D2.6. Intermediate WP2 scientific report

WP2 – Green and Renewable distributed electric energy generation and storing

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Versions:

Version No.	Person in charge	Institution (acronym)	Date	Comments
1	Oleksandr Velihorskyi	CNUT	18.06.2023	First template of the deliverable report
2	Víctor Miñambres	SEPS	06.09.2023	Project - Cooperative Smart Inverters for Green Generation Plants (WP2) edits
3	Fermín Barrero González	UEX	06.09.2023	Project - Cooperative Smart Inverters for Green Generation Plants (WP2) edits
4	Mariusz Malinowski	WUT	06.09.2023	Project - Cooperative Smart Inverters for Green Generation Plants (WP2) edits
5	Enrique Romero	UEX	11.09.2023	Draft of section 3.3
6	Frede Blaabjerg	AUU	18.09.2023	Section 2.4
7	Mariusz Malinowski	WUT	20.09.2023	Compiled contributions from all partners
8	Oleksandr Velihorskyi	CNUT	30.09.2023	Proofreading and minor corrections
9	Enrique Romero	UEX	05.10.2023	Approval and PDF creation for uploading

Technical References:

Project Acronym	**SmartGYsum**
Project Title	Research and Training Network for Smart and Green Energy Systems and Business Models
Project Coordinator (PC)	Enrique Romero (eromero@unex.es) Universidad de Extremadura (UEX)
Project Duration	1 October 2021 – 30 September 2025

Deliverable No.	D2.6
Dissemination Level	Public
Work Package	WP2 – Green and Renewable distributed electric energy generation and storing
Tasks	
Lead Beneficiary	8 - WUT
Contributing beneficiary (ies)	SEPS, WUT, UEX, AAU
Data due of deliverable	01 October 2023
Actual submission date	01 October 2023

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List of abbreviations

BEN	Beneficiary
Dn	Deliverable (number)
DoA	Description of Action
DS	Doctoral School
ESR	Early Stage Researcher
ETN	European Training Network
GA	Grant Agreement
IRP	Individual Research Project
ITN	Innovative Training Network
MSn	Milestone (number)
MSCA	Marie Sklodowska-Curie Actions
PC	Project Coordinator
REC	Research Ethics Committee
RSC	Recruitment and Secondment Committee
WPn	Work Package (number)

1. Executive summary

The present deliverable provides the first report about the scientific activities that were done and the main result obtained related to the implementation of IRPs of ESRs in WP2 of the project.

WP2: Green and Renewable distributed electric energy generation and storing, focused on the research of self-generation and power-sharing infrastructures that ensure a manageable, reliable, and efficient wind and PV generation, as well as storage through distributed systems, enabling connected and isolated energy generation models.

The ESRs associated with the deliverable:

- ESR01 (**Jamil Hassan**) coordinated by the SENERGY "Products and Services (SEPS) with IRP01: "Cooperative Smart Inverters for Green Generation Plants" with the following goals: To optimize load sharing capabilities; To enable cooperative-based medium-sized photovoltaic (PV) plants to regulate the energy flows in renewable energy communities. To design and validate strategies for operating parallel connected inverters to optimize the overall performance and to deliver ancillary services. To integrate the generation of renewable energy from different members of Renewable Communities while maintaining the integrity, reliability, and security of the system
- ESR02 (**Luis Martínez**) coordinated by the Warsaw University of Technology (WUT) with IRP02: "Development of Power Generators for Smart Buildings with Advanced Power Sharing Capabilities"; with the following goals: To develop generators that enable the diversification of power sources (wind and PV) in smart buildings To optimize the energy generation and the load transfer to storage devices among the different households that conform to Smart Buildings,
- ESR03 (**Anas Abdullah Alvi**) coordinated by the University of Extremadura (UEX)l with IRP03: "Design and validation of Virtual Power Plants for operation, both isolated and connected" with the following goals: To develop a virtual power plant (VPP) to aggregate different sources of renewable Energy able to work isolated and connected with other VPPs; To improve the reliability and efficiency of energy generation Enlargement of the life length of storage devices by optimizing charge and discharge periods.
- ESR04 (**Shuyu Ou**) coordinated by the Aalborg University (AAU) with IRP04 "Condition Monitoring for Smart Power Electronic Converter Systems for Distributed Generation" with the following goals: To design devices and mechanisms for continued monitoring of converter systems; to enhance the resilience of power electronic converters under severe conditions or emergencies by integration of IoT technologies; to research the adaptions needed in converters systems for the requirements of distributed generation .

1.1. Objectives of the deliverable

The objective of the intermediate scientific report is to compile the results obtained in the corresponding IRPs included in the WP2, to show the progress of each individual IRP in the WP2 as well as their orientation on achievement of WP2 objectives.

1.2. Organisation of the deliverable

The deliverable under consideration is based on the scientific work of the ESRs supervised by the WP Partners. The outcome of their work has been distilled into an annual report, separate for each ESR. The reports constituted the basis for assembling this report and contained detailed descriptions of the research process, drawings, flowcharts, photos, and plotted results of the studies (simulation or experiment). Other parts of ESRs' outcomes, such as simulation models, raw experimental data, and source code, are not a part of this report.

Overall, the provided outcome has aligned with the project timeline. The presented results ensure that WP2 implementation is heading towards meeting Deliverables 2.1, 2.2, 2.3, and 2.4.

During the action, some minor deviations have been encountered. Due to personal reasons, ESR04 took a 10-week leave, resulting in a one-month delay in the project work. There was also a short delay in ESR01's preliminary research phase due to extended converter topology considerations.

Another delay related to secondment happened to ESR01, due to prolonged processing time for a Temporal Residence Permit.

At the time of writing this report, two ESRs are executing their first secondment, whereas the other two have already been completed.

After all, no significant delays were encountered during the reporting period, and no changes to the execution plan of the WP2 and individual research projects plans of WP2 researchers were necessary.

2. General progress of the action

2.1. WP2 Objectives and tasks

The WP2 has three main scientific objectives:

- To identify and demonstrate new ways of managing electric energy generation by using Renewable Electric Energy Generation (REEG) and Distributed Energy Resources (DER) as agents of a Collaborative Smart Grid (CSG);
- To develop models to describe/predict the behaviour of PV and wind generators and to design the best and safest ways to integrate their generation into existing grids to improve reliability and efficiency;
- To establish power generation patterns and new efficient converters for each technology to determine the best way to coordinate the operation of different and complementary DERs for supplying Smart Buildings or Houses, increasing the Renewable Energy share in the Electric Energy Generation Mix, or providing ancillary services.

The objectives are meant to fulfilled by a proper execution of the following tasks:

- Task 2.1: Cooperative Smart Inverters for Green Generation Plants (SEPS – WUT)
- Task 2.2: Development of Power Generators for Smart Buildings with Advanced Power Sharing Capabilities (WUT – AAU)
- Task 2.3: Virtual Power Plant for operation, both isolated and connected (UEX -TUT)
- Task 2.4: Condition Monitoring for Smart Power Electronic Converter Systems for Distributed Generation (AAU – CAU)

Fifth task of WP (Task 2.5) is an elaboration of partial and final scientific reports (WUT) and is connected more with the project management.

2.2. WP2 – Workpackage progress

ESR	Starting date	General evaluation	Status
1	28/06/2022	Jamil Hassan's contract was signed on the starting IRP date (28/06/2022) which was a date to complete the contract duration inside the duration of the SMARTGYsum project. First tasks included the instruction of Jamil in the photovoltaics plants field of knowledge, including PV panels, plants configurations, inverters, topologies, control algorithms, modulation techniques and business models. Main work until now has been to finish a state of the art in photovoltaic power plants including modelling and simulation of several topologies. This work has led to 4 conference publications, and right now he is finishing other publication related to the state of the art. He has assisted to 2 Doctoral Schools, the second of SMARTGYsum in November 2022 in Badajoz and the third of SMARTGYsum in July 2023 in Caparica. He had the first secondment in the university of Warsaw in beginning of 2023 getting more knowledge of control strategies and modulation techniques. About PhD studies, Jamil has enrolled in the PhD of the University of Extremadura and has passed first-year courses.	Active in Senergyps, Badajoz; expected to meet Task assigned deliverables
2	01/06/2022	Luis Martínez started his contract on June 1, 2022. In following September he enrolled in PhD Program at WUT. During the last 15 months Luis has made a lot of progress in the fields of power electronics (topologies and modulation), control theory and metaheuristics, embedded programming and scientific writing. He attended two Doctoral Schools: the second of SMARTGYsum in November 2022 in Badajoz and the third of SMARTGYsum in July 2023 and one conference CPE23 with two papers. He submitted 1 journal paper. He successfully executed the following steps: Initial training of toolchain and workflow to design and simulate power converter systems and controllers, development of simulation model for system under study with averaging; research on- and proposal of an EMS model with an ancillary service; Implementation of optimization algorithms for energy flow control based weather forecasting and the concept of transactive energy (energy/cost optimization).	Active in WUT, Warsaw; expected to meet Task assigned deliverables

3	1/09/2022	Anas Abdullah Alvi started his contract in the beginning of August 2022, followed by the enrolment in the PhD Program at UEX. During the reporting period he accomplished the following steps: literature review, a case study with a MATLAB/Simulink model of a Virtual Power Plant; research on- and development of a genetic algorithm for optimizing the energy flow in the EMS with regards to cost and operational constraints. He also considered cyber-security aspect for the system under consideration. He is also active publication-wise. Up the reporting point, he has published two paper in conference proceedings, co-authored one book chapter and published one journal paper. Anas has already done his first secondment at TUT, Estonia.	Active in UEX expected to meet Task assigned deliverables
4	01/08/2022	Shuyu Ou started his contract with the beginning of September, 2022 He also enrolled in the PhD program at AAU. During the reporting period research work focused on improving reliability by developing a condition monitoring method for IGBT modules in inverters. Shuyu managed to obtain first experimental results using the Hardware-in-the-Loop setup to validate the model estimating increased on-state resistances via harmonics in control variables. He has also submitted his first conference paper. He is in the middle his first secondment at time of submitting this report	Active in AAU expected to meet Task assigned deliverables

3. WP2 Tasks progress

3.1. Task 2.1 – IRP1 "Cooperative Smart Inverters for Green Generation Plants"

3.1.1. Introduction

The scientific work has been the next:

Conference publications based on the state of the art of photovoltaic power plants including modelling and simulations of several topologies, control strategies and modulation techniques. These scientific outcomes have been obtained during 10 months in the facilities of the Research Department of the Senergy Products and Services, plus 2 months in the secondment at the Research group of the Warsaw University of Technology.

Selection and design of the prototype a Three-phase Cooperative NPC+TLI smart inverter for green generation photovoltaic plants, including the topology and its elements to improve efficiency, harmonic behaviour, leakage currents and reliability. These scientific outcomes have been obtained during the last 3 months in the facilities of the Research Department of the Senergy Products and Services

Doctoral Schools attendance. Attendance to the 2nd SmartgySUM Doctoral School in November 2022 in Badajoz and 3rd SmartgySUM Doctoral School in July 2023 in Caparica.

3.1.2. Scientific outcomes

- From the hiring date up until the 1st of September 2023, research has yielded significant theoretical and simulation results in alignment with the initial research goal:
  - The journey commenced with an exhaustive literature review, thoroughly categorizing renewable energy generation power plants and different inverter topologies for grid-tied applications.
  - The initial work of this research topic focuses on a comprehensive study of converter topologies and innovative control strategies. Through rigorous simulations, different three-phase inverter topologies were investigated to enhance their overall performance, considering the mitigation of leakage currents. A groundbreaking contribution emerged in the form of a novel three-phase three-level inverter design, strategically engineered for the reduction of common mode voltage during the zero switching states. The outcomes of this research culminated in the creation of a conference paper that was presented at the prestigious IEEE CPE Powereng 2023 conference held in Estonia, drawing attention to the innovative insights and contributions of the study.

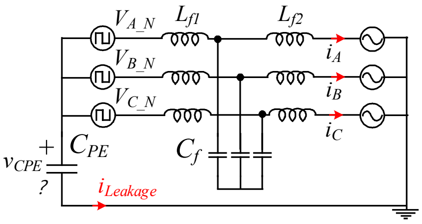


Fig. 1. CMV of the simplified equivalent circuit.

