European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out

Technical Report TA User Project

CYPrus grid optimal integration and control of RES ParkS-CYPRESS

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Abbreviations

AIT	Austrian Institute of Technology
DER	Distributed Energy Resource
DFIG	Doubly Fed Induction Generation
DSO	Distribution System Operator
EAC	Electricity Authority of Cyprus
EMTP	Electromagnetic Transients Program
EPS	Electric Power System
HiL	Hardware in the Loop
KPIs	Key Performance Indicators
LVRT	Low Voltage Ride Through
PoC	Point of Connection
TA	Trans-national Access
TSO	Transmission System Operator
RES	Renewable Energy Sources
RMS	Root Mean Square
RoCof	Rate of Change of Frequency
SGC	Smart Grid Converter

Executive Summary

The electrical power network of Cyprus is slowly migrating from a centralized generation system to a decentralized/distributed generation one, with high shares of renewable energy sources (RES), with wind and especially solar energy playing a central role.

As a matter of fact, in the forthcoming years the penetration of solar energy is expected to grow to 30% of total electrical power supply, with this percentage steadily increasing further in the future. Unlike the majority of power systems in central Europe, which are interconnected together, in Cyprus the electrical power network is autonomous and islanded, not yet interconnected to a larger and bulk power system, establishing stability and robustness. This as a consequence, poses challenges in terms of stability, robustness, resilience, reliability and security of supply when high penetration of variable in nature, distributed energy resources (based on static power electronics converters operation) will be a reality.

These critical attributes and challenges of the Cyprus power network need to be further analysed and observed, beyond computer-based simulations and related analysis. Of course, studying them in the field is not a realistic option due to the following reasons:

- PV is highly dependent on irradiance and temperature.
- Full-load tests required by grid codes are not allowed by Operators, and hence impossible to be carried out.
- High costs associated with field tests in PV.
- Lack of flexibility.
- Risk of equipment
- Risk of security of supplies.

Having said that, testing with the help of Hardware in the Loop (HiL) infrastructures are of critical importance. Figure 1 shows the general configuration of a possible PV testing setup along with the power system.

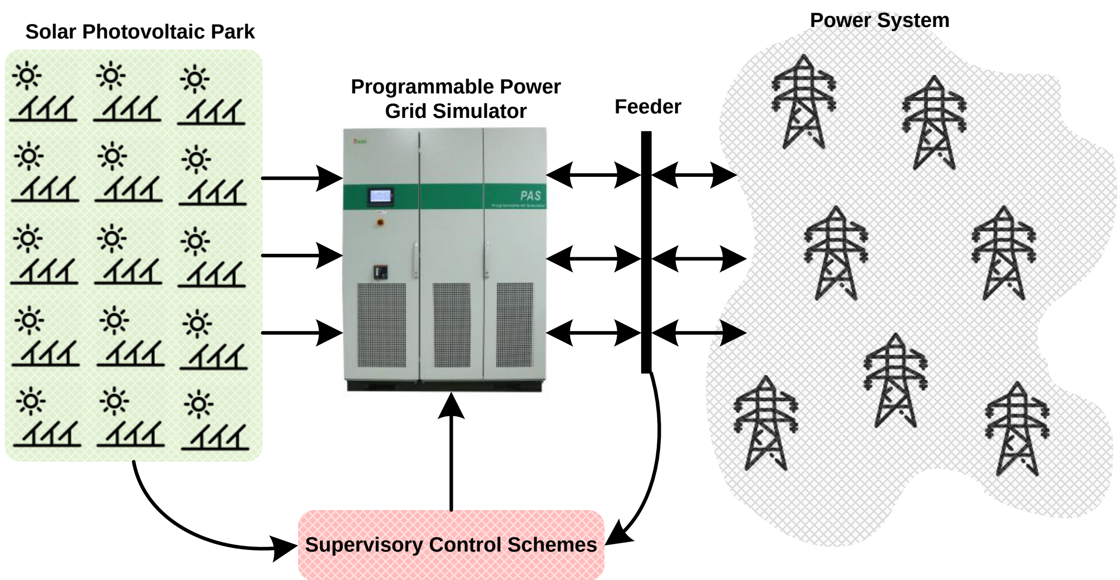

***Figure 1** Overview of the Hardware in the Loop (HiL) configuration synthesizing the solar photovoltaic park, electrical feeder interconnection with the power system, and the developed supervisory control schemes ensuring an optimal integration of the PV park to the grid*

The real-time simulation tests that were performed through the Hardware in the Loop (HiL) framework hosted at the AIT premises, are of high importance for the TSO and DSO operators of Cyprus. These tests reflect a range of different scenarios and realistic test cases of integration of a solar photovoltaic park in the power network of Cyprus.

The scale up of these tests will offer a good insight of the networks for the operator. They also reveal important results associated with power system stability, optimal power flow exchange (active/reactive) between solar park and grid, power flow control and fault right through capabilities. These achieved results are presented in this report.

General Information of the User Project

USER PROJECT PROPOSAL	
User Project acronym	**CYPRESS**
User Project title	**CYP**rus grid optimal integration and control of **RES** Park**S**
Main scientific/technical field	Photovoltaic Grid Integration on the Power System
Keywords (5 max., free text)	Active Power Control, Frequency Control, Reactive Power Control, Stability Control, Voltage Control
Host Research Infrastructures	AIT Austrian Institute of Technology
Starting date for the access	02/September/2019

1 Research Motivation

The research motivation for CYPRESS project stems for the main operational challenges that the DSO confronts- in some extend now and with more intense in the future- due to the high rate penetration of the RES and especially PVs. These challenges differ from the ones that the operators of the main Europe commonly deal with, as the Cyprus grid has no interconnections with other grids.

For the time being, extensive studies through simulation tools were applied for certain operational challenges that are of high priority for the grid operation i.e. anti-islanding testing and LVRT capabilities of the PV inverters. But, these studies cannot mirror the real conditions or capture the interactions between the active assets and the grids.

Having said that, the main motivation of this project is to study the impact and the interactions that a PV system have with a real part of the Cyprus grid under certain events and under different control logics that offer system support capabilities. Of course, a scaling up of these results for an increased rate of penetration is of great use for the DSO and the future studies. Figure 2 presents the sequence of the steps that lead to the motivation of the CYPRESS project.

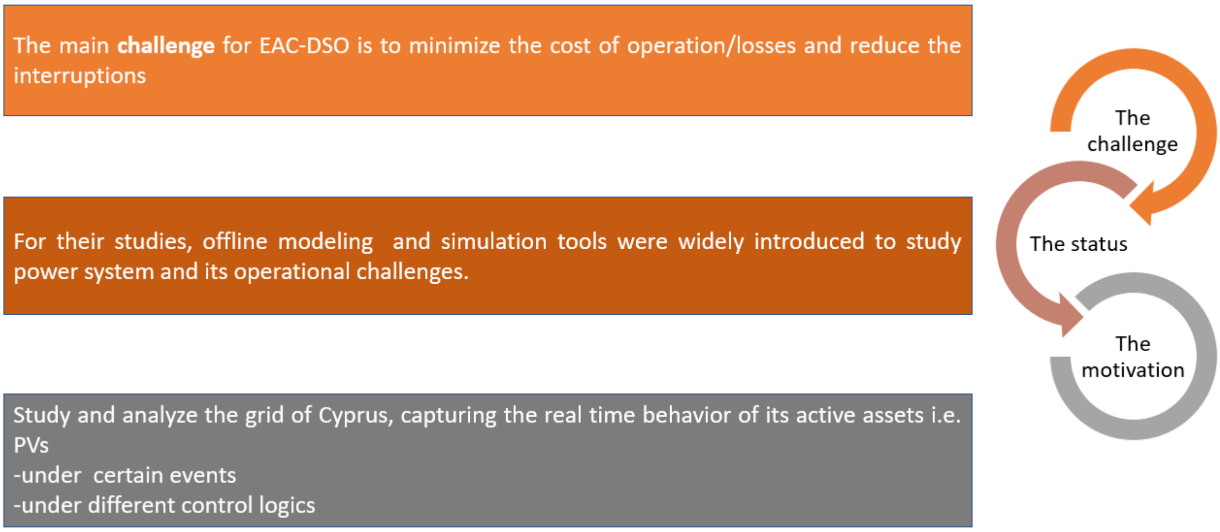

Figure 2 *The motivation for the CYPRESS project.*

1.1 Objectives

The goal of this project was to perform different testing and validation experiments concerning grid integration of selected photovoltaic parks in Cyprus connected on the main power grid. Currently, industry and research communities are mainly relying on off-line modeling and simulation on computer-based tools for power system analysis. This category of products provide insight on RMS system variables (power, voltages, currents) on selected nodes/busbars and steady state power flows within the network . In addition, the grid integration impact of solar photovoltaic parks are modelled utilizing simplistic EMT or average RMS type models of the studied elements provided by the manufacturers. Such models, typically, reflect the response of photovoltaic converters to a number of certain test cases recorded in lab environment and do not represent and implement the holistic control and protection system of the overall power conversion system. Transient behaviour and response during short circuit fault incidents or other abnormal conditions (generation-load imbalance) might not be appropriately reflected or captured by these average models.

Considering the specifics of the Cyprus power system, in terms of sensitivity to penetration of distributed generation, a thorough and detailed grid integration study, exceeding the technical boundaries of software simulation environments, utilizing a Hardware in the Loop (HiL) platform was performed. The hardware in the loop (HiL) technology provides full insight and intricate details of real time behaviour of the selected feeders with integrated solar parks.

The ultimate goal of this project was to perform realistic test cases and validation procedures based on state-of-the-art HiL infrastructure, to examine the feasibility, interaction and potential natural phenomena (over-voltages, high frequency harmonics, reversed power flows, reduction of system inertia, system stability issues, system frequency response) caused as a result of grid integration of a solar photovoltaic park on the main grid.

Following this first phase, mitigation strategies and control schemes enabling a smoother and optimal integration of the PV park, with respect to stability, optimal power flows, enhanced system frequency response, security and reliability of operation and service will be studied, analyzed, and thoroughly tested.

1.2 Scope

The scope of this project is to initiate grid integration studies of selected Photovoltaic parks integrated on the islanded power system of Cyprus. Up to date, industry and research communities were heavily relying on off-line modelling and simulation software-based tools for power system analysis studies. As already mentioned, such tools provide insight on RMS system variables (power, voltages, currents) on certain nodes and power flows between feeders. Furthermore, the grid impacts of solar parks are modelled based on simplified positive sequence EMTP or average "RMS" type models of the studied elements provided by the manufacturers.

Having already outlined the specifities of the Cyprus power network, in terms of being more susceptible to penetration of renewable generation, a thorough and detailed grid integration study, beyond software simulation environments, utilizing Hardware in the Loop (HiL) technology was performed.

