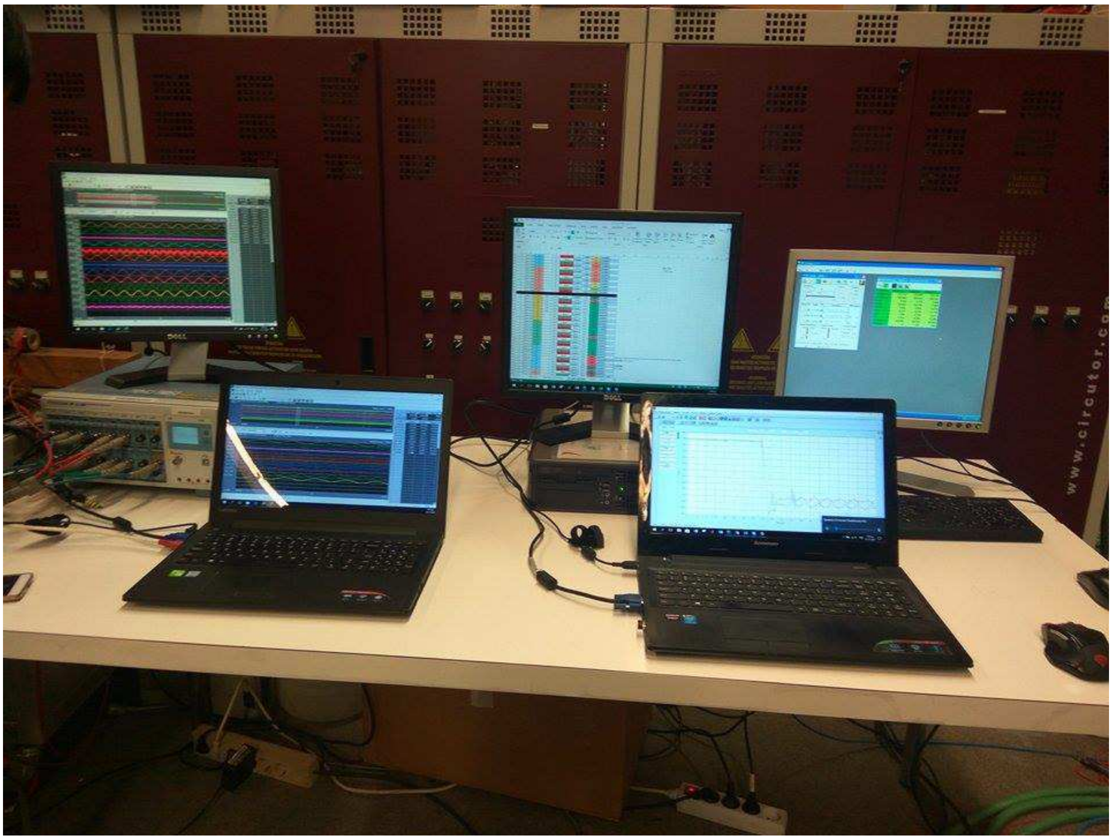


Figure 12: Data acquisition system

Figure 13: Voltage sources

Figure 14: Resistive and inductive load

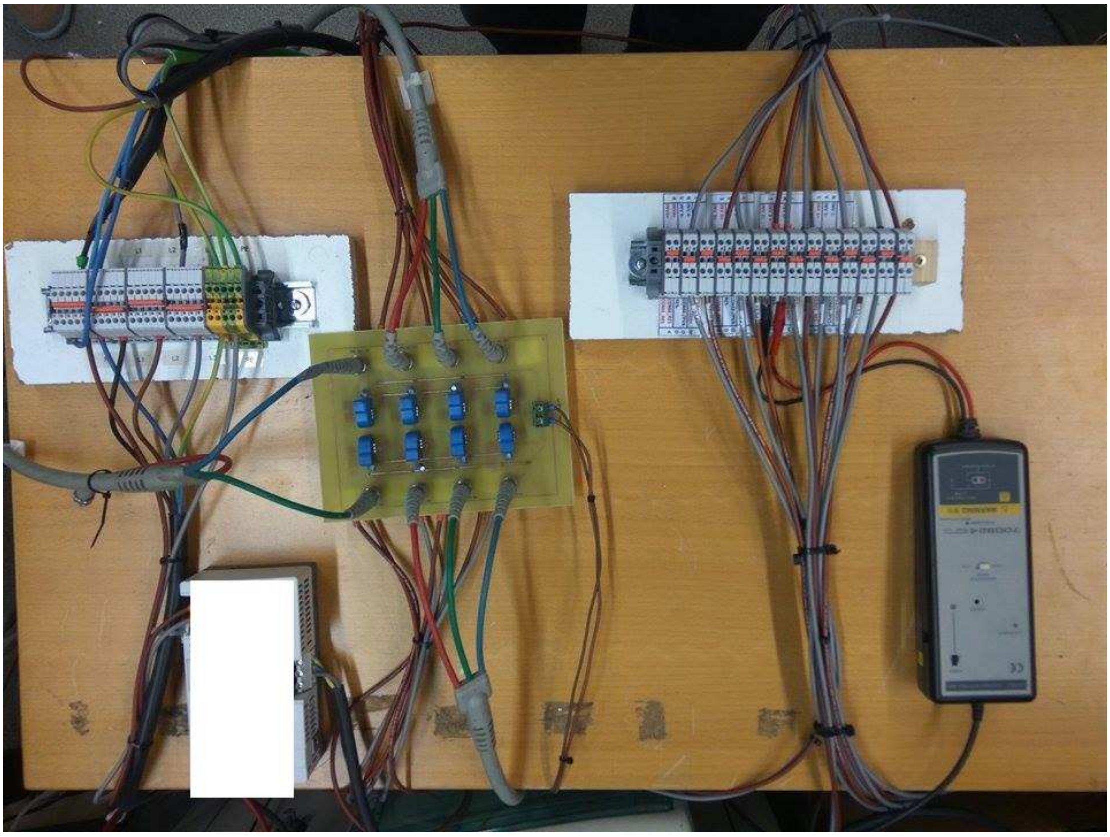


Figure 15: PCC of the experimental procedure