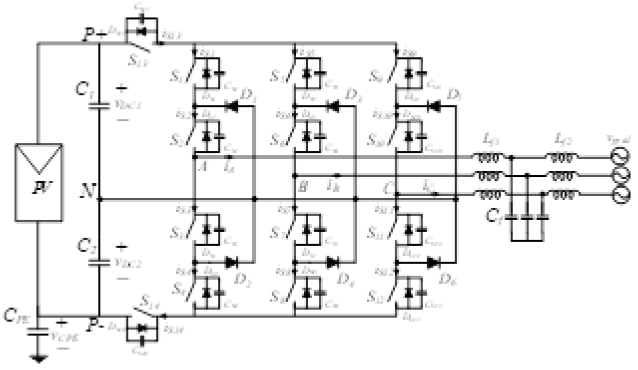
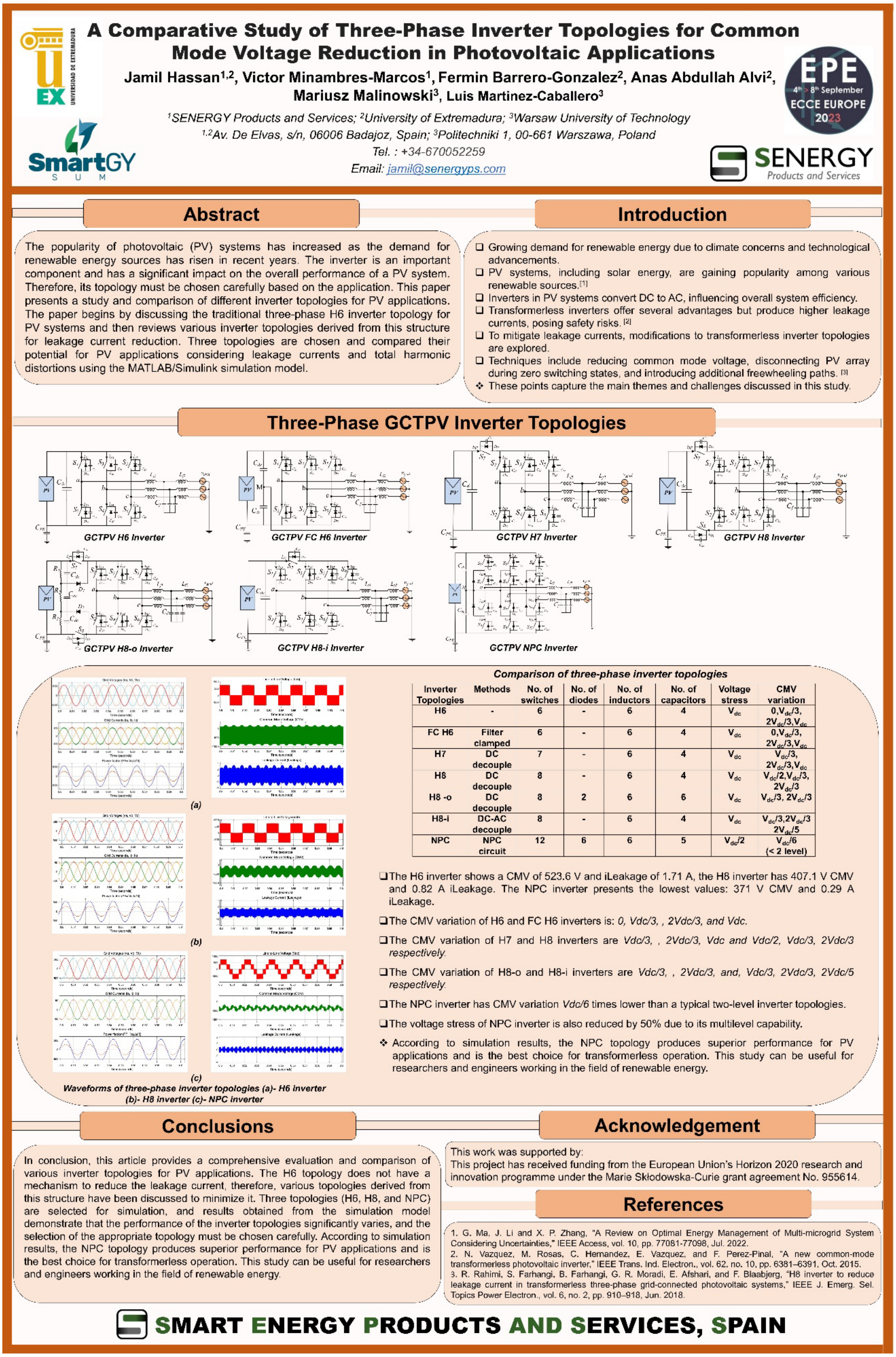


Fig. 2. Circuit diagram of proposed 3-level NPC inverter.

  - Additionally, the journey continues with a forthcoming conference presentation at EPE 2023 ECCE Europe, scheduled from 4th to 8th September in Aalborg, Denmark. The acceptance of this presentation highlights the growing recognition and impact of the research. In this study, three topologies (H6, H8, and NPC) are selected for simulation, and results obtained from the simulation model demonstrate that the performance of the inverter topologies significantly varies, and the selection of the appropriate topology must be chosen carefully. According to simulation results, the NPC topology produces superior performance for PV applications and is the best choice for transformerless operation. This study can be useful for researchers and engineers working in the field of renewable energy.



A Comparative Study of Three-Phase Inverter Topologies for Common Mode Voltage Reduction in Photovoltaic Applications

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Abstract

The popularity of photovoltaic (PV) systems has increased as the demand for renewable energy sources has risen in recent years. The inverter is an important component and has a significant impact on the overall performance of a PV system. Therefore, its topology must be chosen carefully based on the application. This paper presents a study and comparison of different inverter topologies for PV applications. The paper begins by discussing the traditional three-phase H6 inverter topology for PV systems and then reviews various inverter topologies derived from this structure for leakage current reduction. Three topologies are chosen and compared their potential for PV applications considering leakage currents and total harmonic distortions using the MATLAB/Simulink simulation model.

Introduction

- ❑ Growing demand for renewable energy due to climate concerns and technological advancements.
- ❑ PV systems, including solar energy, are gaining popularity among various renewable sources.[1]
- ❑ Inverters in PV systems convert DC to AC, influencing overall system efficiency.
- ❑ Transformerless inverters offer several advantages but produce higher leakage currents, posing safety risks. [2]
- ❑ To mitigate leakage currents, modifications to transformerless inverter topologies are explored.
- ❑ Techniques include reducing common mode voltage, disconnecting PV array during zero switching states, and introducing additional freewheeling paths. [3]
- ❖ These points capture the main themes and challenges discussed in this study.

Three-Phase GCTPV Inverter Topologies

GCTPV H6 Inverter

GCTPV FC H6 Inverter

GCTPV H7 Inverter

GCTPV H8 Inverter

GCTPV H8-o Inverter

GCTPV H8-i Inverter

GCTPV NPC Inverter

(a)

(b)

(c)

Waveforms of three-phase inverter topologies (a)- H6 inverter (b)- H8 inverter (c)- NPC inverter

Comparison of three-phase inverter topologies

Inverter Topologies	Methods	No. of switches	No. of diodes	No. of inductors	No. of capacitors	Voltage stress	CMV variation
H6	-	6	-	6	4	V_{dc}	$0, V_{dc}/3, 2V_{dc}/3, V_{dc}$
FC H6	Filter clamped	6	-	6	4	V_{dc}	$0, V_{dc}/3, 2V_{dc}/3, V_{dc}$
H7	DC decouple	7	-	6	4	V_{dc}	$V_{dc}/3, 2V_{dc}/3, V_{dc}$
H8	DC decouple	8	-	6	4	V_{dc}	$V_{dc}/2, V_{dc}/3, 2V_{dc}/3$
H8 -o	DC decouple	8	2	6	6	V_{dc}	$V_{dc}/3, 2V_{dc}/3$
H8-i	DC-AC decouple	8	-	6	4	V_{dc}	$V_{dc}/3, 2V_{dc}/3$ $2V_{dc}/5$
NPC	NPC circuit	12	6	6	5	$V_{dc}/2$	$V_{dc}/6$ (< 2 level)

- ❑ The H6 inverter shows a CMV of 523.6 V and iLeakage of 1.71 A, the H8 inverter has 407.1 V CMV and 0.82 A iLeakage. The NPC inverter presents the lowest values: 371 V CMV and 0.29 A iLeakage.
- ❑ The CMV variation of H6 and FC H6 inverters is: *0, Vdc/3, , 2Vdc/3, and Vdc.*
- ❑ The CMV variation of H7 and H8 inverters are *Vdc/3, , 2Vdc/3, Vdc and Vdc/2, Vdc/3, 2Vdc/3 respectively.*
- ❑ The CMV variation of H8-o and H8-i inverters are *Vdc/3, , 2Vdc/3, and, Vdc/3, 2Vdc/3, 2Vdc/5 respectively.*
- ❑ The NPC inverter has CMV variation *Vdc/6* times lower than a typical two-level inverter topologies.
- ❑ The voltage stress of NPC inverter is also reduced by 50% due to its multilevel capability.
- ❖ According to simulation results, the NPC topology produces superior performance for PV applications and is the best choice for transformerless operation. This study can be useful for researchers and engineers working in the field of renewable energy.

Conclusions

In conclusion, this article provides a comprehensive evaluation and comparison of various inverter topologies for PV applications. The H6 topology does not have a mechanism to reduce the leakage current, therefore, various topologies derived from this structure have been discussed to minimize it. Three topologies (H6, H8, and NPC) are selected for simulation, and results obtained from the simulation model demonstrate that the performance of the inverter topologies significantly varies, and the selection of the appropriate topology must be chosen carefully. According to simulation results, the NPC topology produces superior performance for PV applications and is the best choice for transformerless operation. This study can be useful for researchers and engineers working in the field of renewable energy.

Acknowledgement

This work was supported by:
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3. R. Rahimi, S. Farhangi, B. Farhangi, G. R. Moradi, E. Afshari, and F. Blaabjerg, "H8 inverter to reduce leakage current in transformerless three-phase grid-connected photovoltaic systems," IEEE J. Emerg. Sel. Topics Power Electron., vol. 6, no. 2, pp. 910–918, Jun. 2018.

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In summary, the research has effectively progressed from a comprehensive literature review to the development of innovative converter topologies, and control strategies. The dissemination of findings through conference presentations underscores the significance of the contributions made towards the overarching goal of enhancing renewable energy generation and grid integration. The next step is to use two inverter topologies in parallel for cooperative operation which will be validated by simulation and experiments.

- ❖ The research also includes the collaboration in 2 more conference publications also related to photovoltaic field of knowledge:
  - o In DoCEIS 2023 a study about different functions along with cybersecurity measures of modern-day smart grids in the context of Virtual Power Plants. It can be observed that, islanding mode of operation of a Virtual Power Plants can be an effective way to supply electrical power to the loads in a microgrid in case there is a cyber-attack in the main generation plant.
  - o CPE-POWERENG. Deep analysis of renewable inverters' operation is important when working in non-ideal situations. The main aim of this paper was to analyze the operation of a three-phase photovoltaic power plant (rated at 250 kW) supplying power to both three-phase and single-phase loads. The novelty of this paper was to identify a case in which the islanding detection fails due to the connection of a single-phase load in the point of low voltage.

3.1.3. Contribution to the WP objectives

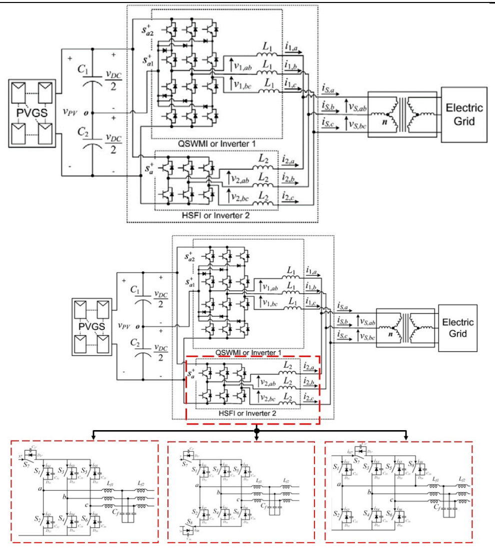
The main objective is to design a ready to market converter which improves the energy production of renewable generation power plants. Considering the results until now one could see how they are contributing to the objectives of the WP:

- Almost finished state of the art paper related to photovoltaic energy. This study has given the basic knowledge in the field to the ESR in order to develop the project.
- PhD enrollment in the University of Extremadura. The ESR must obtain the PhD during the project, so first step is to enroll in a university. This has already been done and he has passed first year courses.
- Simulations of photovoltaic inverter topologies and publish the results. Some novelties has been published including leakage currents inverter improvements, topologies comparisons, modulation techniques and cyber attack immunity on smart grids.
- Selection and design of the inverter topology that is going to be implemented in the prototype. A critical part considering the prototype must be ready in the following months.

In general and particular, the first and third contributions are fully corresponds with the WP objective "**To identify and demonstrate new ways of managing electric energy generation by using Renewable Electric Energy Generation (REEG) and Distributed Energy Resources (DER) as agents of a Collaborative Smart Grid (CSG)".**

3.1.4. Scientific achievements

Experimental prototypes

#	Name	Description	Status (designed, assembled, tested)	Photo
1	Cooperative inverter for photovoltaic plants	Three-phase Cooperative NPC+TLI smart inverter for green generation photovoltaic plants. The objective is to improve efficiency, harmonic behaviour, leakage currents and reliability of the equipment, leading to easier maintenance and better carbon footprint. Business model will focus on scale production, energy injection improvement, losses reduction and CO2 emissions avoidance.	The inverter is already designed, and we are working on selecting the components to assemble the prototype	

Publications

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
1	An Improved Three-Phase Transformerless Neutral Point Clamped Inverter Topology for Common Mode Voltage Reduction	Conference	Published	10.1109/CPE-POWERENG58103.2023.10227487
2	A Comparative Study of Three-Phase Inverter Topologies for Common Mode Voltage Reduction in Photovoltaic Applications	Conference	Accepted	-
3	An Overview of the Functions of Smart Grids Associated with Virtual Power Plants Including Cybersecurity Measures	Conference	Published	10.1007/978-3-031-36007-7_7
4	Performance Evaluation of a Three-Phase PV Power Plant under Unbalanced Conditions with Islanding Detection Reliability Test	Conference	Published	10.1109/CPE-POWERENG58103.2023.10227391

3.2. Task 2.2 – IRP2 "Development of Power Generators for Smart Buildings with Advanced Power Sharing Capabilities"

3.2.1. Introduction

The following results are related to the Energy Management Systems in the context of a residential environment, i.e. Low voltage distribution network, where renewable energy sources are integrated together with energy storage (ES) which helps to mitigate the inherent variability of renewable sources. The excess of energy production from renewables is stored, and later delivered when the renewable sources are not available. One of the simplest approaches is to utilize the ES when the production from renewables is higher or lower than the demand. However, with the development of forecasting tools of power generation and demand, more complex strategies can be implemented in order to obtain economic benefits, or to promote self-consumption to minimize the energy exchange and reduce the stress on the electrical grid.

Overall, the scientific outcomes detailed in this report reflect the effort of harnessing the resources, facilities, and expertise provided by the Institute of Control and Industrial Electronics from the Warsaw University of Technology and Aalborg University, for the successful development of the project, from June 2022 to September 2023.

3.2.2.Scientific outcomes

In the early stage of the project, the main activities were related to the acquisition of skills in software tools to develop models of power electronics converters (PECs) that are needed to interface renewable energy sources and batteries. The software utilized at the institution is PLECS. Additionally, the adopted approach for implementing control algorithms in the simulated model is used to easily migrate the developed algorithms from the simulation model to real applications that use a microcontroller where the devices' software is embedded.

On the other hand, research on the state of the art regarding energy management systems at the residential and distribution levels was conducted. The objective of this activity was to get familiar with the methodology, tools, techniques, and solutions that have been proposed in the literature and to identify the current trends and gaps in research. Besides, one of the energy management techniques from the literature was implemented as a first approach to later propose a novel solution that addresses the limitations found in the literature. Once the simulation tools and software for collaborative cooperation were set, the first stage was to develop the topology of the system under study in the simulation model and propose the power ratings at which the system has to operate; one of the determining factors was the capacity of the batteries that are available in the market, which is in the range of 10-15 kWh.