2 State-of-the-Art

Renewable Energy Sources (RES), Distributed Energy Sources (DER) or Distributed Generation (DG) grid integration is a field of study that attracted a significant attention in recent years due to the newly established decarbonized policies established by European Union and the need to replace conventional synchronous generators. Scientific and research community turned their attention into the detailed analysis and study of photovoltaic systems, as well as wind parks grid integration and interaction, and the benefits these technologies can offer to the system with respect to system stability, optimal power flow control, voltage regulation, frequency control, and synthetic inertia provision. Several studies have been contacted analyzing all these elements and control actions that can be achieved through RES technologies, as well as the impacts these have on the power system. The study performed in [1], underlines the impact increased penetration of photovoltaic generation has on the performance measures of a power system, whereas large-scale and distributed solar Photovoltaics (PV) integration studies analyzing their impact on transmission and distribution grids have been performed and recorded on actual power networks around the world [2], [12], [13], [15]. A considerable research undertaken in this field focus on the stability metrics (small signal stability, transient stability, inter-area oscillations, damping performance) PV integration has on the power network [2], [3], [9], [10], [12], [15]. Furthermore, attention was also drawn on the frequency stability and synthetic inertia provision of photovoltaic systems [6], [7], [13], as well as the fault right through flexibility offered by these technologies [4]. As it is well known, large photovoltaic systems and electrical voltage of the feeder at the point of common coupling (PCC) are highly depended, a significant research was also undertaken on the field of voltage control through sophisticated operation of the PV power electronic inverters [7], [11]. In addition to the above, potential benefits of PV parks grid integration have been examined by authors in [5] and [8], where independent control of active and reactive power flow is analyzed and reported. Finally, the research community has also engaged with the integration of Doubly Fed Induction Generators (DFIG) wind farms on the power grid, which is a well-established and mature technology by now, offering a number of benefits, especially in synthetic inertia provision and inter-area power oscillation damping control [13], [14]. Focus of this proposal will be given on the integration of solar PV parks on the Cyprus power system.

The aforementioned technologies and innovations established and repeatedly reported and validated in open literature, have not yet been accommodated and applied on the islanded power network of Cyprus, and as a result, there is a potential gap of test cases and validation tests, examining the smooth integration and interaction of photovoltaic parks with the power system, especially through the use of a real-time simulation environment, such as a Hardware in the Loop (HiL) test platform [16], [17], [18].

Therefore, there is an urgent need by research community, industry and Transmission System Operators (TSOs)/Distribution System Operators (DSOs) for realistic test cases and validation tests based on HiL infrastructure to examine the feasibility, interactions and potential effects that the increased integration of solar parks have on Cyprus power system performance and healthy operation.

3 Executed Tests and Experiments

According to the above approach, a series of tests were performed under the following configuration (Fig.3):

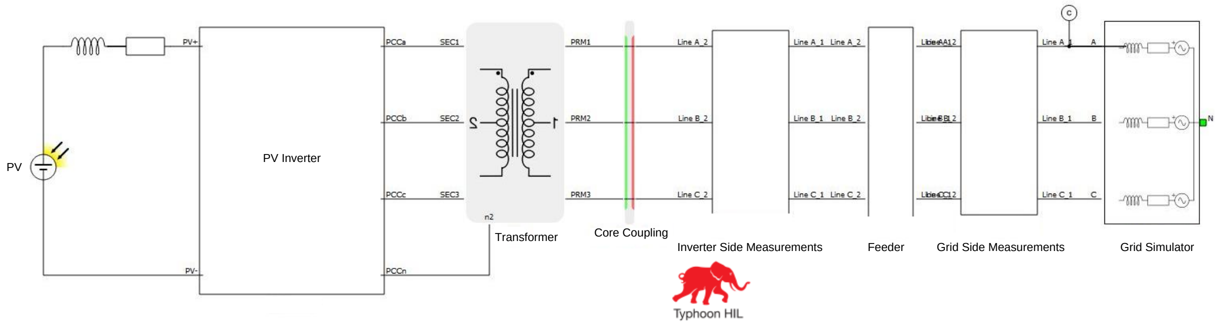

Figure 3 Modelling the PV system integrated distribution feeder on Typhoon HIL (v2019.3) control hardware in the loop environment.

More details for the system configuration will follow in the next subsections. Three series of testing were performed, namely:

-Anti-Islanding functionalities: The anti-islanding functionalities of the PV inverter due to loss of mains according to IEEE1457.

-LVRT studies: The PV inverter capability of supporting the voltage and hence serving the grid with ancillary services.

-**Rocof studies:** Study and analysis of the Rocof measurements on the feeder in relation to the PV integration.

-Studies where the stability of the system was tested under change in the irradiance e.g. cloud passing

3.1 Test Plan

HIL Setup and Configuration

Figure 4 demonstrates the synthesis (set-up) between the Controller HIL (CHIL) based the Typhoon HIL 602+ hardware infrastructure and Typhoon HIL (v2019.3) software environment, the PV inverter (with control features), modelled on the AIT SGC HIL controller, and the computer unit (user interactive interface). The system comprises of the PV plant, the PV inverter, a step-up transformer, the medium voltage feeder (with corresponding measurement devices installed at the inverter side and grid side), and the distribution grid simulator.

3.2 Standards, Procedures, and Methodology

3.2.1. Standards used in the test

IEEE 1547-2018 for PV inverter

This standard establishes criteria and requirements for interconnection of DER with electric power systems (EPS), and associated interfaces. These requirements are mandatory, uniform, universal and apply at the PCC or Point of DER Connection.

So, this standard was followed throughout the two first series of testing i.e. the anti-islanding testing and the LVRT testing of the PV inverter to induce some useful results for the capabilities of the controllers to meet the requirements of the standard. Figure 5 shows the level of response of DERs showing the hierarchy of the standard's requirements, while Figure 6 shows the disturbance performance terminology. When we are referring that a DER" ceases to energize" we:

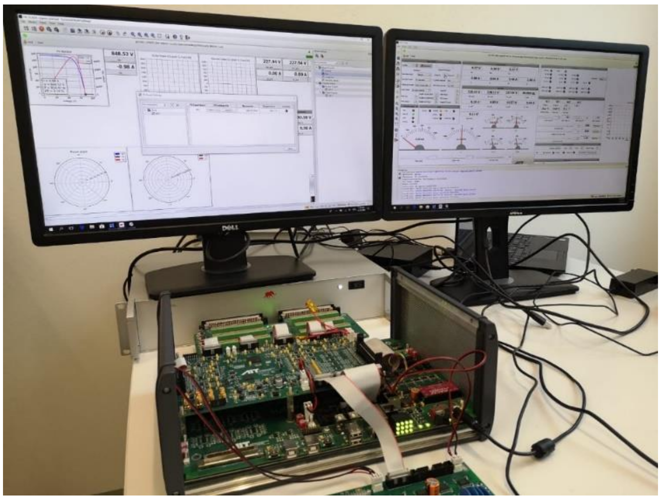

Figure 4 Typhoon HIL (v2019.3) control hardware in the loop configuration utilizing a PV power electronic inverter and an intel Core i7-8850H CPU, 2.60GHz, 16GB RAM computer unit.

- Refer to Point of DER Connection (PoC) of individual DER unit
- Mean no active power delivery
- Limitations to reactive power exchange
- Do not necessarily mean physical disconnection
- Used either for momentary cessation or trip

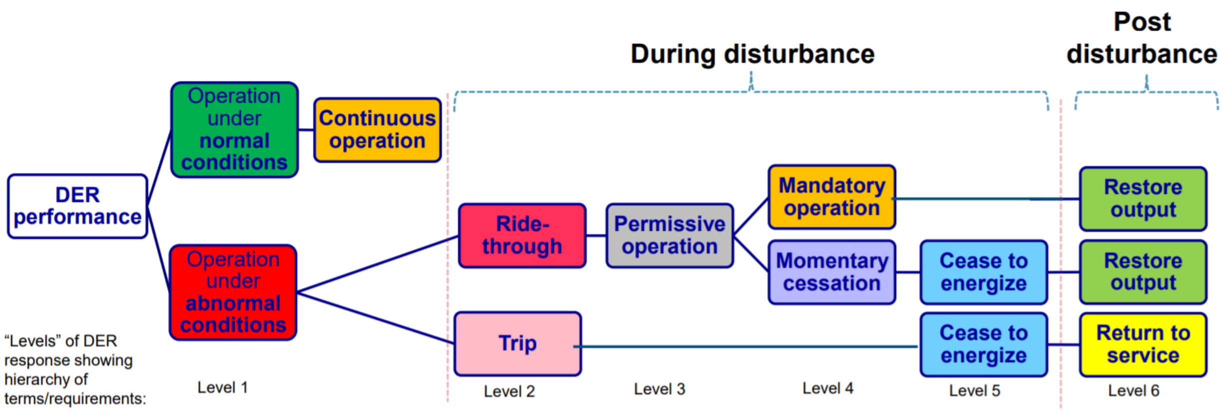

Figure 5 Hierarchy of the standards requirements [19]

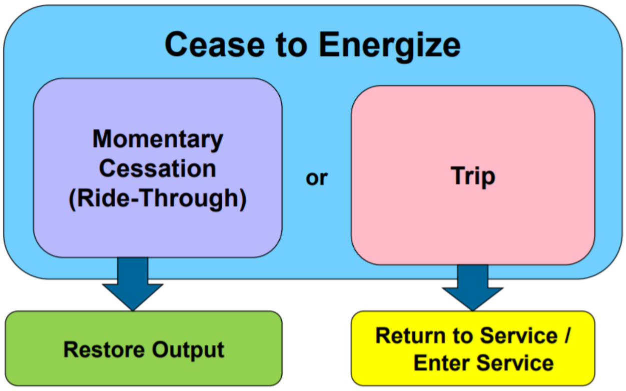

Figure 6 Disturbance performance terminology [19]

3.2.2 Procedures within testing

ROCOF protection technical requirements within DSO of Cyprus (EAC)

RoCoF relays are mandatory for all distributed generators connected to the grid for securing islanding requirements thus acting as anti-islanding protection to connected consumers from being supplied not quality supply from the connected DGs since the mains have been disconnected.

RoCoF relays are mandatory to be set to 1.7 Hz/sec as the threshold setting to be sustained for 600 msec. If higher values prevail for longer times than 600 msec the relay operates and isolates the DG since this is the proof for a disconnected system.

Hence, any investigation carried out at AIT simulated system should answer to the following questions that are not known to the DSO:

- The connected inverter supplying power from the PV park with the RoCoF relay set to the above setting does it really operate after 600 msec, thus implementing isolation in case of prevailing islanding conditions?
- Under high penetration of PV resulting in an interconnected system with lower inertia under what penetration the RoCoF under a normal fault on a section of the system generates a rate of change of frequency which is higher than 1.7 Hz/sec for more than 600 msec thus condition for isolation hence unnecessary tripping of PV parks that can lead to total black out conditions hence unstable, thus calling for use of electronic inertia coming from a combination of appropriate battery and power electronics

Reactive power requirements for inverter within DSO of Cyprus (EAC)

Figure 7 shows the reactive power requirements for interconnected inverters in Cyprus grid. According to the cosφ of the system certain amount of reactive power is required (to be injected or absorbed).

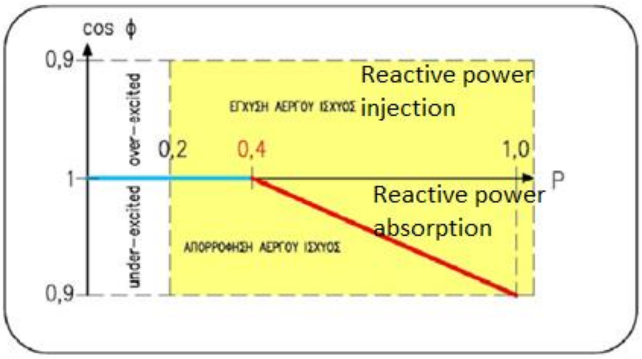

Figure 7 Reactive power requirements for inverters

3.2.2 Network model

In the next figure, the network model under testing is shown. As already mentioned, this is a part of the real distribution grid of Cyprus and the highlighted feeder is the one under testing for a case where the PV inverter is connected at the end of the feeder. An intentional selection of this site was made as the PV integration may impact on overall power system stability as well as indicate the performance of the developed PV inverter controllers in the next.

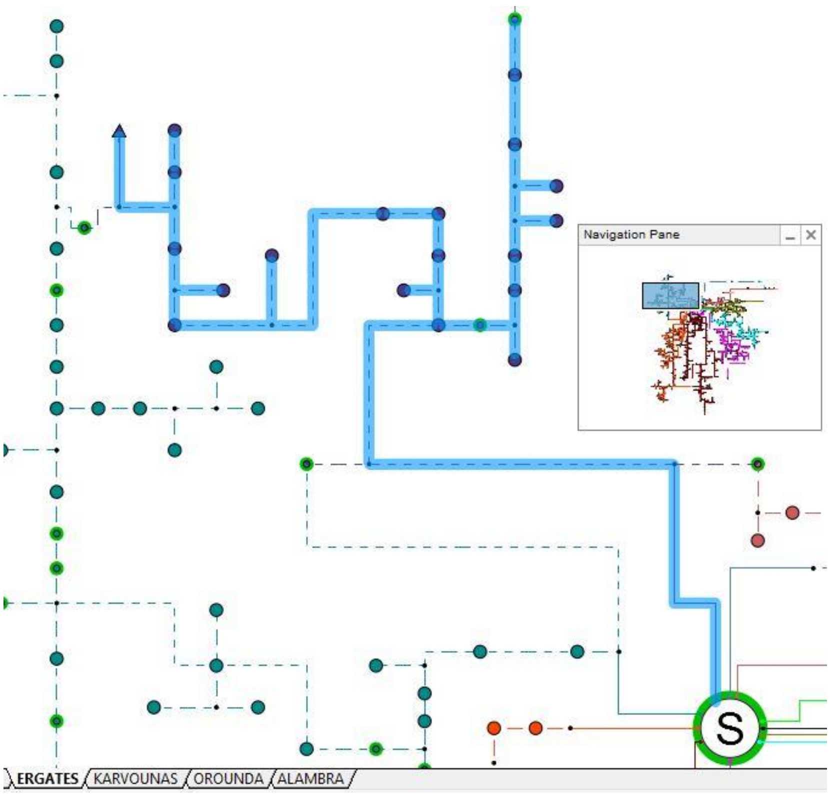

Figure 8 Network model under testing

3.3 Test Set-up(s)

For performing grid integration studies of a selected Photovoltaic park integrated on the island power system of Cyprus the following main equipment was employed:

- Typhoon HIL 602+
- AIT Smart Grid Converter Controller card B model
- AIT HIL Controller

Figure 9 shows the setup of the feeder along with the measurement points.

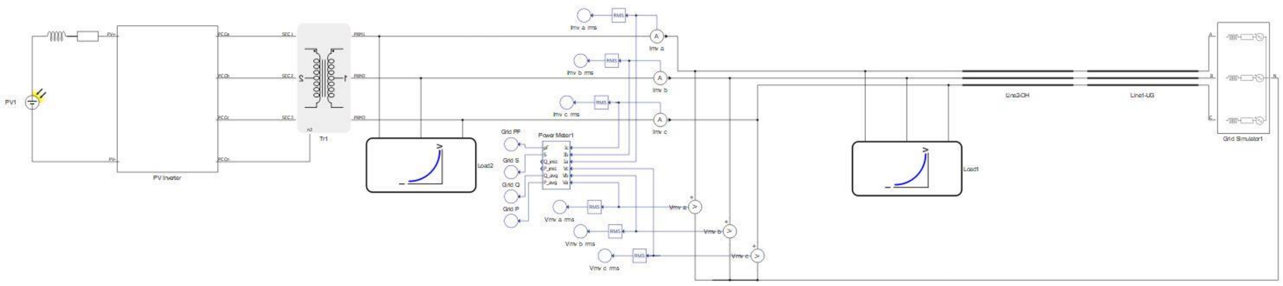

Figure 9 Modelling the PV system integrated distribution feeder on Typhoon HIL (v2019.3) control hardware in the loop environment with loads and measurement details.

Also, for modelling purposes the following were used:

- Models as Typhoon HIL files
- Time series of the Typhoon HIL scope data
- Scopes from the ASGC internal scopes, but it seems that only the graphics was copied
- Firmware of the ASGC, adopted for the solar park

The solar park PV arrays and modules were modelled according to PV module published data considering module temperature and irradiation. The PV panel taken under consideration is included in Annex1.The solar park PV inverters were modelled with aggregated AIT's Smart Grid Converter (SGC) PV inverter. The rest of solar photovoltaic park power system components, such as transformers and switch gears, will be modelled accordingly. The feeder data was modelled according to existing DIgSILENT PowerFactory feeder data provided by Electricity Authority of Cyprus (EAC).

Throughout the testing the following data are monitored and recorded.

- Frequency and RoCof in three different parts of the feeder
- Voltage throughout the feeder
- Active and Reactive power
- Currents in all phases

Figure 10 shows the monitoring panel of the system under test

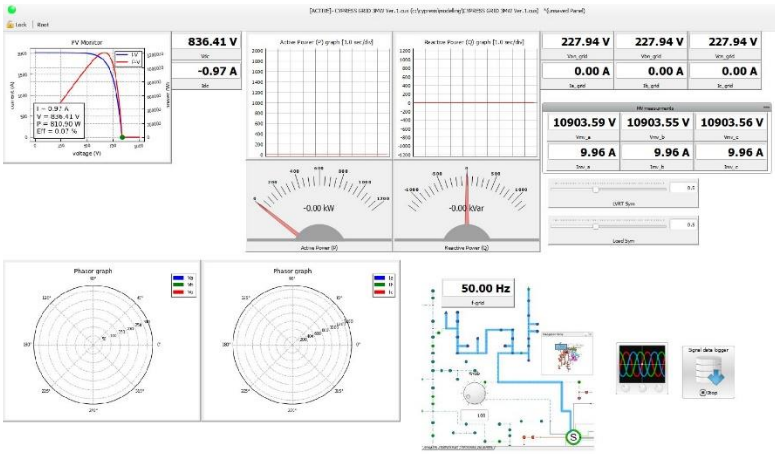

Figure 10 Monitoring panel of the system under testing

4 Results and Conclusions

Anti-Islanding functionalities: The anti-islanding functionalities of the PV inverter due to loss of mains according to IEEE1457 were tested.

As dictated by the standard, due to an abnormal situation i.e loss of mains in this case, the inverter protection needs to trip and cease to energize the grid within 2 sec. As seen in Fig.11, when no anti-islanding functionalities are enabled within the inverter, the protection of the grid disconnects the inverter within 0.1 sec. When anti-islanding protection is enabled, the inverter within msecs cease to energise the grid and disconnects. This time difference is diminishing the risk of equipment and operation many folds.

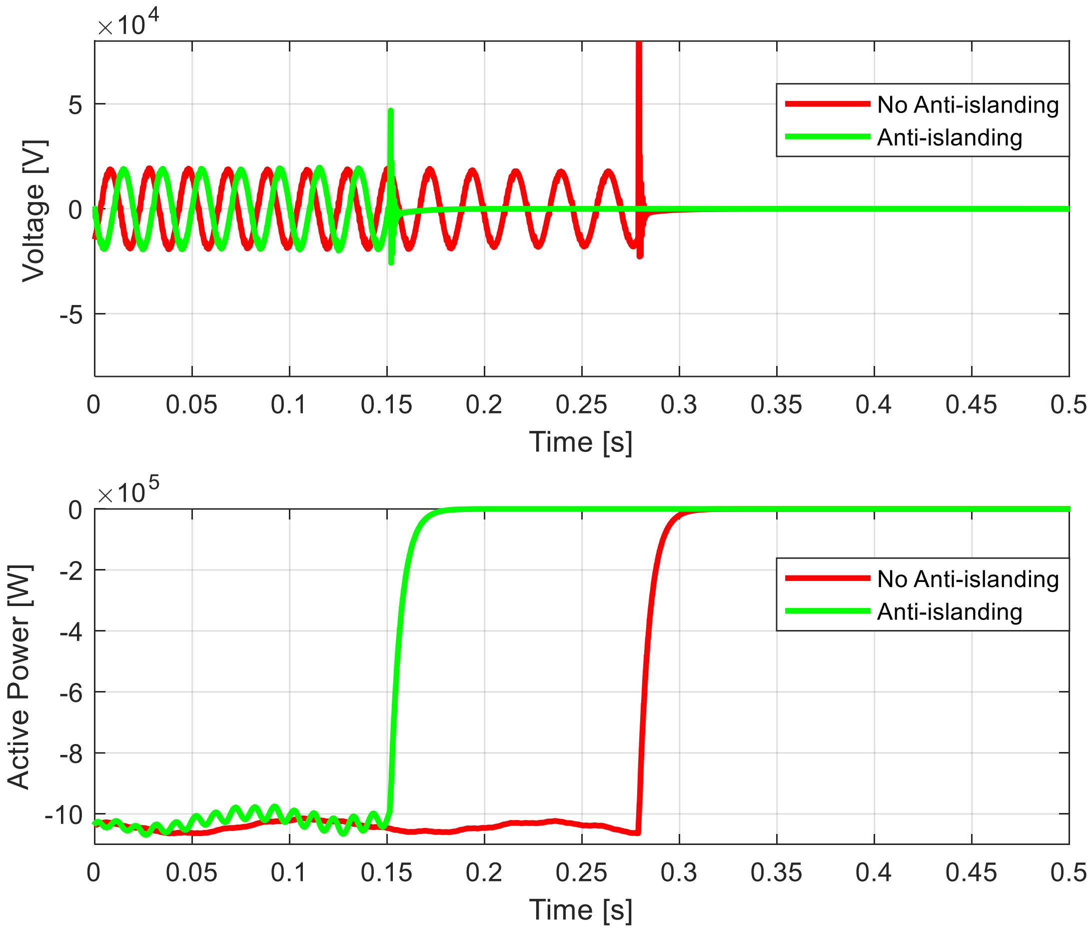

Figure 11 System performance under islanding case

LVRT studies: The PV inverter capability of supporting the voltage and hence serving the grid with ancillary services when voltage sags occur is tested. The voltage sag is taken from the most common real operation conditions seen in EAC real system (symmetrical 60% sag from the nominal value). At the same time the tests were performed under different load conditions (0%,10%,50%,90%). In all cases, the PV inverter enables LVRT functionality when the voltage sag takes place. The inverter ceases to deliver active power to the grid while supports the voltage by injecting reactive power to the system. The amount of the reactive power that is delivered is dictated by both EAC grid codes and standard specifications (VDE AR-N 4105/4110). The amount of power coming from the PV system is the same for the different loading conditions as this is dictated by the prevailing irradiance that was kept constant together with the control setpoints. When the voltage is restored, the inverter ceases to energize the system 0.3 sec before the PV inverter starts injecting active power to he system.