System under study

The description of the system is as follows: a photovoltaic (PV) array serves as a renewable energy electricity source. A Li-ion technology battery is selected to support the limitations of intermittent power generation of the PV source and considering that the system must be able to operate in grid-connected conditions and also in standalone mode, which is of utmost importance, for example, in the case of planned (maintenance) or unplanned (faults) outages. The power electronics stage was designed considering that the system is connected to the low-voltage distribution network, which is typically three-phase. In this context, it is essential to consider that in the case of standalone operation, the system has to supply unbalanced loads. PV arrays and batteries operate with DC, meanwhile, loads in a grid-connected environment work with AC.

For the PV array and the battery, DC-DC converters are used for each source, and the converters are then connected to a DC-AC converter that interfaces with the residential loads and/or the electrical grid. For the PV array the converter is unidirectional meanwhile for the battery the converter is bidirectional as it is necessary to provide current in both directions. Finally, for the DC-AC stage, a three-phase four-leg converter is selected as this configuration allows for better support in the case of unbalanced loads. The details for each configuration are discussed in the following.

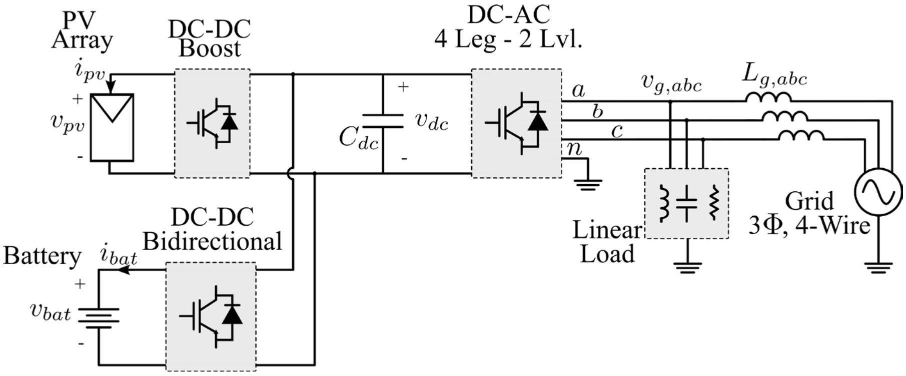
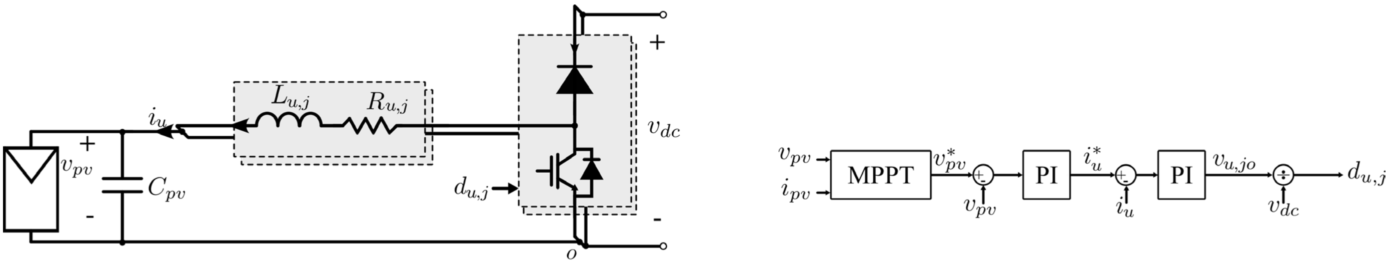


Figure 1. System under study.

PV system modeling and control

The PV array is modeled using the single-diode Shockley equation and an irradiance-dependent current source, for this model, the inputs are the solar irradiance and the temperature and the model accounts for the temperature drift of the open circuit voltage as well as the short-circuit current. Additionally, the model is flexible in the sense that different power ratings can be achieved using the same model. The DC-DC converter used is an interleaved boost converter, that is connected to the DC bus capacitor that couples the DC sources with the grid-side converter.

The main task of the converter is to extract the maximum available power from the PV array, to either be used by the DC-AC converter or by the battery converter. To achieve this objective the controller structure has to account for a Maximum Power Point Tracking (MPPT) algorithm, which will produce a voltage reference that has to be controlled at the input terminals of the converter, to follow the voltage reference two cascaded proportional-integral (PI) regulators are chosen, the outer one provides a current reference to the inner loop, and the latter produces the duty cycle that commands the switches of the converter, Figure 2 shows the topology of the PV converter and the local controller configuration.

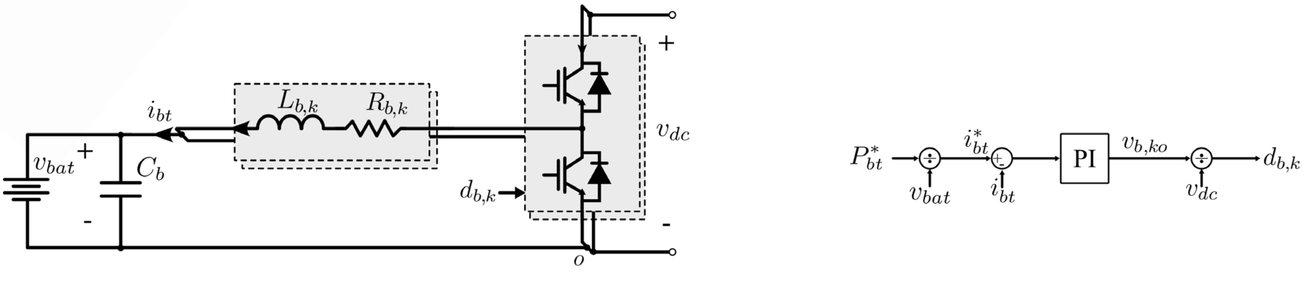


(a) (b)

Figure 2. PV system structure. (a) PV converter. (b) Local controller.

ES system modeling and control

For the development of the battery model, research of the different options available in the literature was conducted, to determine which was the most suitable option for this application. After a comparison of the different characteristics, a run-time model was selected in which is possible to include the capacity, dynamic behavior of the battery, and the non-linear relation between the State of Charge (SoC) and the battery voltage. The latter is one of the most important features as the energy level of the battery has to be monitored and kept within allowable limits during operation to preserve the battery's lifetime. The PEC selected for this application was a bidirectional interleaved converter, that is in charge of controlling the charging and discharging of the battery. The lithium-ion battery can be operated in constant current mode in the range of 20% to 90%, therefore a current controller is used, the power reference is converted to a current reference and then a PI controller is used to track the reference current to command the switches of the converter. The power stage and local controller of the ES system are shown in Figure 3(a) and Figure 3(b), respectively.

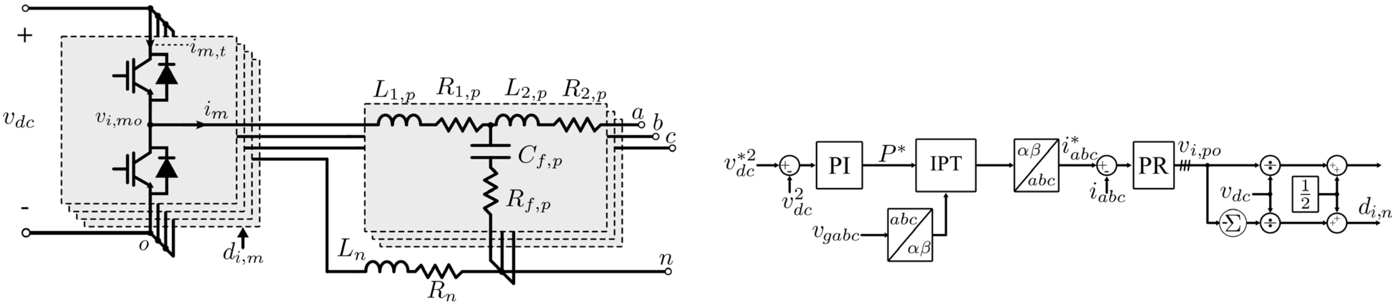


(a) (b)

Figure 3. ES system structure. (a) ES power stage. (b) Local controller.

DC-AC converter and control

The DC-AC converter comprises four legs, this configuration provides better support to the unbalanced loads, to interface the converter to the grid it is necessary to reduce the harmonics produced at the switching frequency, therefore an LCL + L filter is used, compared to the L filter this configuration reduces the total inductance needed for the same attenuation. The controller of this converter is in charge to regulate the power between the DC-DC converters (battery and PV) and the grid as needed, to allow to provide energy from the PV and battery to the loads or to take the power from the grid to charge the battery. As part of this task the voltage on the capacitor that couples the DC and the AC stages has to be controlled. A cascaded control structure is used, in this case the DC bus voltage error is fed to a PI controller, its output and the grid voltage measurements are used to generate appropriate sinusoidal current references that are tracked using a proportional-resonant controller, to finally activate the switches of the converter accordingly. The converter and the local-controller are presented in Figure 4(a) and Figure 4(b), respectively.



(a) (b)

Figure 4. DC-AC stage structure (a) Converter. (b) Local controller.

Simulation results of transient and steady state conditions

The system has been tested considering different scenarios that are faced during the operation of the system. Due to the variability of the solar irradiance the system is evaluated under changes of irradiance. Furthermore, transitions from charging to discharging is also tested, which in turn can be leveraged to test scenarios in which the power is taken or sent to the grid. In Figure 5(a), results of steady-state and transient behavior of the ES system are shown, on the other hand the waveforms for validating the DC-AC converter model are presented in Figure 5(b).

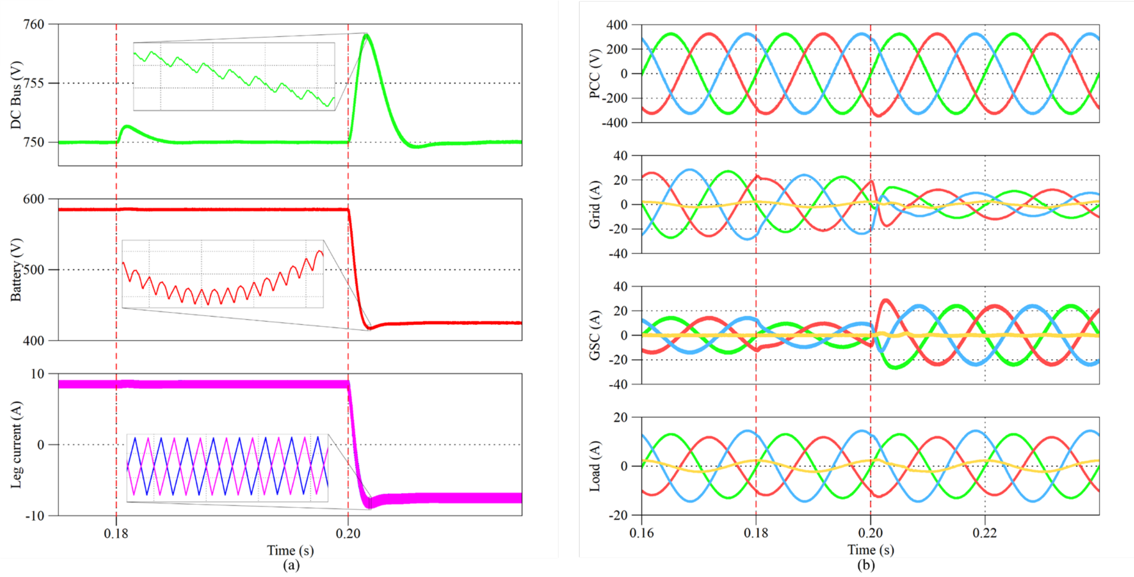


Figure 5. Simulation results for switching model. (a) From top to bottom: DC bus voltage, Battery voltage, and Leg current of the battery converter. (b) From top to bottom: Voltages at the PCC, Grid currents, converter currents, and load currents.

Simplified model to reduce computational burden and time during simulation

Up to this point the modeling and validation was conducted considering the switching conditions of the converter, however this modeling-simulation approach is time consuming, with a high computational burden. As one of the objectives is to develop energy management systems, these, have to be studied in longer time scales compared to the low-level controllers. A well-known approach is to use an averaged model, as this reduces the state-space matrixes used for simulation. Therefore, the proposed model was further modified from a switching one to an averaged one. The main idea of this technique is to replace each switching leg with one current and one voltage-controlled source and the rest of the elements of the model as the PV array, battery, passive components and even the controllers remain the same. The averaged model of the system was carried out and validated under both transient and steady-state conditions. Details of the description of the system and comparison of operating modes was conducted. It was demonstrated that with this approach the execution time is reduced to up to 67% compared to the switching model.

Research on different EMS for grid-connected environments

Once the model of the system in grid-connected operating mode was developed, the following step is to implement one of the energy management systems found in the literature for residential-level applications. A diagram of the methods found in the literature is shown in Figure 6, from the research on the state of the art a summary of the literature was conducted, there are two approaches that are found in the literature.

a) Rule based EMS: A set of rules for the continuous operation of the system is determined. The most common objective is to promote self-consumption which is to charge the battery when generation exceeds demand and discharge the battery when there is no generation available from renewable sources. The main advantage is the simplicity of the approach; however, this comes at the expense of having to rely on the expertise of the designer, and as more elements are included in the system the complexity increases. From the rule-based approaches those can be further developed with the use of fuzzy logic theory or once that the set of rules have been set with algebraic engines.

b) Optimization based EMS: In this case an optimization problem is formulated and not only the operation of the system is guaranteed, but with the help of emerging technologies such as load and generation forecast services, additional objectives as cost minimization and energy minimization can be achieved. Plenty of research has been conducted using different algorithms to solve the optimization problem, however there is a lack of experimental validation compared to numerical one and the dynamics of the PECs is often neglected.