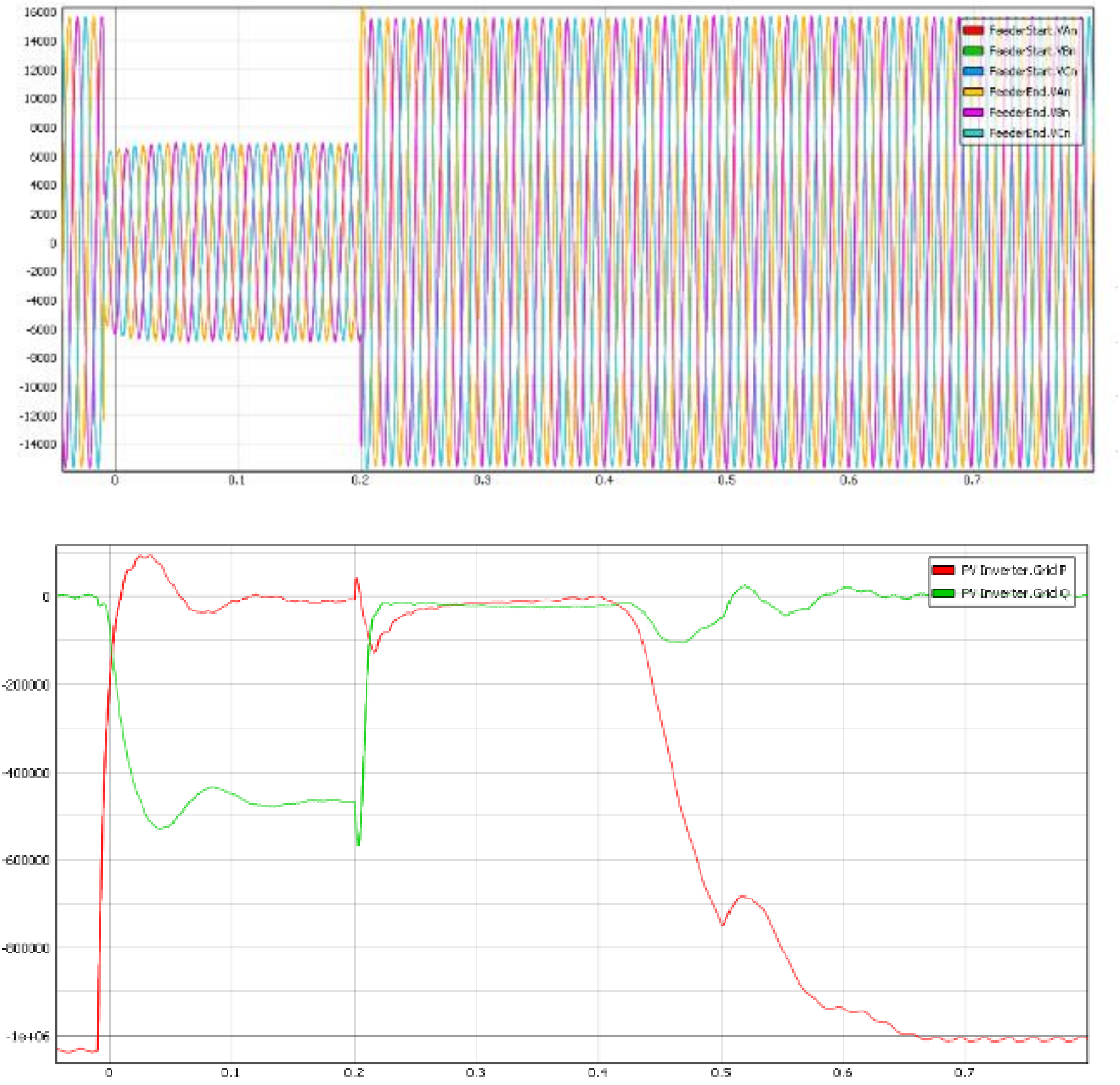

Figure 12 System performance with LVRT under 0% loading

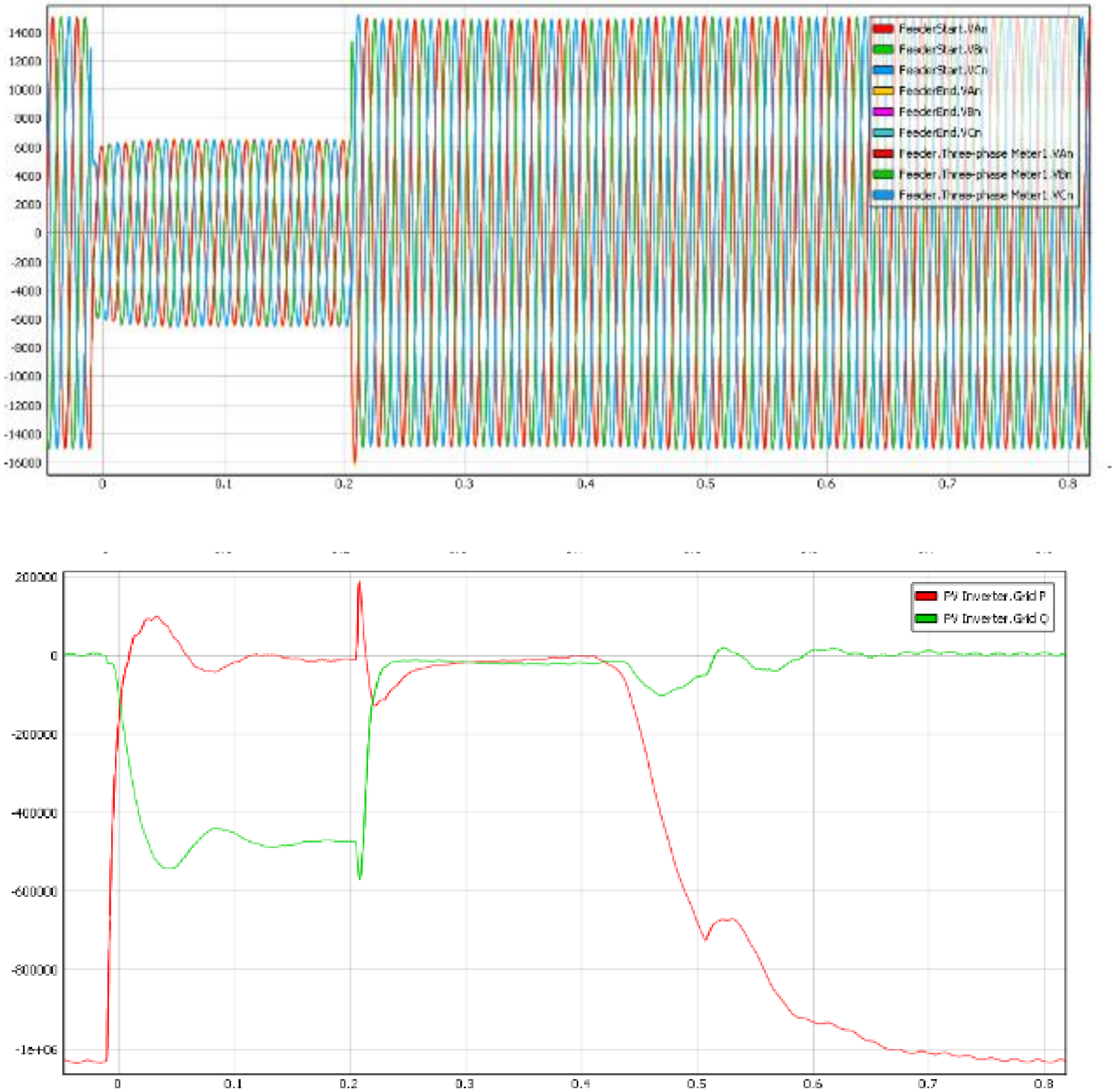

Figure 13 System performance with LVRT under 10% loading

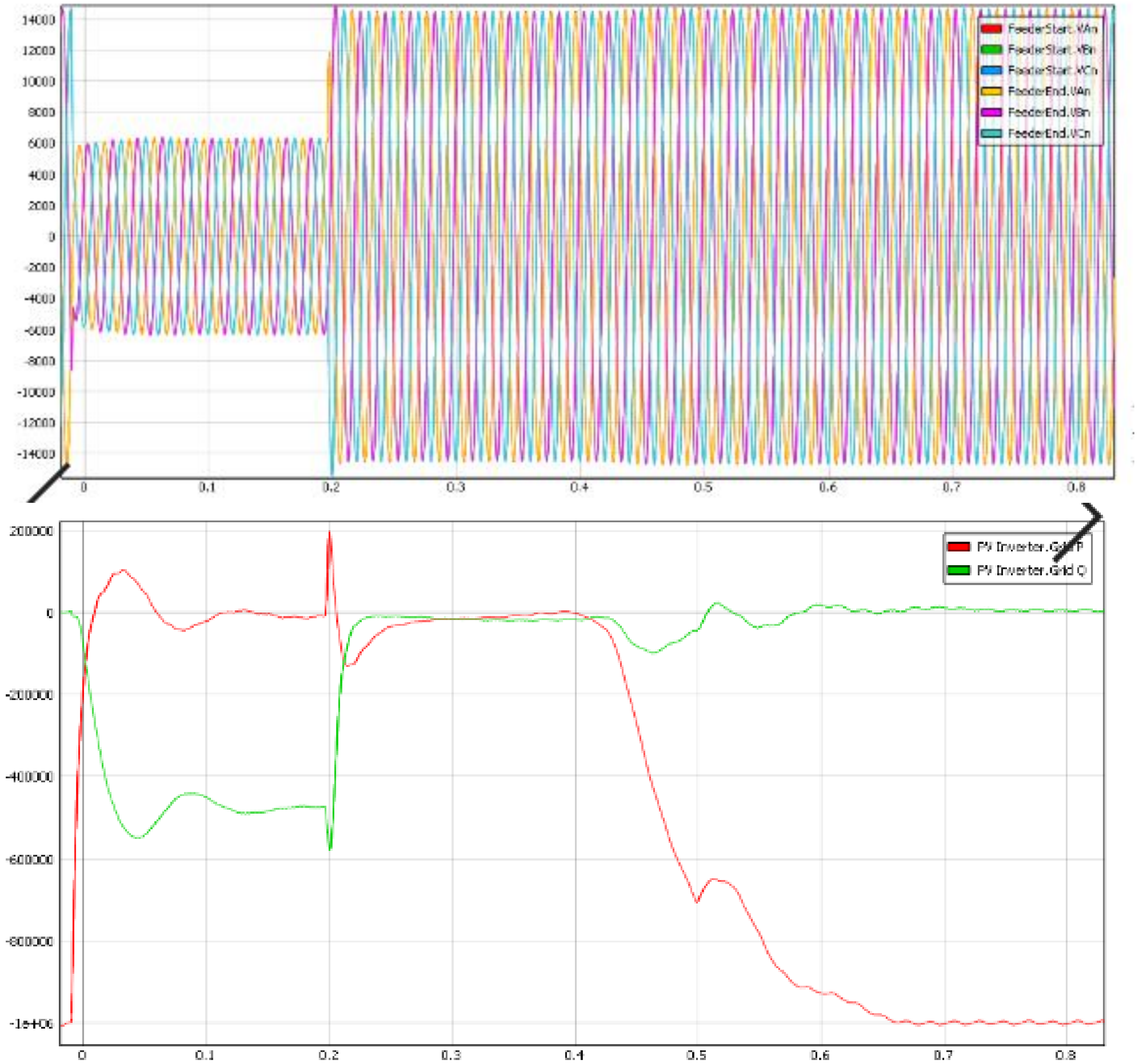

Figure 14 System performance with LVRT under 50% loading.

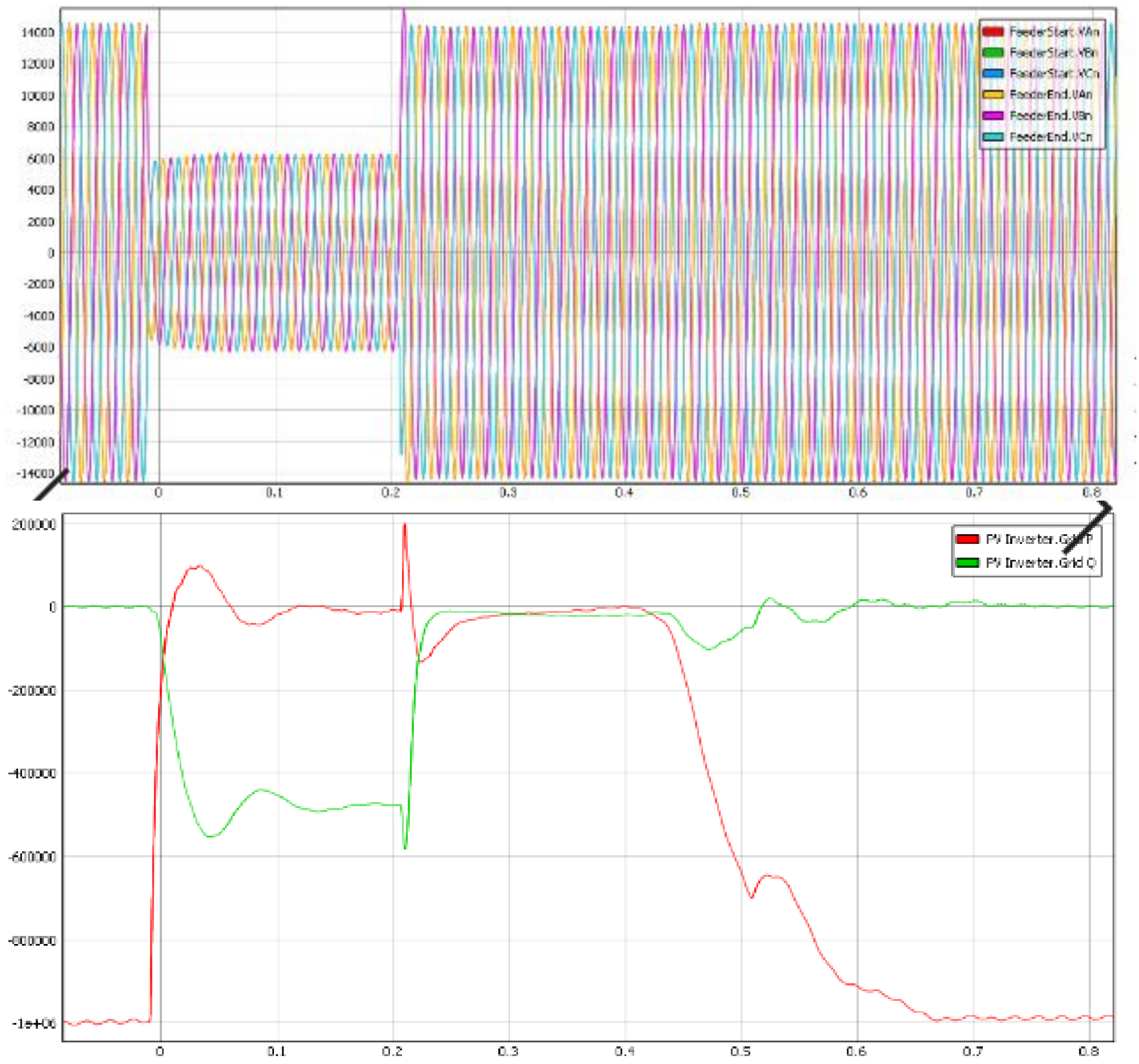

Figure 15 System performance with LVRT under 90% loading

Rocof studies: During the anti-islanding functionality Rocof studies with different irradiation, different loading and throughout the feeder were carried out.