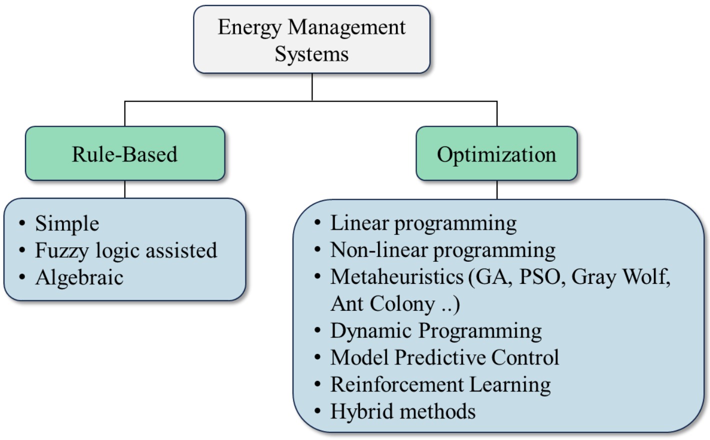


Figure 6. Classification of existing EMS in the literature.

Implementation of rule-based EMS

As a first approach a simple EMS is implemented in the developed model. However, it is important to highlight that an additional ancillary service is proposed in which the power is kept constant at the point of interconnection with the grid. This is implemented by means of a PI controller that tracks the desired power reference from the grid and harnesses the available power from the battery to compensate from the power fluctuations produced by the grid and loads. An additional rule-based diagram, (Figure 7(b)) is used to disable the operation of the battery when it reaches the upper or lower limit of the SoC. The power profiles for keeping a constant power from the grid are shown in Figure 7(a), P_{PV} is the power of the PV array, P_L is the power demanded by the loads, P_B is the power of the battery and P_G is the grid power. It can be seen that when the SoC is within allowable limits P_G is kept constant, and when the SoC reaches either the lower or upper limit, the battery is disabled.

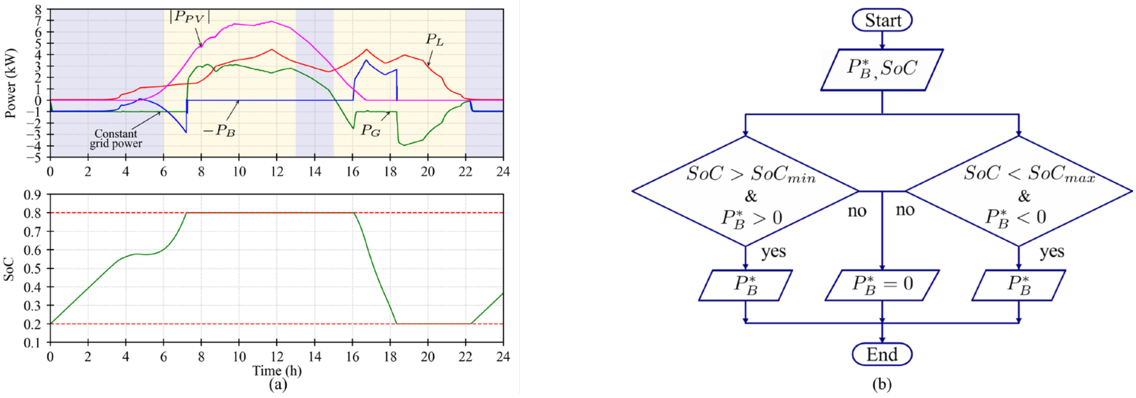


Figure 7. Rule based EMS for constant grid power. (a) Power profiles of the system. (b) Flow chart of rule-based EMS.

Implementation of optimization EMS

After the investigation of optimization-based approaches for EMS, the metaheuristic approach was selected as it is not limited to the constraints or the form of the objective function of the optimization problem that must be solved. The problem is formulated taking into consideration the operational constraints of the system.

Energy Management for cost minimization

After reviewing the characteristics, advantages, and disadvantages of the different optimization methods a Genetic Algorithm is selected and implemented, where the objective is to get the best economic benefit possible. With this approach, it is possible to leverage the information of forecast services from generation and load demand for one day to determine the battery charging and discharging cycles. The constraints under consideration are the following:

Constraints

Power limits: According to the manufacturers' specifications a battery has to be operated around 0.5 C rate which means that it has to be charged/discharged to up to half of the capacity of the battery, and is described by the following equation

$$P_{B,min} \leq P_{B,t} \leq P_{B,max}$$

SoC target: In this case the proposal allows to set a desired SoC at the end of the day, therefore not only the battery will be fully exploited but this constraint can guarantee a level of charge for the next day operation.

$$\sum_{t=1}^{k} \Delta SoC_t + SoC_0 = SoC_k$$

Where ΔSoC_t, is the change of the SoC at time t and is approximated as:

$$\Delta SoC_t = P_{B,t} \cdot \frac{\Delta t}{C_{bat}}$$

For this approximation Δt, represents the time period for a given battery power P_B, and C_{bat}, corresponds to the battery capacity.

SoC limits during operation: To guarantee that the sequence of charging and discharging cycles doesn't cause overcharge or under discharge of the battery, a set of constraints has to be included and can be written as:

$$SoC_{min} \leq SoC_0 + \sum_{t=1}^{T=1,2,\ldots,23} \Delta SoC_t \leq SoC_{max}$$

The cost of the energy depends on the time of the day and the amount of the energy used during that period, in this case study, the power balance of the system can be approximated as:

$$P_G = -(P_L + P_B + P_{\mathrm{PV}})$$

And the cost function is represented by,

$$f = \sum_{t\,=\,1}^{24} P_{G,t} \cdot \Delta t \cdot c\left(P_{G,t}, t\right)$$

The coefficient $c\left(P_{G,t}, t\right)$ represents the cost of the energy, and it depends on the time of the day and the sign of the grid power, it is desired to use the battery power, P_B as the decision variable, and assuming that the load and generation profiles are know, the power balance equation can be replaced in the cost function resulting in:

$$f = \sum_{t\,=\,1}^{24} -\left(P_{L,t} + P_{B,t} + P_{\mathrm{PV,t}}\right) \cdot \Delta t \cdot c\left(P_{G,t}, t\right)$$

Energy Management for energy minimization

Instead of promoting self-sufficiency, only when there is an excess of production, a new optimization problem was formulated where the objective function is the minimization of the energy exchange of the grid during one day, in this case the same constraints are used as they are proposed in light of the operational requirements, but the cost function is modified accordingly, in this case the goal is to minimize the energy exchanged with the grid in the whole day, the cost function is the following:

$$g = \sum_{t=1}^{24} \left| -\left(P_{PV,t} + P_{B,t} + P_{L,t}\right) \right| \Delta t$$

Comparison

In the context of the Time of Use tariff, typically there are two energy tariffs, one for high-demand hours of the day and the other for low-demand periods. A simple strategy is proposed in which the battery is charged during low-price periods to reach the maximum SoC before the high price period in which the battery is discharged to the minimum possible SoC. Results of the power profiles and SoC profile of the tariff-driven, cost and energy minimization are presented in Figure 8(a), Figure 8(b) and Figure 8(c), respectively.

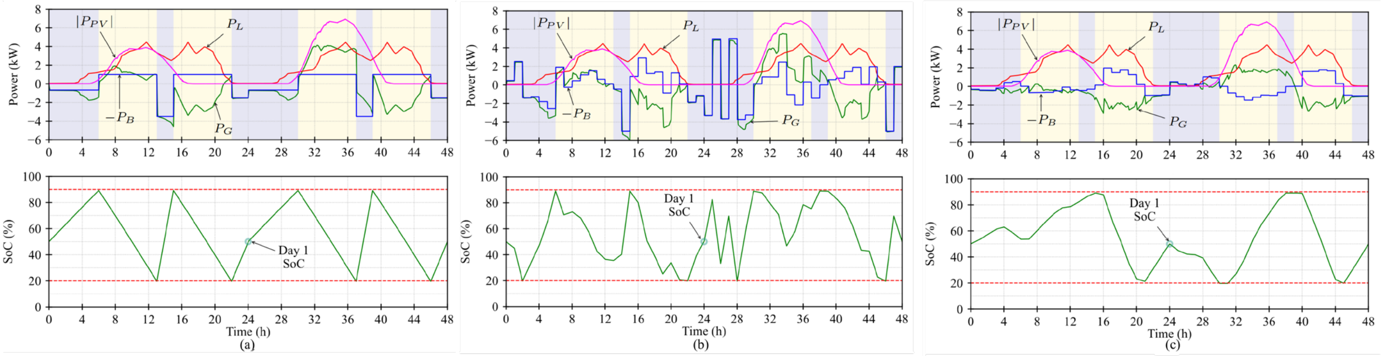


Figure 8. Results for EMS, top: Power profiles, bottom: SoC profile. (a) Simple strategy. (b) Cost minimization. (c) Energy minimization.

Study of the optimal battery state of charge considering different power profiles for consecutive days.

Previous results were extended considering two consecutive days of operation under different combinations of power profiles, the goal of this study was to set find out what is the best setting of SoC at the end of the first day considering different combinations of power profiles, either sunny or cloudy days for each

Submission of journal paper

A paper has been submitted to the IEEE Open Access Journal of Power and Energy, with the latest results for the different EMSs implemented, considering different generation profiles, and different targets of SoC at the end of the first day to determine the option that minimizes the overall cost or energy depending on the utilized cost function.

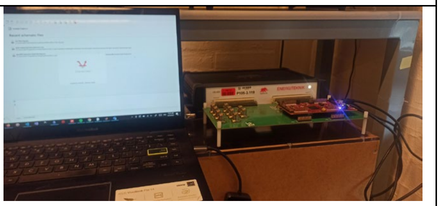
3.2.3.Contribution to the WP objectives

The development of a simulation testbench that includes power converters, and local controllers to interface renewable energy sources and ES technologies to the electrical grid was carried out. One step ahead was taken with the implementation of a HIL model which allows for real-time simulation and further test of controllers of the system developed in a microcontroller. This stage contributes to the third objective demonstrating the operation of different and complementary DERs for supplying Smart Buildings.

Development and comparison of EMS was conducted, demonstrating operation strategies for the grid-connected mode of operation, and the constant power controller proposal that serves as an ancillary service contributing to objectives 1 and 3 ("To identify and demonstrate new ways of managing electric energy generation by using Renewable Electric Energy Generation (REEG) and Distributed Energy Resources (DER) as agents of a Collaborative Smart Grid (CSG)" and "To establish power generation patterns and new efficient converters for each technology to determine the best way to coordinate the operation of different and complementary DERs for supplying Smart Buildings or Houses, increasing the Renewable Energy share in the Electric Energy Generation Mix, or providing ancillary services").

3.2.4.Scientific achievements

Experimental prototypes

#	Name	Description	Status (designed, assembled, tested)	Photo
	Hardware-in-the-loop (HIL) test setup	Test target: implement the primary level controller on the target hardware. Test setup: plant is built in Typhoon HIL and the controller is designed for TI TMS320F28379D microcontroller	Assembled and testing.	

Publications

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
1	L. Martínez-Caballero, R. Kot, A. Milczarek and M. Malinowski, **"Converter Averaging Approach for Modeling a Residential Supply Subsystem,"** *2023 IEEE CPE-POWERENG* Tallinn, Estonia, 2023, pp. 1-6.	Conference	Published	10.1109/CPE-POWERENG58103.2023.10227479
2	A. Milczarek and L. Martinez-Caballero, **"Control Strategy of Hybrid Energy Storage System for High-Dynamic Load Changes,"** *2023 IEEE CPE-POWERENG*, Tallinn, Estonia, 2023, pp. 1-5.	Conference	Published	10.1109/CPE-POWERENG58103.2023.10227479
3	L. Martínez-Caballero, R. Kot, A. Milczarek and M. Malinowski, **"Energy Management Techniques for Grid-Connected PV- and Battery-supplied Residential System"**, IEEE Open Access Journal of Power and Energy, 2023	Journal	Submitted	

3.3. Task 2.3 – IRP3 "Virtual Power Plant for operation, both isolated and connected"

3.3.1. Introduction

The scientific outcomes have been obtained during 10 months in the facilities of the PE and ES Research Group of the University of Extremadura, Spain and 2 months in the Power Electronics Group of Tallinn University of Technology, Estonia. The main research work was started by performing a complete literature review of Virtual Power Plants (VPP). This was followed up by writing a review paper on some of the functions and roles of VPPs. After completing the literature review, a case study was performed in which simulation work was done by using MATLAB Simulink. The main idea of this case study was to get familiarized with the design and performance of a grid connected PV inverter consisting of single-phase unbalanced loads and observing its effects in different points of the microgrid. Even though a single microgrid is studied in this case, the idea is to follow it up with a system consisting of more than one microgrid which can offer grid support as well as ancillary services during unbalanced condition. Next research work was followed up with a genetic algorithm developed and tested to control the energy storage system and the charging and discharging of electric vehicles consisting of technical and financial goals.

3.3.2.Scientific outcomes

Virtual Power Plant:

The virtual power plant (VPP) is the integration of distributed energy resources (DER) under a coordinated management system. A VPP is an interconnected network of decentralized, small-scale power resources, such as solar panels, wind turbines, power converters, energy storage systems and manageable loads that work together under the control of an aggregated control system. Like a conventional centralized power plant, the VPP may be regulated to adapt to changes in energy demand and supply and can offer grid services like balancing and stability. The purpose of this integration of dispersed energy resources into a unified utility grid is to improve the energy system's dependability, flexibility, and efficiency.

Large, centralized generation units were intended to be managed by the power system so that real-time monitoring and control of their safe operation and dependability was possible. Renewable energy sources (RES), such as solar, wind, and hydro power, have been growing in popularity due to their environmental benefits and decreasing costs. However, their integration into existing power systems has presented new challenges for control and operation. The overwhelming amount of information including weather forecasts, power demand, and supply, that operators must process in real-time and the dependability of the power electronics-based systems working in parallel, as hundreds of power converters would be simultaneously exchanging energy with the grid, is the main obstacle to increasing the expansion of RES. In practice, it has already been observed that generation systems powered by power converters are having an impact on the stability and dependability of power systems due to the dynamics of the converter not matching well with the dynamics of the grid or due to the introduction of voltage and current harmonics into the power system. Even though distributed RES-based units are currently only considered because of their modest involvement, this will change soon due to the rapid increase in RES integration and the diminishing situation of fossil fuel power facilities. To balance generation and demand while also contributing to the stability of power systems, utility-scale renewable power facilities must be designed and operated in a certain method.

Microgrids:

The global Photovoltaic (PV) cumulative installed capacity crossed a total of 1000 GW by the end of 2022. This rapid growth in PV based power plants comes with a greater challenge of successful operation and grid integration of the aforementioned power plants along with testing the system with different types of diverse conditions.

In order to have a performance similar to the conventional power plants, the replacing grid-connected power inverters used in distributed power generation systems should be carefully designed and controlled.

One of the most important tasks to be considered in controlling grid-connected power converters is the proper synchronization of the inverter output voltage with the three-phase voltages of the electrical grids it is connected to. The three-phase voltage should be understood as a vector consisting of three voltage components, which provides the capability of generating and consuming power in a three-phase system.

The module and the rotation speed of the three-phase grid voltage vector remain constant when balanced sinusoidal waveforms with equal amplitude, frequency, and relative phase shift are present in the three-phases of the system. Large synchronous generators in power systems initially produce this rotating voltage vector, and electrical devices at the transmission, distribution, and usage levels are designed to presume that such a voltage vector has both a constant module and a continuous rotation speed. However, in fact, there are several non-idealities in power systems that lead to disturbances on the three-phase voltage or current vector, as unbalances or harmonics. Synchronization system should be able to detect voltage vector disturbances, and the power converter's control system should be able to ride through such operating situations while also providing some grid support.

Engineers and researchers have been working to improve traditional grid-connected power converter control solutions, studying their operation under abnormal grid conditions including the critical case of supplying unbalanced loads. Unbalanced loads frequently result in uneven grid voltages at the power converter's connection point. The currents injected into the grid lose their sinusoidal and balanced look under unbalanced situations. The interaction of such currents with uneven grid voltages could result in uncontrollable oscillations in the active and reactive power sent to the network. Under such circumstances, maintaining the appropriate operation of the power converter is a control challenge. For grid-connected inverters the control of currents injected into the grid is critical. While the initial developments were primarily aimed at providing solutions for balanced grid systems, the focus of engineers and researchers has recently shifted to controlling the current injection of grid-connected power converters under unbalanced grid voltage conditions. Situation is different, in the case of islanding operation, during which the voltage reference is set directly. The grid requirements are a very important specification having a big impact on the design and performances of the PV inverter. The operative limits are established by standard European regulation, in grid-connected mode voltage and frequency limits are Un ± 10% and 50 Hz ± 1% respectively, in isolated mode these limits are extended to Un + 10% / -15% and 50 Hz ± 2%.

VPP roles:

Function that VPP can implement should cover:

- Inertia Support Capability

The VPP offers inertia support by synchronizing the parameters of grid-forming inverters. Additionally, an online learning-based parameter sets method is created that allows the VPP's inertia to be adjusted. Constant voltage and constant frequency control (V/f control), constant power control (PQ control) and virtual synchronous generator control (VSG control) are the three control techniques that the majority of DERs use to function. Grid-following (GFL) inverters frequently use PQ control, which is dependent on pre-determined frequency and voltage reference values. As a result, it cannot deliver active adjustable inertia support. V/f control, which is commonly adopted in grid-forming (GFM) inverters, can function in a microgrid's islanding mode but cannot supply inertia. A possible method to reduce system inertia is VSG control, which replicates the inertia and damping properties of traditional synchronous generators (SGs). By modifying the GFM inverters' control parameters (i.e., damping coefficient D and the moment of inertia J) in VSG mode, the DERs' inertia can be changed.

- Power Quality and Stability

The grid-supportive capabilities of smart grids help the system to maintain power quality and stability. For network managers to directly observe and control every single inverter and DER, however, would not be feasible. VPPs and distribution energy resource management systems (DERMS) are therefore being studied in global states with high penetration of renewable energy. The DERMS software organizes various DERs to achieve local feeder-specific advantages such as optimal power flow, locational capacity relief, and voltage and active power management. The management system can send control signals to smart inverters in DERMS-type applications to control demand-flexible DERs to assist the grid, such as discharging batteries to match the demand or halting electric vehicle (EV) charging to reduce demand. The inverter can function as an interface between the grid and the local energy asset because of its position at the point of intersection in the power network.

- Voltage Stability and Transient Frequency Analysis

The flow and control of energy were the main objectives of the VPP models in the past. A dynamic VPP model must be implemented for the system transient response study, a model that works well for system analysis and that the Transmission System Operator (TSO) can use to assess the effect of VPPs in the entire grid. The suggested framework can support the transient response of the vital controllers that comprise the distributed generators that constitute the VPP. The suggested aggregated model's validity is confirmed by comparison with a real-time detailed Electro-Magnetic Transients (EMT) model of the VPP.

- Reactive power compensation, Frequency Support and grid-forming capability

Transmission system operators (TSOs) are increasingly demanding power plants with power converter interfaces to provide frequency support, reactive power compensation, and grid-forming capabilities. In these plants, a substantial number of converters are run concurrently, and each one must be properly coordinated to offer these services. The virtual synchronous machine (VSM) control approach is frequently used for this purpose. The number of connected converters, their size, control settings, and electrical connections all affect how dynamically the entire plant behaves. Because of this, it is challenging to understand how each VSM affects the plant's response and its aggregated dynamic characteristics.

- Fast frequency support

System operators have been obliged to tighten grid rules to require renewable power plants (RPPs) to offer fast frequency support, such as power oscillation damping and inertia response, because of the growing contribution of renewables to power systems. This can be achieved by implementing virtual synchronous power plant controller (VSPPC) for RPPs. Since it allows for the reproduction of inertia and offers capabilities for power oscillation damping, the VSPPC benefits the most from replicating the behavior of a SG, particularly in the case of grid events. The primary benefit of the VSPPC is that it avoids the need to modify the converter controllers in the plant, which are frequently controlled as grid-following generation units.

At present, RPPs are required to offer dynamic services like power oscillation damping and inertia response in addition to traditional control services, such as voltage regulation and frequency. One of the approaches to establish these newly required services is to use the grid-forming power converters instead of grid-following power converters, which may use a controller based on a virtual synchronous machine. Each power converter that forms a grid can function as a synchronous generator to give the grid damping and synthetic inertia, primarily managing the current or power reference. It has been shown that the implementation of a grid-forming power converter is practical for a single power converter. This strategy might not be financially viable for RPP, though, as it would be necessary to spend more time and money to design a new control system for the power converters. Moreover, the grid-forming power converters' independent parallel functioning may result in problems with power oscillation in the plant.

- Active and Reactive Power Control

Distributed generation helps to improve the quality of power. Distributed generation (DG) provides significant advantages for the enhancement of the voltage profile and power factor in places where voltage support is challenging due to constraints on the primary (central) power grid. Large-scale decentralized power generation unit implementation may also cause instability. This is caused by the ineffective power control of the DG units, which also causes reactive power imbalance and fluctuations in the voltage of the power network. These factors make operating DG sources in a regulated environment crucial. As a result, DG control paradigms have been proposed, with MicroGrid and VPP being the two primary ones. For synchronous generators, there are currently no control paradigms that permit independent control of the machine's active and reactive power output. For any network to be stable, the power balance must be maintained. Generator instability, which can include rotor angle instability, voltage instability and frequency instability can be brought on by an improper balance of active and reactive power in the network.

A VPP is a network-based system which combines and controls numerous DERs as if they were a single power plant. The VPP communicates with the grid operator and the combined DER. While physical power is exchanged between DERs and the grid, the VPP communicates with both the grid operator and the aggregated DERs as shown in Figure 9.

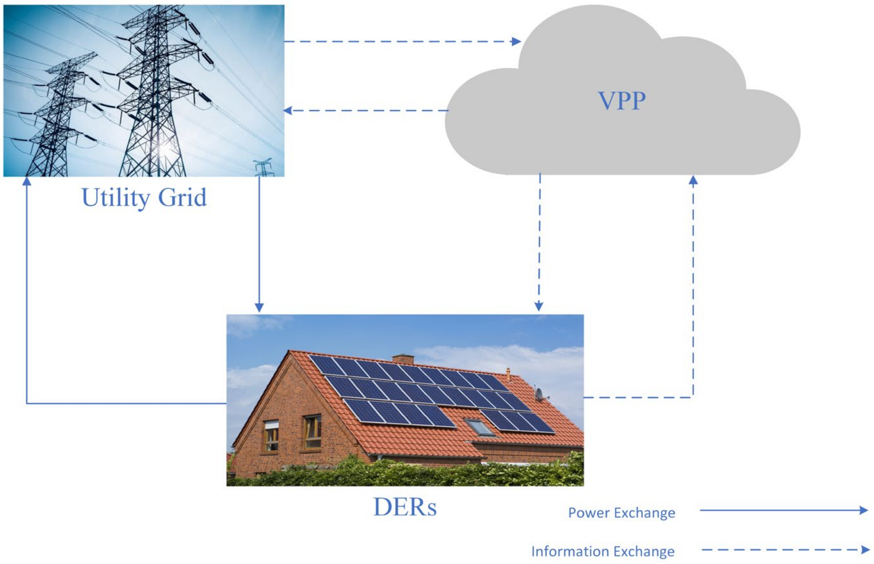


Figure 9. Overview of VPP interactions.

Operation in unbalanced situation

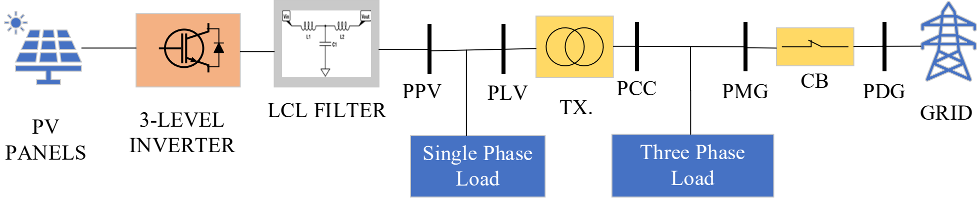
In previous studies, the effect of unbalanced or single-phase loads in the point of low voltage (PLV) to that in the microgrid are observed either in case of grid connected operation or in case of islanded mode operation. Different types of power balancing techniques have been developed to mitigate this problem of unbalanced condition in islanded microgrid. The situation is similar for the case in which only grid connected operation is considered. Also, there is a research gap in the operation of this type of system considering different values of irradiances. Moreover, an islanding detection based on field-programmable gate array (FPGA) considering voltage and frequency deviation of the phase locked loop (PLL) at the PCC is a common practice in disconnecting the grid and operating the system in grid forming mode. The islanding detection failure due to the introduction of unbalanced loads is also a common occurrence where the islanding detection fails and results in a false trip command due to different types of loads such as constant impedance, constant current, and constant power loads. However, this type of islanding detection should be tested under unbalanced conditions to evaluate the islanding detection failure in case the detection parameters exceed the operation mode boundary values resulting in a false islanding trip command under different values of irradiances. In this paper the operation of a three-phase photovoltaic plant (rated at 250 kW) will be analyzed when it supplies power to a single-phase load in the PLV and compared with situation of being totally balanced. The analysis will be not only done in grid connected but also in isolated mode considering different values of irradiances. The paper includes a basic method to detect the islanding condition to be able to perform the analysis in both grid connected and islanded modes and to study the transient behaviour from one mode to the other. The main analysis and novelty of the paper is the identification of cases in which the islanding detection method fails due to the unbalanced condition in the PLV along with variation in irradiances values and verify the reliability of the islanding detection method.

The operation in unbalanced situation has been studied use the case shown in Figure 2 that discusses about the performance of a 250 kW three-phase photovoltaic power plant that supplies electricity to both single-phase and three-phase loads. The analysis considers voltage and frequency deviation of the phase locked loop (PLL) at the Point of Common Coupling (PCC) and the effect on the entire system taking into account unbalanced situations with different values of irradiances is observed. The analysis covers both connected and disconnected modes. It also includes the performance of a basic islanding detection method. This work is unusual in that it identifies a situation in which single-phase loads are connected at the location of low voltage and the islanding detection fails.

Figure 10 represents the general block diagram of the overall system. It consists of a PV field composed by 616 solar panel modules (with parameters shown in Table I) connected in an array of 7 in series and 88 in parallel, totalling a power of 250kW.

Table I. Main parameters of Solar Panel Module

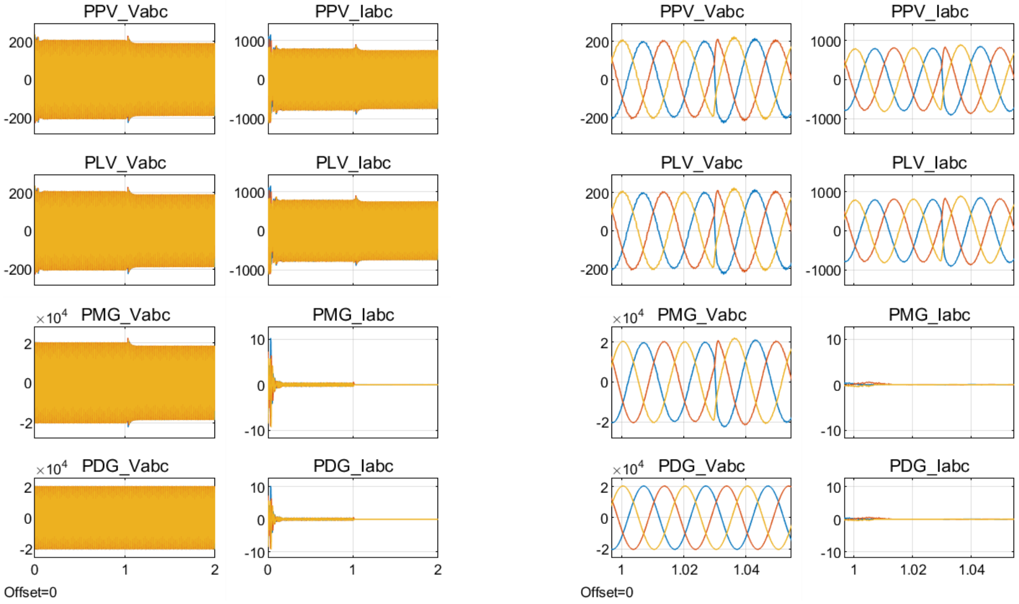
Parameter	**Value**
Reference	SunPower SPR-415E-WHT-D
Open voltage	85.3 V
Short circuit current	6.09 A
MPP Current	5.69A
MPP Voltage	72.9V
MPP Power	414.801W



PPV- POINT OF PV
PLV- POINT OF LOW VOLTAGE
PCC- POINT OF COMMON COUPLING
PMG- POINT OF MICROGRID
PDG- POINT OF DISTRIBUTION GRID
TX.- TRANSFORMER
CB- CIRCUIT BREAKER

Figure 10. Power System Under Study

In the balanced situation, the microgrid is initially connected to the main grid and at 1s, it is disconnected after opening the corresponding breaker. Simulations results are shown in Figure 11 where it can be seen that the system operates properly in both modes. The reference voltages, both in LV and HV points of the inverter are 250 VRMS L-L and 25kVRMS L-L respectively. In the balanced situation, the microgrid is initially connected to the main grid and at 1s, it is disconnected after opening the corresponding breaker. Simulations results are shown in Figure 11 where it can be seen that the system operates properly in both modes. The reference voltages, both in LV and HV points of the inverter are 250 VRMS L-L and 25kVRMS L-L respectively. Figure 12 shows the main magnitudes of the photovoltaic field, where it can be seen that the PV power is adjusted during the islanding operation. Figure 13 shows the main variables related to the islanding detection and operation mode. It can be seen that the detection time is about 30 ms (lower than the limit established to 2s by norms-IEEE-STD 1547) and the detection in this case is mainly based in the frequency deviation (50.1 Hz) since the system detects the frequency deviation before the voltage deviation. The control algorithm for islanding modes achieves that the frequency and voltage of the system goes back to acceptable values, i.e. 50Hz and 0.86 p.u. (higher than the lower limit of 0.85).