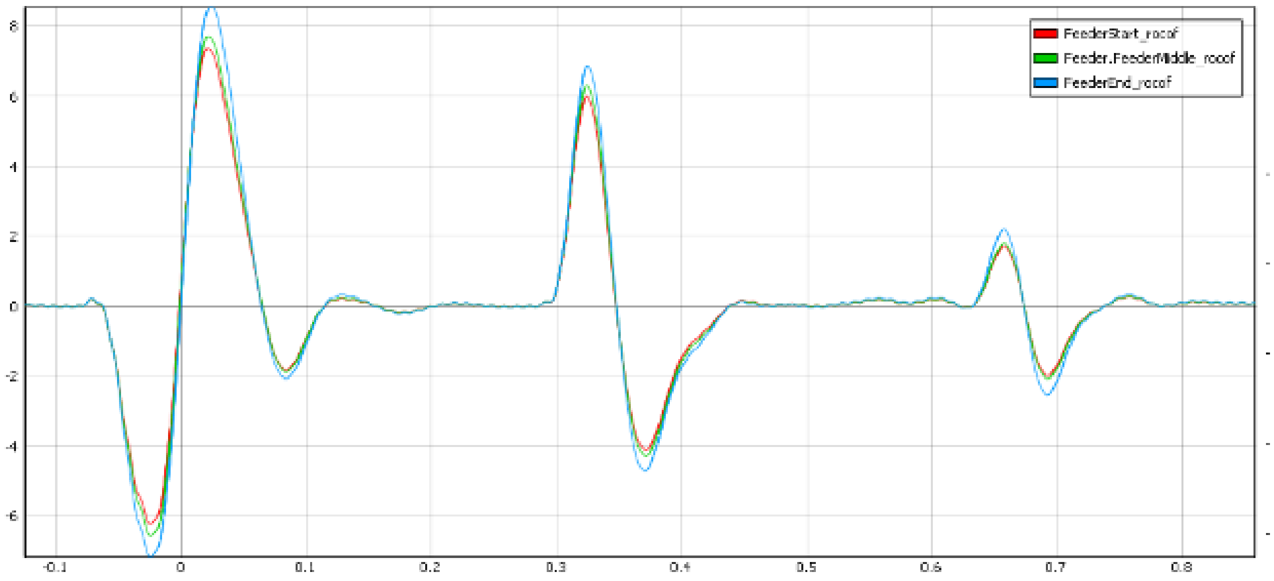

Figure 16. Rocof performance under 10% of PV nominal generation

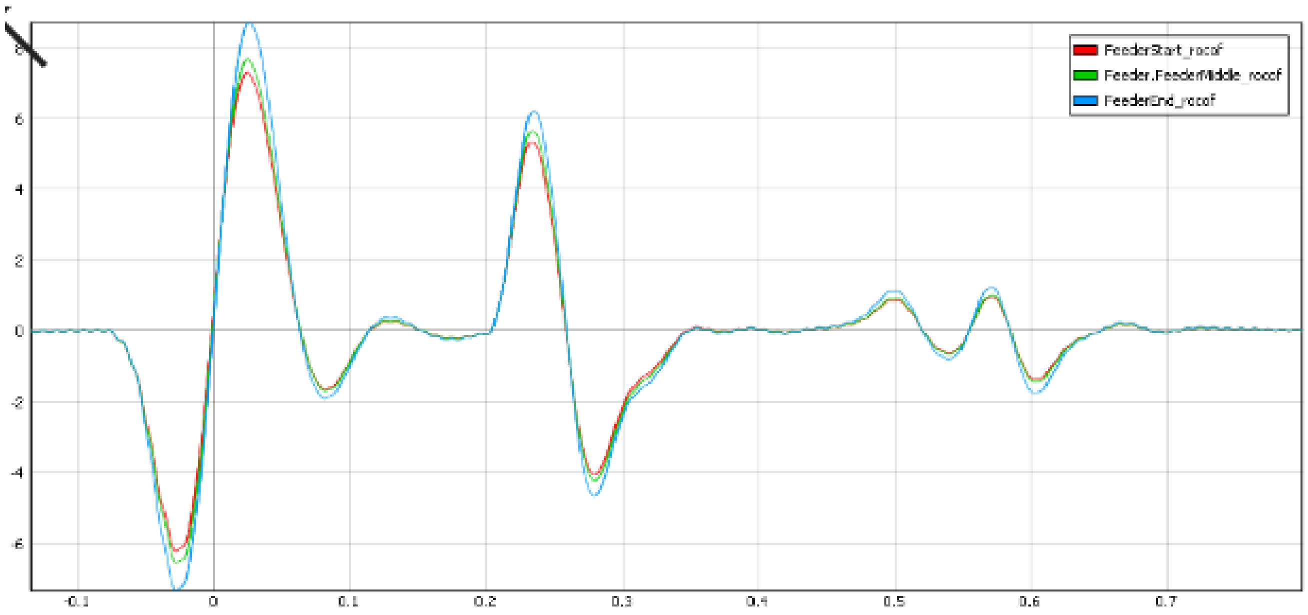

Figure 17. Rocof performance under 25% of PV nominal generation

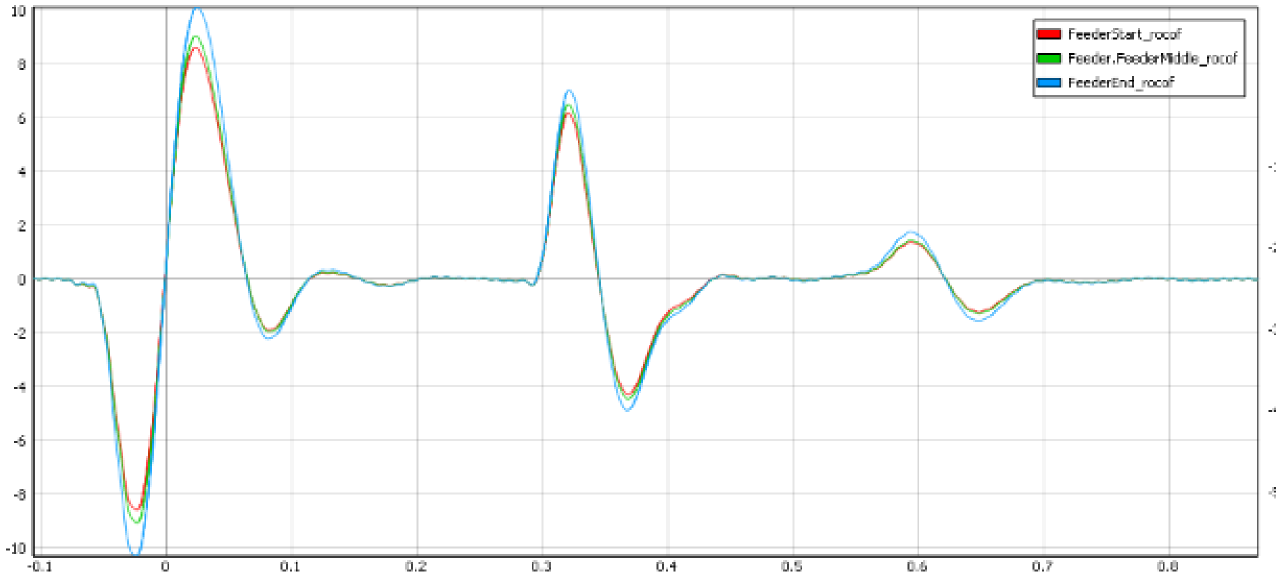

Figure 18. Rocof performance under 50% of PV nominal generation

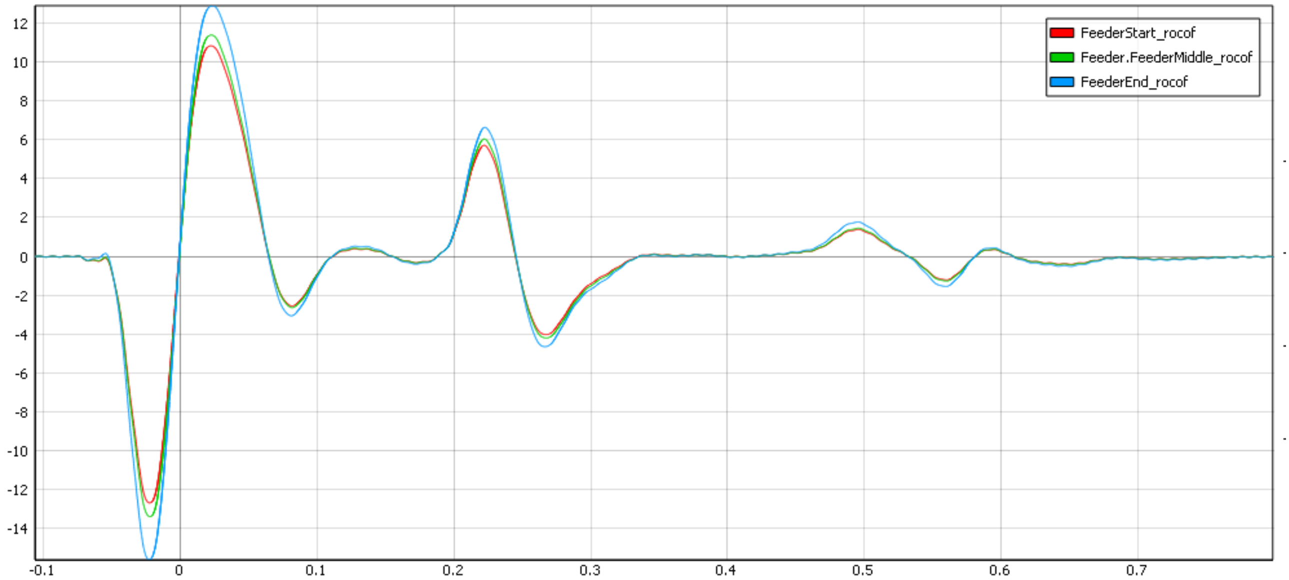

Figure 19. Rocof performance under 75% of PV nominal generation