(a) (b)

Figure 11 Voltage (in V) and current (in A) waveforms in different points of the microgrid, as indicated in Figure 10a: (a) Simulated results, (b) Zoom at 1s (disconnection)

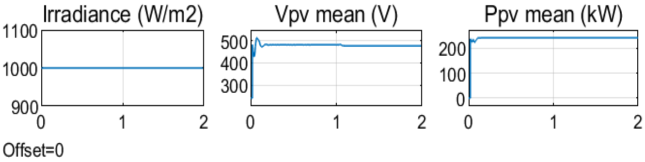


Figure 12. Sun Irradiance, PV voltage and PV power during the case under study (connected and disconnected).

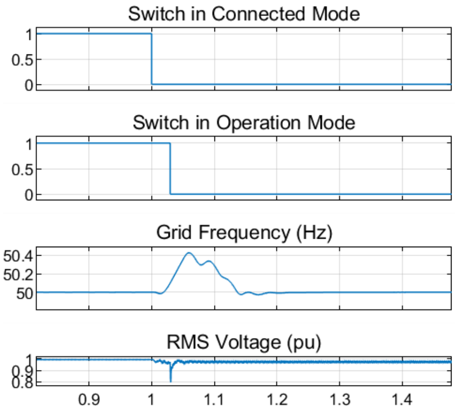


Figure 13. Detection of the Islanding condition based on the frequency and voltage deviation in the PMG.

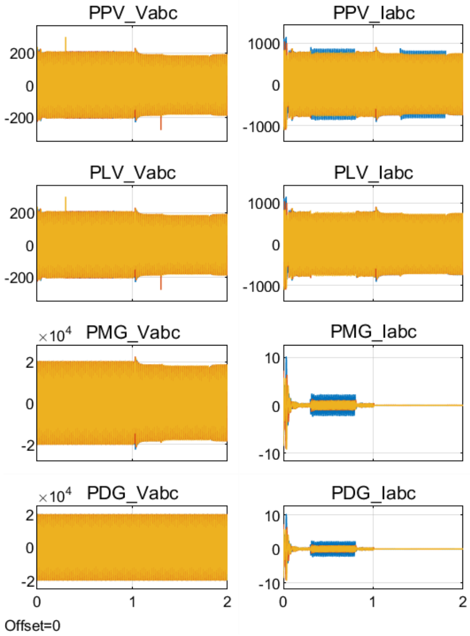
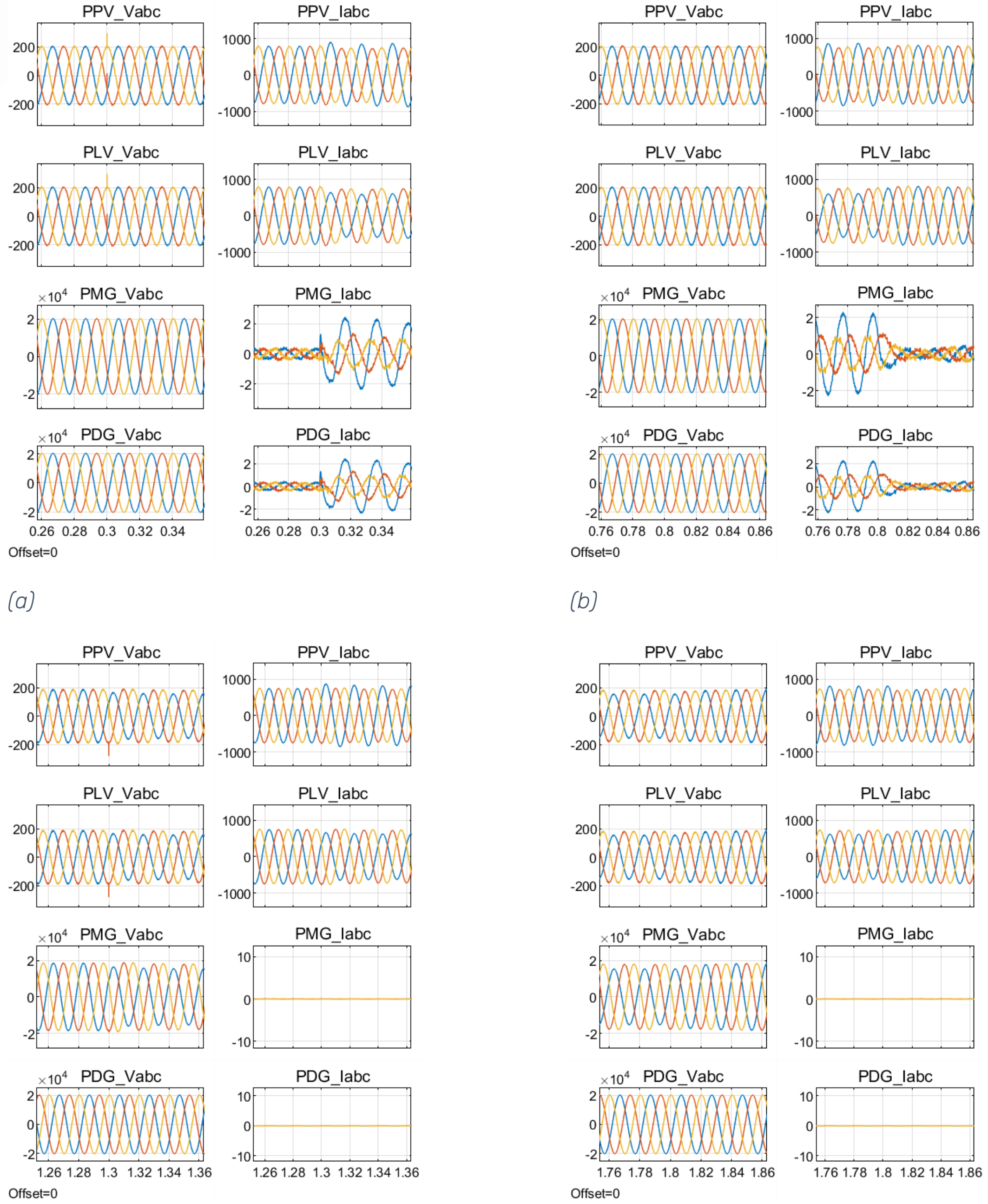


Figure 14. Simulated results, voltage (in V) and current (in A) waveforms in different points of microgrid, as indicated in Figure 10.

The analysis of operation under unbalanced condition is done by considering the case where a single-phase load of 80kW is connected in phase a of the low voltage feeder (between 0.3s to 0.8s and 1.3s to 1.8s). The response of the proposed system is analysed both, in connected to the grid mode from 0s to 1s and in disconnected mode from 1s to 2s.

The whole system is also analysed considering different values of irradiances. Figure 14 shows the results for the proposed case when the irradiance level is 1000 W/m2.In this case, when the single-phase load is not connected the power generated by the PV is close to the power demanded by the local load in the microgrid. Figure 15 shows the transient details when connecting and disconnecting the single-phase load in both grid-connected and isolated modes. It can be observed that, even though the voltage waveforms are not affected considerably due to the synchronization to the grid voltage, the current waveforms in the low voltage feeders are affected considerably and results in unbalanced condition between 0.3s and 0.8s of the simulation time. The effect of unbalanced condition in the low voltage feeder results in an even greater unbalanced current in the high voltage distribution grid. This in turn may affect the power quality of the grid and must be taken under consideration while designing a grid connected power inverter. After 1s, the grid is disconnected from the system and a single-phase load is introduced at 1.3s. A similar type of behaviour can be observed in the grid disconnected mode as well. However, the current as well as voltage waveforms are now greatly influenced by the unbalanced condition. This is because of the disconnection of the grid from the system due to which the grid can no longer support the unbalanced condition of the inverter output voltage. The negative sequence voltage rises to a peak value of approximately 9.7% during islanding mode from grid connected mode.

Table II represents the results obtained during the simulation. It can be concluded that, with the increase in irradiance, the negative sequence voltages during unbalanced condition remain unchanged in grid disconnected mode but the peak values of the negative sequence voltages increase while disconnecting the grid from the system. However, the negative sequence currents decrease in grid connected mode with the increase in irradiance. During a fault condition, the system starts operating in islanded mode due to the tripping of the switch and hence the system must be restored back to the grid connected mode of operation.



(a)

(b)

(c)

(d)

Figure 15. Details of voltage (in V) and current (in A) waveforms in different points of microgrid, as indicated in Figure 10: (a) Zoom at 0.3 s, (b) Zoom at 0.8 s (c) Zoom at 1.3 s, (d) Zoom at 1.8 s

Table II. Results obtained during Simulation.

Simulation Time (s)	GCM (Y/N)	SPL (Y/N)	Negative Sequence Voltage (%)			Negative Sequence Current (%)		
			Irradiance (W/m^2)			Irradiance (W/m^2)		
			800	1000	1200	800	1000	1200
0 to 0.3	Y	N	0	0	0	0	0	0
0.3 to 0.8	Y	Y	0	0	0	3.8	3.5	2.6
0.8 to 1	Y	N	0	0	0	0	0	0
1 to 1.3	N	N	0	0	0	0	0	0
1.3 to 1.8	N	Y	1.2	1.2	1.2	1.2	1.2	1.2
1.8 to 2	N	N	0	0	0	0	0	0

Here, GCM: Grid Connected Mode, SPL: Single-Phase Load, Y/N: Yes/No

It can be also concluded that, the negative sequence currents decrease in grid connected mode with the increase in irradiance due to the influence of a single-phase load in the system whereas it remains constant in islanded mode. To effectively design a more robust solar power-based grid connected inverters, the effects of single-phase loads in the low voltage feeders must be taken into consideration in the distribution grid now so even more than ever with the growing presence of inverter-based generators connected to the distribution grid. It is also important to identify the problems caused due to the connection of single-phase load (decreasing voltage quality) and perform a reliability test of the islanding detection. The future work will focus on balancing the currents in the PCC produced by the single-phase load and thus reducing the effects of unbalanced condition. Moreover, an advanced detection method of islanding condition can be implemented in the system.

Cyber-security hazards

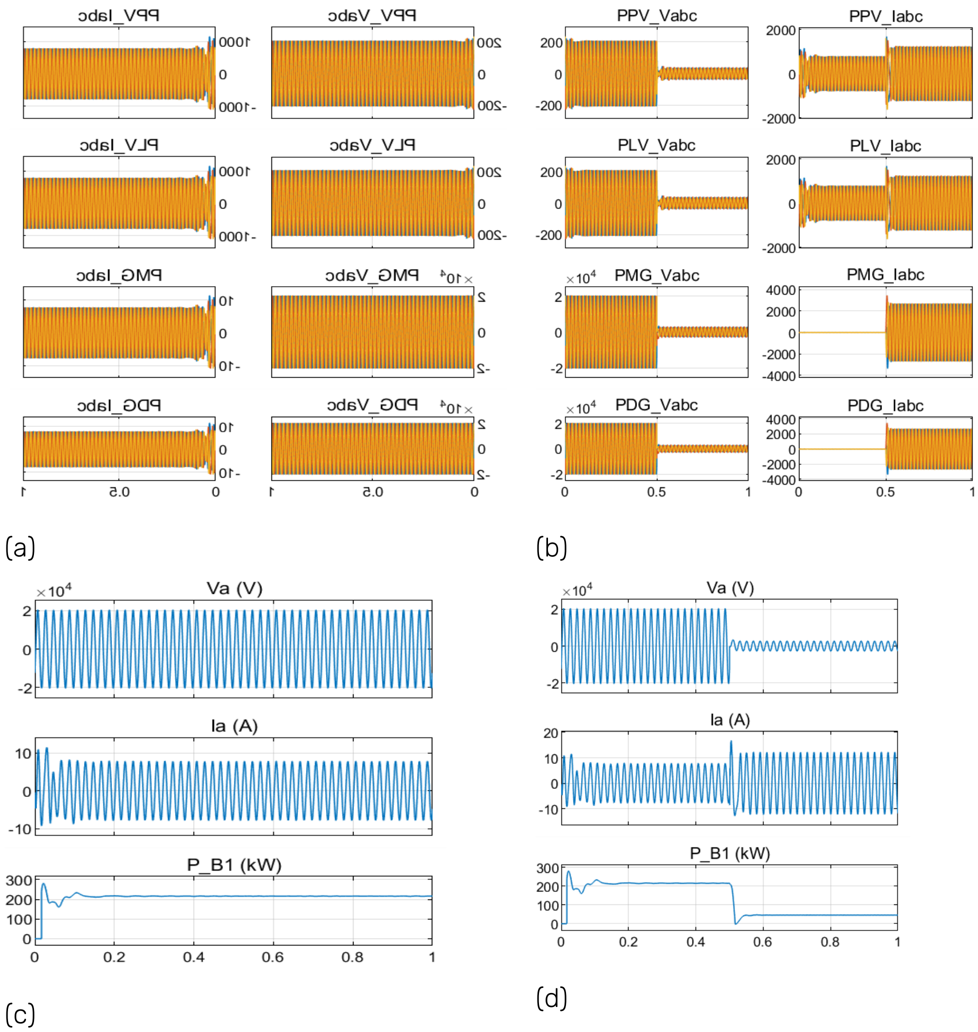
Cyber-security is another important feature that must be taken into consideration for present-day smart grids. This paper consists of cyber-attack detection along with a novel solution by using islanding mode of operation of the VPPs when an attack takes place in the main grid. It also deals with the contribution of modern-day smart grids in the context of VPPs.

The increased implementations of VPPs also comes with the challenges affiliated with data protection, securing physical systems and information privacy. Cybercriminals can now deliberately attack the energy sector to disrupt operations thanks to recent technological breakthroughs. Despite efforts by security researchers to reduce the dangers and vulnerabilities, it is still difficult due to the evolution of VPPs into a cyber-physical based system. This is why it is important to have technological innovation in the cyber physical spaces to keep up with the new and unknown methods of cyber-attacks in the energy sector. The energy sector has recently been one of the most targeted industries. Over time, the attackers' motives have evolved. Table III illustrates the increase in other incentives, such as cyberwarfare and causing disruptions, even though money is still the dominant driver.

Table III. Effects of Cyber-Attack.

Name of Cyber Attack	Place	Year	Impact	Vulnerability
BlackEnergy	Ukraine Power Grid	2014/2015	In Ukraine, a power disruption for a duration of 6 hours occurred which affected almost 230,000 people.	Poor infrastructure, corruption, and tensed relations with external countries
Industroyer/Crash Override	Ukraine Power Grid (North City of Kiev)	2016	Ukraine lost 1/5 of its electrical capacity due to an hour-long power outage.	Direct control of the switches and circuit breakers at power grid substations using four ICS protocols
Triton	Oil and Gas Plant Saudi Arabia	2017	The attackers were interested in causing an explosion to spread throughout the entire plant, but their plan was thwarted due to a virus flaw and vulnerability.	Malicious TriStation protocol use by a malware framework to target the Triconex Safety Instrumented System (SIS) controllers

One of the basic methods of identifying a cyber-attack is determining the manipulation of the voltage and current and as a result the power at different setpoints in a transmission line which are also known as Point of Common Coupling (PCC). The voltage and current in these PCCs are constantly compared with a fixed set of values in the cyber security outer layer. If there is a drastic change in either the voltage or current and as a result, the active power in these PCCs, it should be assumed that there is a high chance of the system being attacked during that period. In the given illustration of N number of DEGs Technical Virtual Power Plant (TVPP) for the closed form derivation of Thèvenin voltage, the cybersecurity analytics system's methodology for identifying normal operation region serves as the foundation. This region of regular operation is used as a confirmation approach to separate malicious set-points that the network cyber-layer requires. A cyber attacker who controls the set-points for the VPP cyber-layer is the source of these harmful set-points. Based on a derived one-to-one mapping between the cyber-layer generated set-points and the internal PCC bus voltages of the network, the normal operation region is defined. Using internal PCC bus voltage monitoring, this derived mapping is contrasted with an inverse mapping to look for anomalies. The voltage anomaly is caused by an intrusion after the cybersecurity analytics system notices a discrepancy between the one-to-one mapping and the inverse mapping.



(a) (b) (c) (d)

Figure 16. Voltage (in V) and Current (in A) waveforms in different points of microgrid, as indicated in Figure 2a (a) during normal condition, (b) after the attack; and Voltage (in V), Current (in A) and Active Power (kW) waveforms of a single phase during (c) normal condition, (d) under attack.

The system is simulated for a total of 1s by using MATLAB Simulink software as demonstrated in Figure 16. It is assumed that at 0.5s, the system is attacked by the hacker in between the point of microgrid and distribution grid and as a result the voltage, current and power values are changed from their rated values. From these manipulated values, it can be easily identified that the system is under attack by the hacker and necessary steps must be taken to bring the system back to normal operating condition.

In the second case, it is assumed that a cyber-attack takes place in between the main grid and the distribution grid. Often in many circumstances, a hacker has no prior knowledge regarding the total network of VPPs across the whole transmission system. However, the hacker may have the total information regarding the main grid. In this case, the hacker tries to manipulate the data in the main grid system and makes the system unstable and as a result, a blackout may occur. One of the many solutions in this scenario is to isolate the grid from the system and use the islanding mode operation for the microgrid. In this case, the detection takes place if the voltage changes to ± 15% and frequency to ± 0.1Hz.

In Figure 17, a flowchart based on the algorithm can be established based on these aforementioned conditions.

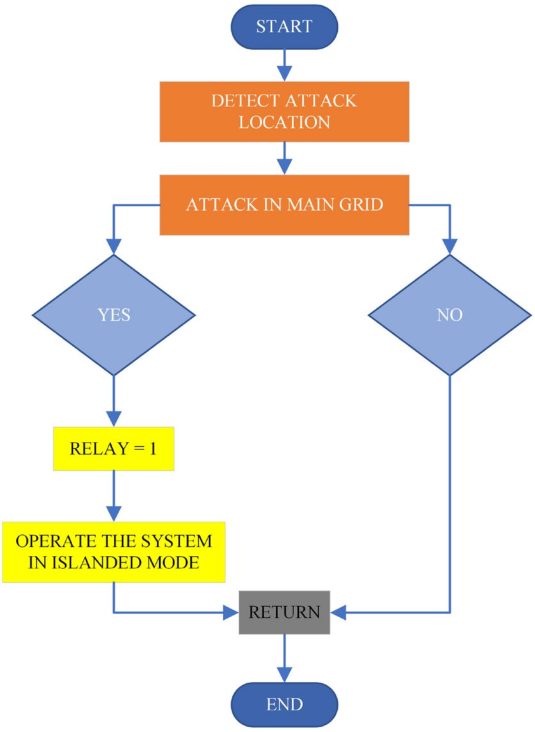
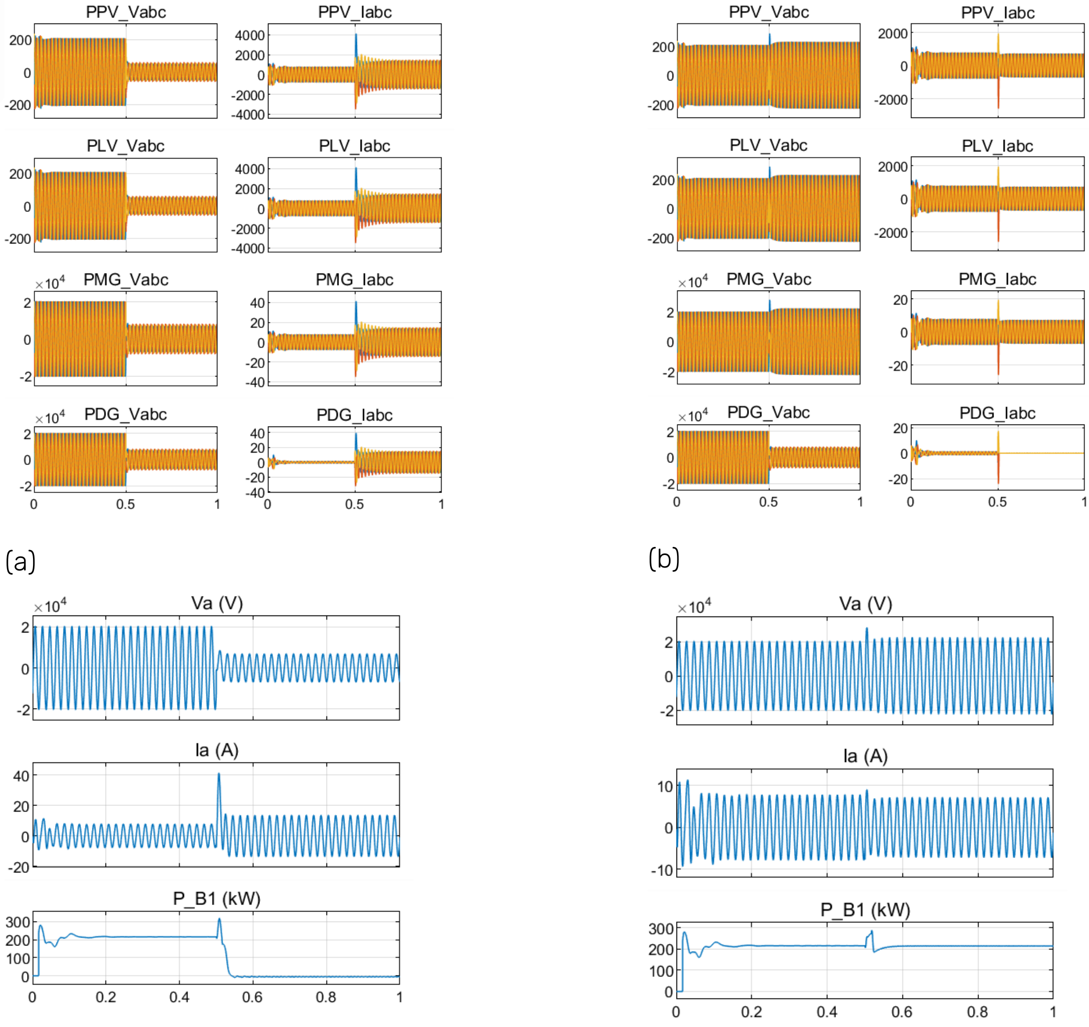


Figure 17. Flowchart for operating the system in islanded condition due a cyber-attack in the main grid.

In this case in Figure 18, the simulation results are observed for a total duration of 1s. At 0.5s, a hacker tries to manipulate the system in the main grid location. It can be observed that, if the main grid is not isolated from the grid connected PV based solar power plant, the system becomes unstable and is not able to generate any active power. However, if the grid is disconnected from the system by means of a relay, breakers and using islanding mode of operation, it can be observed that the solar power plant is able to supply active power into the loads and the system remains stable.

Use of Advance AI algorithms

It is important to incorporate the use of AI for enabling the VPPs for being a useful tool in the integration of distributed resources such as renewable generation, electric vehicles, manageable loads, and energy storage systems under a coordinated management system to obtain economic advantages and provide ancillary services to the grid. A management system for a virtual domestic power plant that comprises photovoltaic generating, household loads, energy storage technologies, and electric vehicles is suggested in this case. The virtual power plant is economically optimized (like commercial virtual power plants) with the proposed management system while delivering ancillary services (like technical virtual power plants) to the distribution grid. With a number of technical and financial goals, a genetic algorithm is developed and tested to control the energy storage system and the charging and discharging of electric vehicles. In order to demonstrate that single-objective optimization techniques outperform multi-objective ones in the circumstances under study, they are put side by side. The effectiveness of the genetic algorithm is additionally verified using a deterministic gradient-based optimization technique. The findings demonstrate that these technical and economic targets, which are often designated for larger virtual power plants, may be successfully managed in smaller virtual power plants.



(a)

(b)

(c)

(d)

Figure 18. Voltage (in V) and Current (in A) waveforms in different points of microgrid, as indicated in Figure 2a (a) before islanding condition, (b) after islanding condition; and Voltage (in V), Current (in A) and Active Power (kW) waveforms of a single phase (c) before islanding condition, (d) after islanding condition.

For this study, a genetic algorithm has been defined and programmed to optimally obtain the charge/discharge power of storage system and of electric vehicles (restricted to their availability time slot). Different objectives functions and constraints have been tested and compared. An economic target is defined by means of an objective function related to the cost of the net electricity bill, including purchase and sale of electric energy. A technical target is included in two alternative ways: by means of an objective function to minimize the power interchange with the grid, or with a peak-shaving restriction. Table IV compares the results, in terms of self-consumption index (SC), self-sufficiency index (SS), cost saving and extreme power peak. The table shows that the best saving is obtained using only the minimum cost objective function (case 2), but only combining this objective function with a peak shaving constraint (case 3), the extreme power is bounded in 10 kW. Figure 19 shows the power interchange between the VPP and the grid in base case and after optimization process in case 3, proving the accomplishment of the constraint. Results obtained outperform both classical deterministic optimization methods an even multi-objective genetic algorithm.

Table IV. Comparative analysis of results.

Case	Base	1	2	3	4
Description	Without ESS	Min. power interchange	Min. cost	Min. cost + peak shaving	Multi-objective
SC (%)	59.87	**79.10**	58.16	62.88	57.75
SS (%)	33.89	**53.30**	39.19	42.36	38.91
Electricity bill (EUR/day)	23.47	20.58	**19.95**	21.94	22.53
Cost saving (%)	0	12.3	**15.0**	6.5	4.0
Extreme power peak (kW)	−36.44	−11.09	−23.67	**−10**	−18.32

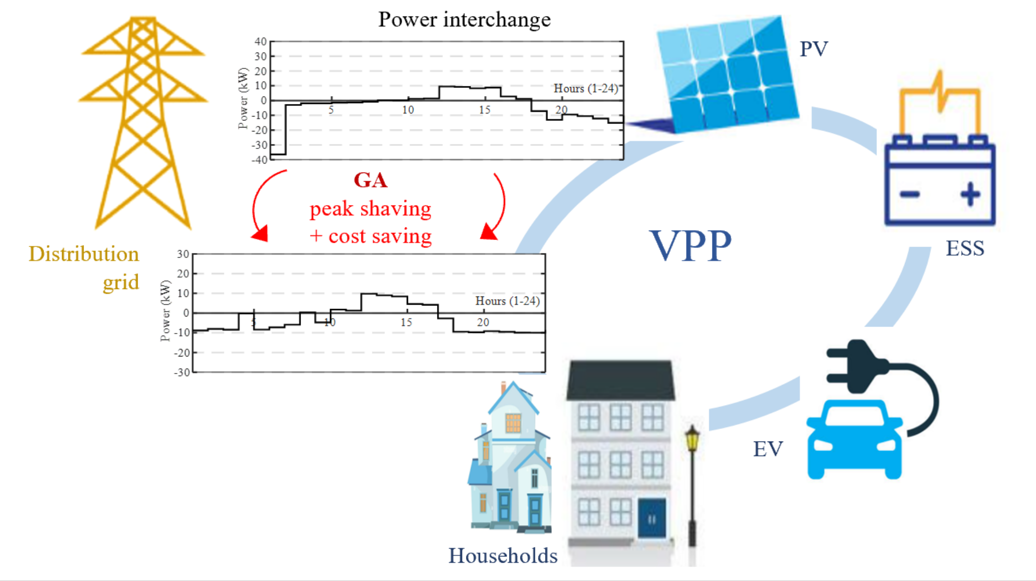


Figure 19. Power Interchange between the VPP and the grid before and after the optimization process.