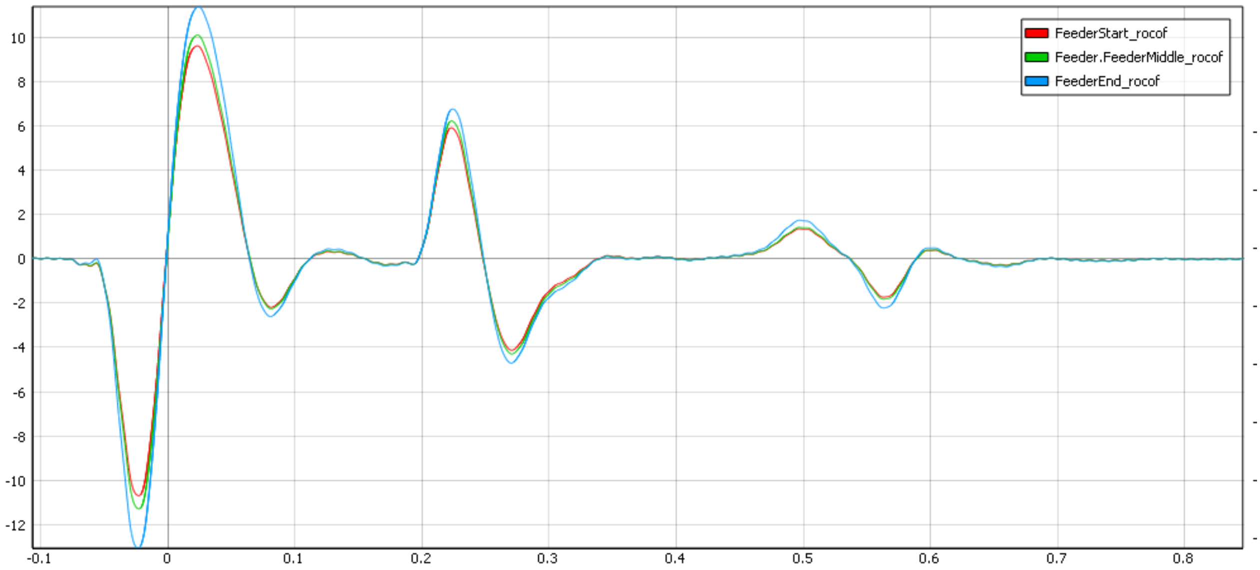

Figure 20. Rocof performance under 100% of PV nominal generation

As expected, frequency distortion is growing bigger when the PV inverter ceases to energize when previously was injecting larger amount of active power.

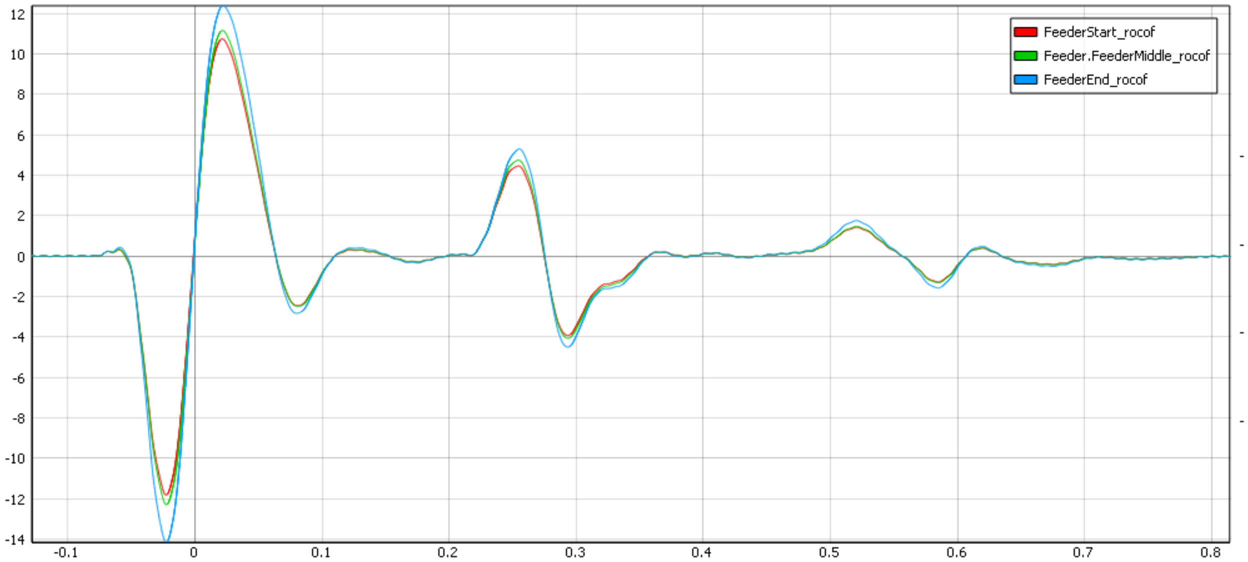

Figure 21. Rocof performance under 0% loading.

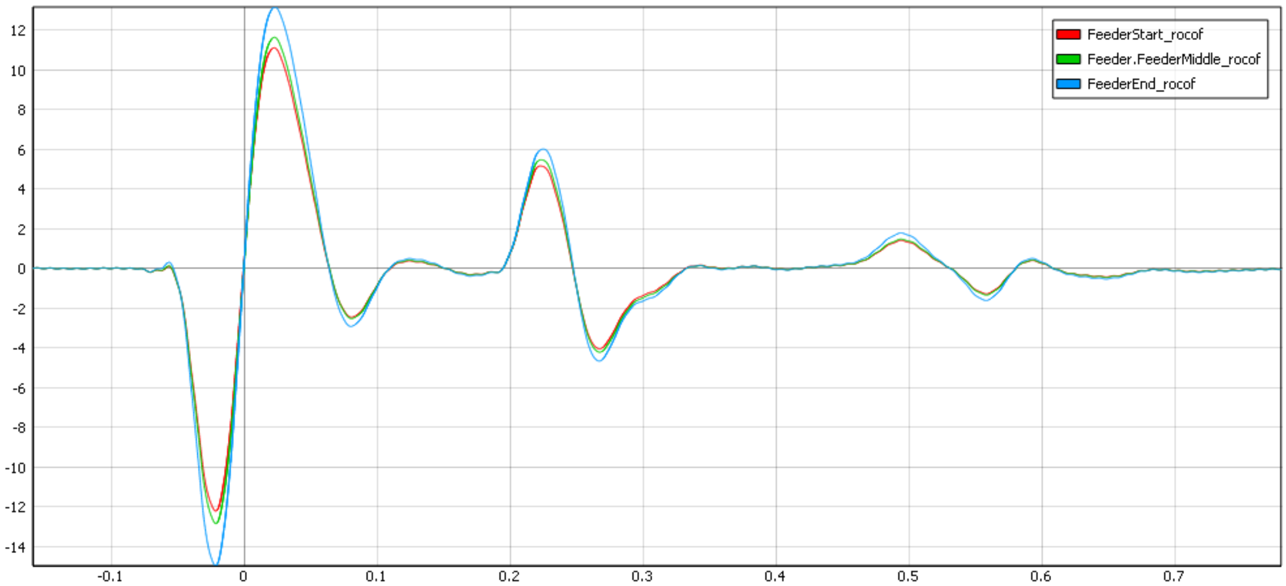

Figure 22. Rocof performance under 25% loading.

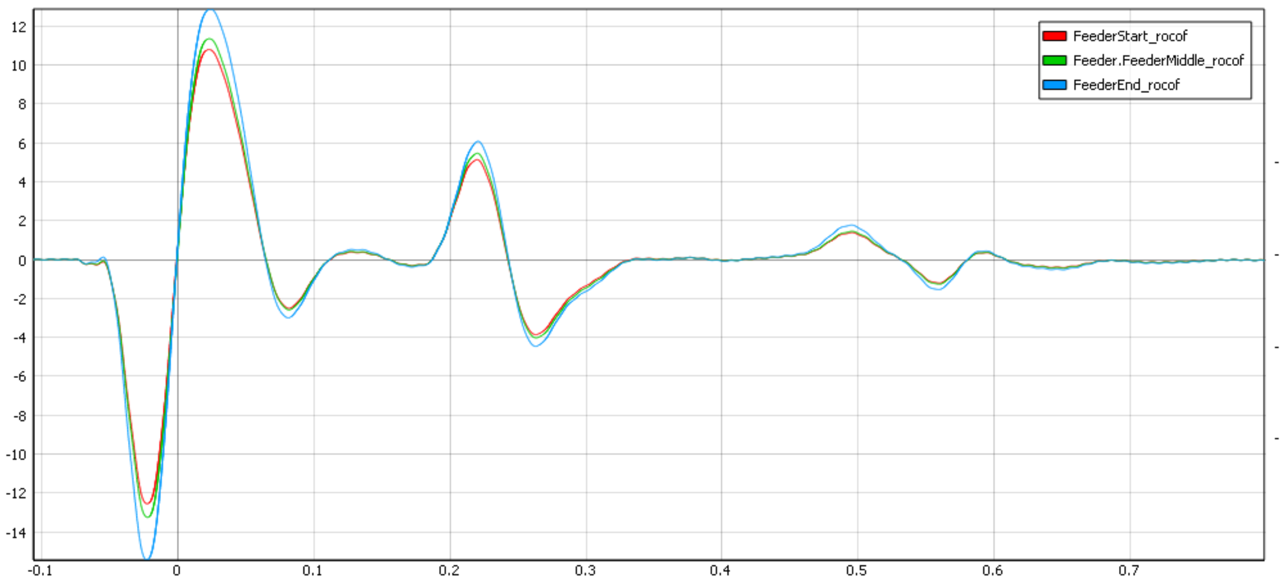

Figure 23. Rocof performance under 50% loading.

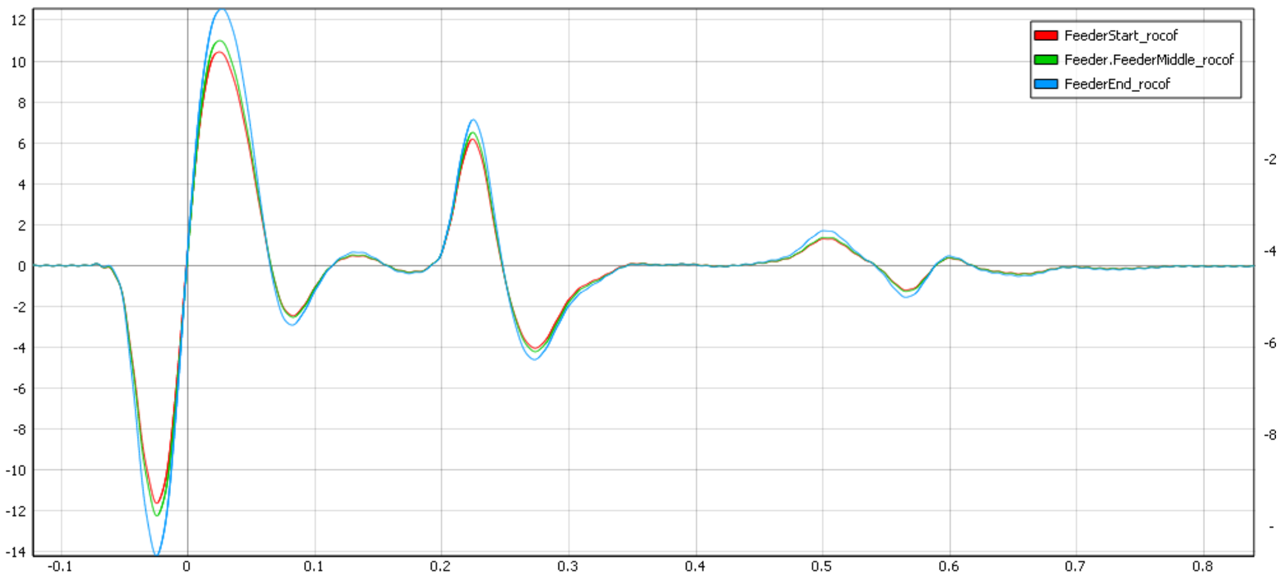

Figure 24. Rocof performance under 75% loads.

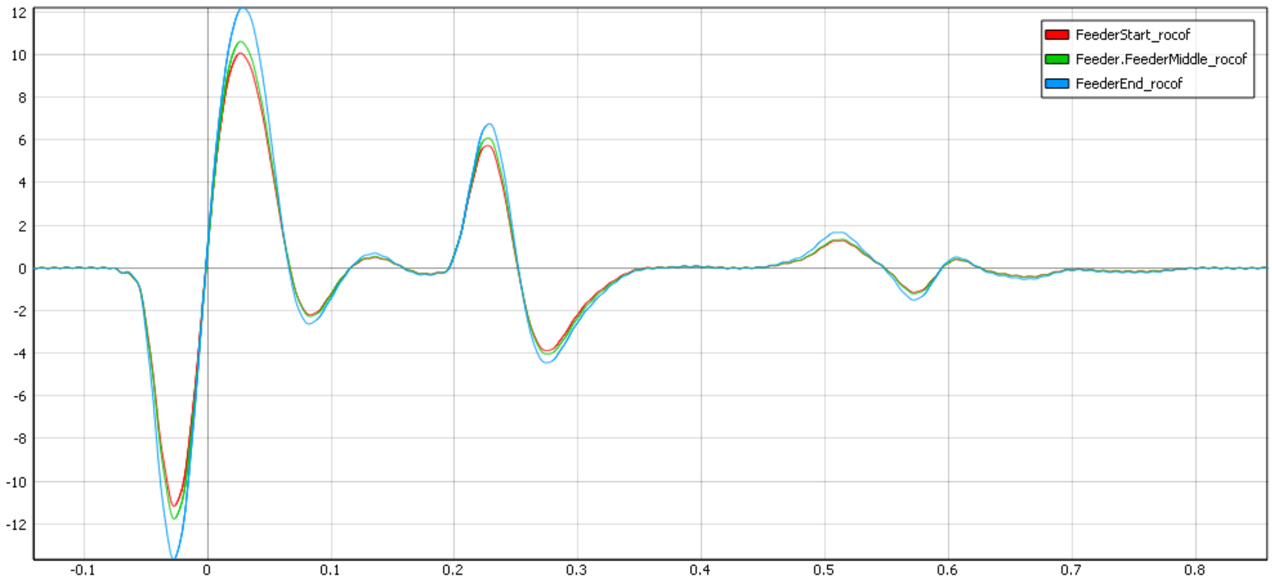

Figure 25. Rocof performance under 100% loading.

Fig. 21-25 shows that Rocof response does not seem to have strong correlation with the loading of the feeder.

In the next, the line of the interconnection of the PV plant was changed from its original length to draw safe results of how it can affect the Rocof response.

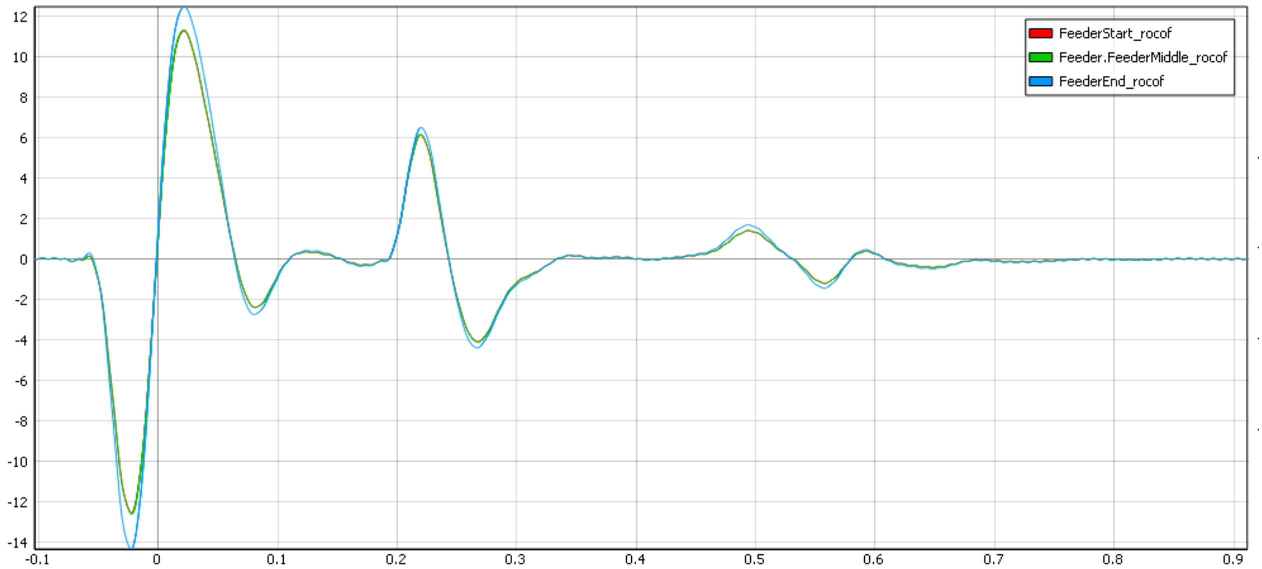

Figure 26. Rocof performance under 10%,20%,30% and 50% of the original line length (5.3 km).

From Fig.26, it is shown that small differentiations of the line length have small or no correlation with the Rocof response. This seems to be expected as the inductance of the line is slightly changed.

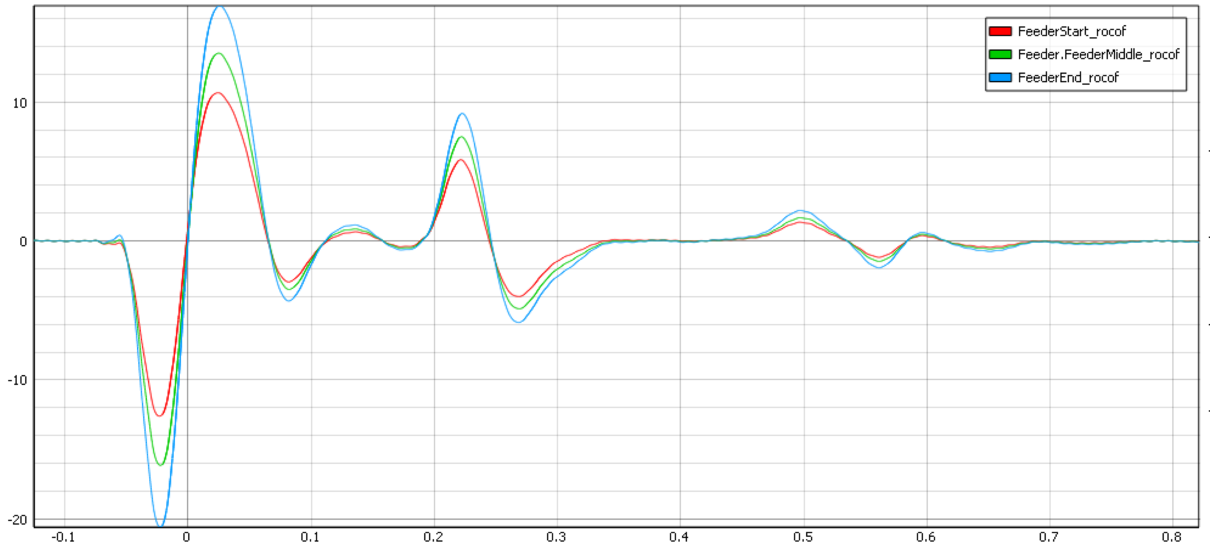

Figure 27 Rocof performance under 5 folds longer than the original line length

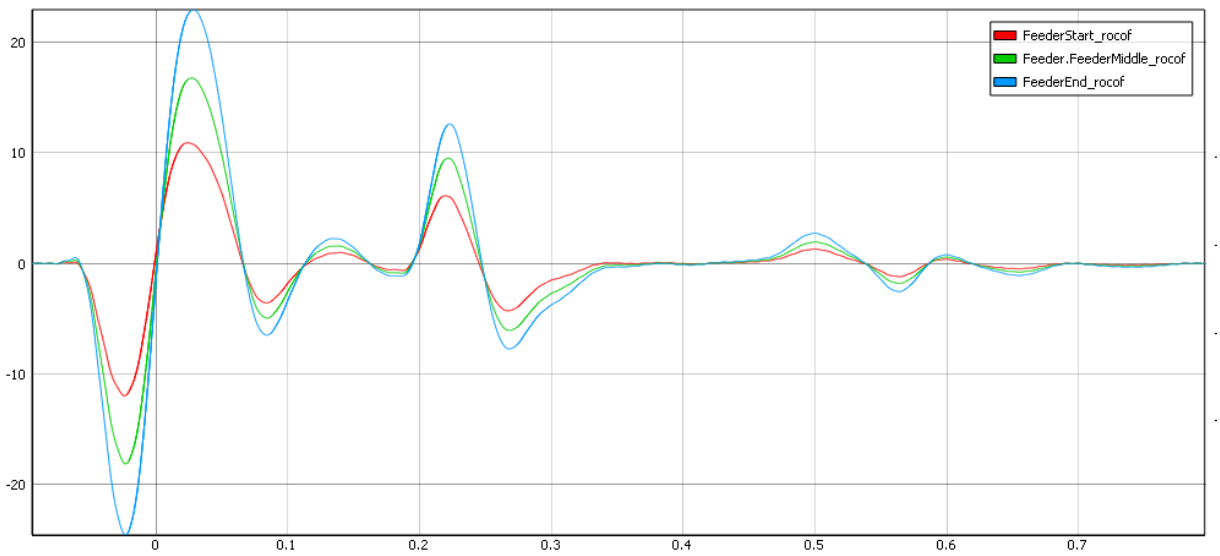

Figure 28. Rocof performance under 10 folds longer than the original line length

In Fig.27 and 28 the length of the line was increased many folds. It is drawn that the longer the line, the larger the Rocof response is expected to be.

Studies with Irradiance changed

In the next, cloud passing that affected the Irradiance and thus the production of the PV inverters were considered.
In Fig.29 – 30 frequency distribution is captured along with the new values of the powers delivered by the inverters. In these cases, frequency is restored within 0.2 sec while the controllers of the PV inverters reshape the power delivery.

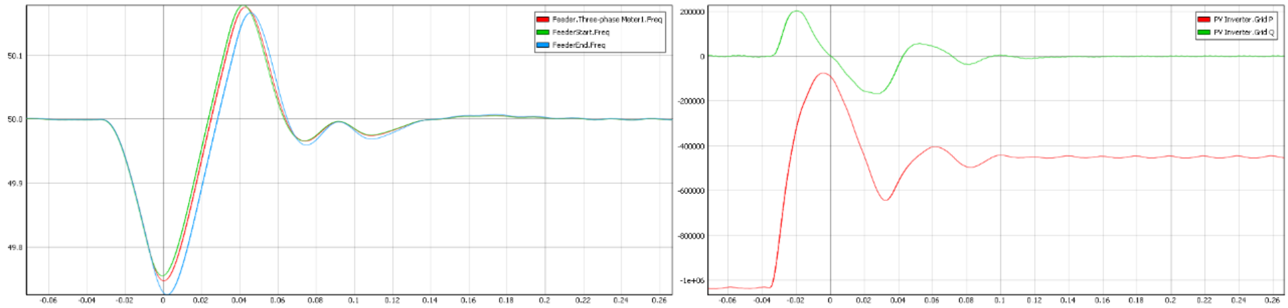

Figure 29 Frequency and Powers delivered with shading per 40%

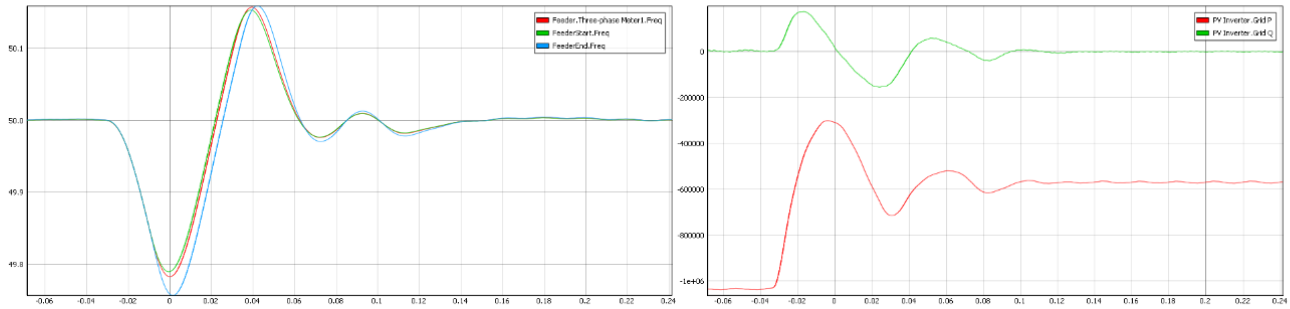

Figure 30. Frequency and Powers delivered with shading per 50%

5 Open Issues and Suggestions for Improvements

As mentioned, the main contribution of this project is its offering to both FOSS and EAC to study the real interactions of the PV inverters with the real distribution grid in Cyprus in HIL environment. Some of the most common operational challenges when it comes to PV integration were tackled. Yet, some open issues for further research can be considered:

- The integration of more than one PV inverter should be considered.
- Some more ancillary services functionalities apart from LVRT should also be considered according to the standard.
- Some more correlations for Rocof and ancillary services should be considered.

6 Dissemination Planning

The main outcomes of this project can be disseminated through the dissemination channels of both FOSS and EAC aiming at both the research and industrial community.
Having said that,the main scientific channels will be:

- Lecture for the IEEE Austrian branch
- Publication of obtained results on CIRED 2020
- Publication of obtained results on Medpower 2020
- Dissemination of results within University of Cyprus, as well as within European funded projects where FOSS is sharing partnership (Horizon 2020, Interreg, SOLAR ERANET, ERASMUS+, LIFE+, JRC)

Whereas the main channels of EAC is the presentation of the results and main findings within the related sectors of the company or the international affiliations that EAC takes part in i.e Eurelectric, eDSO etc.

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7.1 List of Figures

7.2 Annex 1

SolarDesignTool Features Pricing LOGIN

Hansol HS300ME-V01 (300W) Solar Panel

Generate a Solar Permit Package for a design using Hansol HS300ME-V01 (300W)

With SolarDesignTool, you can create a design from scratch and generate a full PV permit package in as little as 15 minutes.

Learn More Sign up

This page contains information about the Hansol HS300ME-V01 (300W) solar panel. To compare this to other PV modules, click here.

DC Electrical Characteristics	
STC Power Rating	300W
PTC Power Rating	269.5W [1]
STC Power per unit of area	14.6W/ft² (156.8W/m²)
Peak Efficiency	15.68%
Power Tolerances	0%/+2%
Number of Cells	72
Nominal Voltage	not applicable
Imp	8.2A
Vmp	36.6V
Isc	8.72A
Voc	45.1V
NOCT	46°C
Temp. Coefficient of Isc	0.02%/K
Temp. Coefficient of Power	-0.43%/K
Temp. Coefficient of Voltage	-0.138V/K
Series Fuse Rating	15A
Maximum System Voltage	1000V

Mechanical Characteristics	
Type	Polycrystalline Silicon
Output Terminal Type	Multicontact Connector Type 4
Output Cable Wire Gauge	12 AWG
Output Cable Wire Type	PV Wire
Output Cable Wire Length	47.2in (1,200mm)
Frame Color	Clear
Backsheet Color	Clear

Length	76.7in (1,948mm)
Width	38.7in (982mm)
Depth	1.7in (42mm)
Weight	49.2lb (22.3kg)
Installation Method	Rack-Mounted

Warranty and Certifications

80% Power Output Warranty Period	25yrs
90% Power Output Warranty Period	10yrs
Workmanship Warranty Period	10yrs
UL 1703 Fire Classification	Type 1
Compliances	UL 1703, IEC 61215, IEC 61730, TUV
CSI Listed	No

1. California Solar Initiative (CSI) list of Eligible Modules