3.3.3.Contribution to the WP objectives

The present research work has contributed to the WP objectives by designing and optimization of VPPs, covering a study case consisting of grid connected PV based inverter and a coordinated system for the integration of distributed energy sources. The case study includes the design and performance evaluation of a 250kW grid connected inverter based on PV panels as the energy source. This system can be operated in both grid-connected as well as islanded mode. This research has also contributed to analyse the effects in power quality and efficiency in the case of unbalance produced by a single-phase load in the microgrid by observing the magnitude of the second-order harmonics in different nodes of one proposed system taken as a prototype. The research has identified some operation strategies for the energy management system based on genetic algorithm and how these strategies can optime the operation of the whole system.

Different criteria have been used in the optimization process: minimizing the cost of the electricity bill or providing ancillary services to the distribution grid (namely peak shaving), During the research process, advanced algorithm techniques are being studied to be used in VPPs that integrates more than one microgrid to improve reliability and resilience.

The work is contributing in particular objectives 1 and 3 of the WP:

- To identify and demonstrate new ways of managing electric energy generation by using Renewable Electric Energy Generation (REEG) and Distributed Energy Resources (DER) as agents of a Collaborative Smart Grid (CSG);
- To establish power generation patterns and new efficient converters for each technology to determine the best way to coordinate the operation of different and complementary DERs for supplying Smart Buildings or Houses, increasing the Renewable Energy share in the Electric Energy Generation Mix, or providing ancillary services.

3.3.4. Scientific achievements

Publications

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
1	**Alvi, A.A.**, Romero-Cadaval, E., González-Romera, E., Hassan, J., Vinnikov, D. (2023). An Overview of the Functions of Smart Grids Associated with Virtual Power Plants Including Cybersecurity Measures. 14th Advanced Doctoral Conference on Computing, Electrical And Industrial Systems, 5-7 July 2023. Caparica, Portugal	Conference with peer review	Published in Conference Proceedings	-
1	**Alvi, A.A.**, Romero-Cadaval, E., González-Romera, E., Hassan, J., Vinnikov, D. (2023). An Overview of the Functions of Smart Grids Associated with Virtual Power Plants Including Cybersecurity Measures. Technological Innovation for Connected Cyber Physical Spaces. IFIP Advances in Information and Communication Technology. Springer 2023, ISBN: 978-3-031-36006-0	Book Chapter	Published	https://doi.org/10.1007/978-3-031-36007-7_7
2	**A. A. Alvi**, E. Romero-Cadaval, E. González-Romera, D. Vinnikov and J. Hassan, "Performance Evaluation of a Three-Phase PV Power Plant under Unbalanced Conditions with Islanding Detection Reliability Test," 2023 IEEE 17th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG), Tallinn, Estonia, June 2023, pp. 1-6,	Conference	Published	https://doi.org/10.1109/CPE-POWERENG58103.2023.10227391
3	González-Romera, E.; Romero-Cadaval, E.; Roncero-Clemente, C.; Milanés-Montero, M.-I.; Barrero-González, F.; **Alvi, A.A.** A Genetic Algorithm for Residential Virtual Power Plants with Electric Vehicle Management Providing Ancillary Services. Electronics 2023, 12, 3717.	Journal In Q2 (second quartile in JCR)	Published	https://doi.org/10.3390/electronics12173717

3.4. Task 2.4 – IRP4 "Condition Monitoring for Smart Power Electronic Converter Systems for Distributed Generation"

3.4.1. Introduction

The objective of this research is to improve the reliability and resilience of distributed generation systems by providing innovative condition monitoring methods to critical power converters. The current research work uses harmonics in control variables of inverters to monitor the health status of IGBTs, which provides a noninvasive, online monitoring interface without additional hardware. The current research work has been obtained during 12 months in Aalborg University.

3.4.2. Scientific outcomes

Background

Power electronic-based converters are critical devices in a distributed generation system. The health status of power electronic-based converter has impacts on system reliability and cost. Based on reports collected from 350 PV inverters [1] and 350 wind turbines [2], it has been estimated that these systems can contribute upto 43% and 13% of failures as well as 36% and 18% of power downtime, respectively. Hence, monitoring the health of the conversion units is vital in improving the operational reliability of the system.

The power semiconductor devices in inverters, e.g., IGBT, constitute 10% of system failures and have high repair costs [3][4]. There are several fault precursors that can be used to estimate the health status of power semiconductor devices, wherein measuring on-state voltage can provide accurate results [5]. Some previous works measure the on-state voltage of power semiconductor devices by adding measurement circuits [6][7][8][9][10]. These methods can derive the on-state voltage accurately, but most of them are invasive, hard to measure online, and involve deployment of additional measurement circuits. These aspects thereby are costly alternatives from an implementation perspective, making them hard to implement.

To bridge the gap between previous works and industry applications, there is a need to build a practical and economical condition monitoring method for power electronic-based distributed generation systems. The objective of this research is to monitor the health of power semiconductor devices. Based on the health status of each component and inverter, the maintenance schedule can be optimized, system reliability can be improved, overall cost is reduced, and waste is reduced.

One way to implement condition monitoring is using harmonic in control variables to monitor the health status of power semiconductor devices. This method has the advantages of non-invasive, online monitoring, and avoiding extra measurement circuits. The following sections discuss this method in detail. First, the reason why power semiconductor degradation increases the on-state voltage is explained. Second, the impact of power semiconductor device degradation on the inverter circuit is modelled. Third, the characteristics of controller response is analyzed and modelled. Finally, the result from simulation is used to validate the theory.

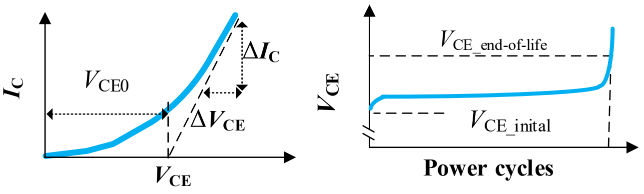
On-state Voltage of IGBT

This section introduces the trend of the on-state voltage with package-related degradation.

The on-state voltage of IGBT has two equivalent parts: a constant voltage part V_{CE0} and a resistive voltage part, as shown in Fig. 1 (a). The constant voltage part V_{CE0} is independent of the collector current I_c, while the resistive part is current dependent since it represents the parasitic resistances. The on-state resistance R_{on} can be defined as the slope of the transfer characteristic, as given in equation (1).

$$R_{on} = \Delta V_{CE} / \Delta I_C \qquad (1)$$

The on-state resistance depends on the health status of bond wires, surface metallization, and die attachment; the potential failure causes can be temperature cycling, power cycling, and coefficient of thermal expansion (CTE) mismatch between different materials [11]. Therefore, the on-state resistance can indicate the health status of packages. When the package is degraded, the on-state resistance usually increases, leading to an increment in the on-state voltage. In an accelerated degradation test triggering the package-related failures, the on-state voltage keeps increasing from the initial voltage $V_{CE\_initial}$ to a value exceeding the end-of-life threshold $V_{CE\_end\text{-}of\text{-}life}$, as shown in Fig. 1 (b).



(a) (b)

Fig. 1: (a) Transfer characteristics of an IGBT. (b) The on-state voltage increases in the accelerated degradation test.

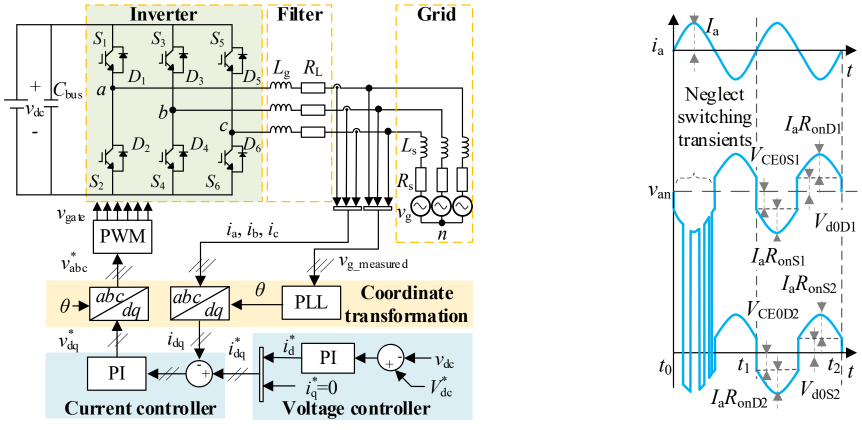
Modelling Impact of On-state Voltage on Inverter

This section explains the mechanism of on-state voltage affecting the inverter operation.

There are various topologies for inverter applications, and this work selects a widely used three-phase, two-level voltage source inverter to study. An inverter system diagram is illustrated in Fig. 2 (a). The inverter consists of six IGBTs $S_{1\text{-}6}$ and six diodes $D_{1\text{-}6}$. The controller consists of a voltage controller and a current controller. The voltage controller maintains the bus voltage v_{dc}, while the current controller regulates the inverter output current i_{abc} and i_{dq}. The current controller is implemented in a direct-quadrature *dq*-synchronous rotating frame.

From the inverter point of view, the on-sate voltage is a voltage disturbance. The on-state voltage reduces the inverter output voltage v_{an}, v_{bn}, and v_{cn}. Then, the reduced inverter output voltage affects inductor current i_a, i_b, and i_c. The current controller observes the variation in the inductor current and compensates for the variation. Consequently, the current controller output v^*_{dq} and v^*_{abc} are affected by the increased on-state voltage.

Fig. 2 (b) illustrates how the on-state voltage of IGBTs and diodes affect the waveform of the phase A output voltage v_{an}. The phase A current i_a is positive when time t is between t_0 and t_1. In this period, the upper envelope of v_{an} is affected by the on-state voltage of S_1, and the bottom envelope is affected by the on-state voltage of D_2. In the negative current period from t_1 to t_2, the envelope is affected by S_2 and D_1. When the on-state resistance of IGBTs or diodes increases, the waveform is further reduced from the original v_{an} waveform.



(a) (b)

Fig. 2: (a) A three-phase two-level grid-connected inverter controlled by an outer bus voltage loop and an inner current loop.

(b) Inverter output voltage showing the voltage disturbance induced by parasitic parameters of power semiconductor devices.

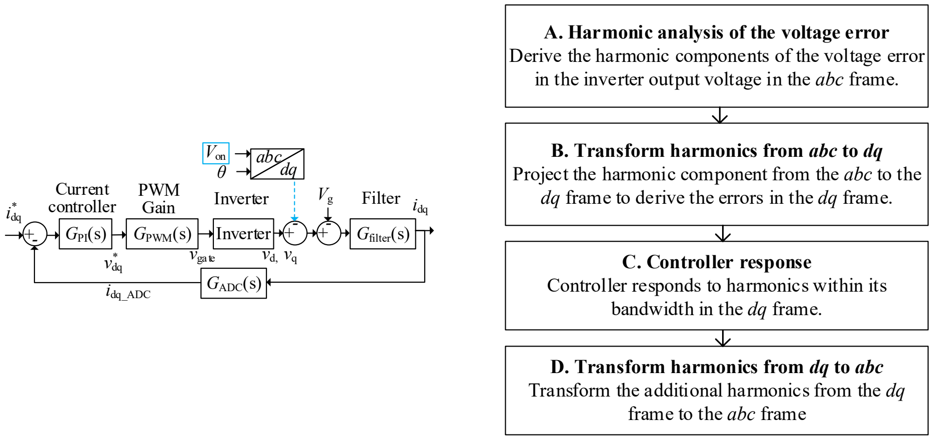
Modelling of Controller Response

The above section analyses the disturbance in the time domain. This section models the disturbance and response in the frequency domain.

Fig. 3 (a) is a control diagram of the current control loop. The disturbance is added to the inverter output voltage v_d and v_q. After the filter stage, the disturbance is added to the inverter output current i_d and i_q, as well as sensed current $i_\mathrm{dq\_ADC}$. The disturbance can also be observed from the proportional-integral (PI) current controller output v^*_dq and v^*_abc (also known as the voltage reference) and the gate signal v_gate. The gain between the on-state voltage and the disturbance at each variable can be calculated based on the transfer functions of the plant and the controllers. This work selects the current controller output v^*_dq and v^*_abc to estimate the increased on-state voltage because these variables have higher gains and are known variables to the controller.

There are some frequency-domain characteristics need to be considered: the zero-sequence components cannot flow in the topology and the controller can only compensate for disturbances lower than the control loop bandwidth. As a result of which, the frequency-domain characteristics should be studied, and low-frequency harmonics are used for increased on-state voltage estimation.

Fig. 3 (b) is a flowchart showing the calculation process of the harmonics in the current controller output v^*_dq and v^*_abc. The first step is calculating the harmonic components in the voltage disturbance in the *abc* frame, which means the increased harmonics induced by the increased on-state resistances of power semiconductor devices are calculated. Then, the voltage disturbances are converted into the *dq* frame to be consistent with the controller. The next step is calculating the controller responses both in the *dq* frame and the *abc* frame.



(a) (b)

Fig. 3 (a) Control diagram of the current control loop. (b) Flow chart of harmonic calculation based on the increased on-state voltage disturbance in v^*_dq and v^*_abc.

Validation

Theory in the above sections is validated through PLECS simulation. The simulation condition is adding on-state resistance ΔR_on to one of the IGBTs S_1 to study the increased harmonics in the v^*_dq and v^*_abc. Fig. 4 (a) compares low-frequency harmonic components in the *abc* frame and the *dq* frame from both calculation and simulation. When the increased resistance of S_1 is 1 mΩ, the increased harmonic components are in the range of several millivolt. The results from calculation and simulation have similar magnitude and trend in when the harmonic order is between 0 and 5. In addition, the phase A harmonics are two times of the harmonics in the other two phases. In another simulation condition, the increased resistance of S_1 varies from 0 to 1 mΩ with a step size of 0.1 mΩ. The harmonic components from 0 to 5th order are shown in Fig. 4 (b). It is worth to note that the example only shows the harmonic components of adding ΔR_on to S_1, but the method can be applied to more complicated cases with multiple degraded power semiconductor devices and their increased on-state resistances.

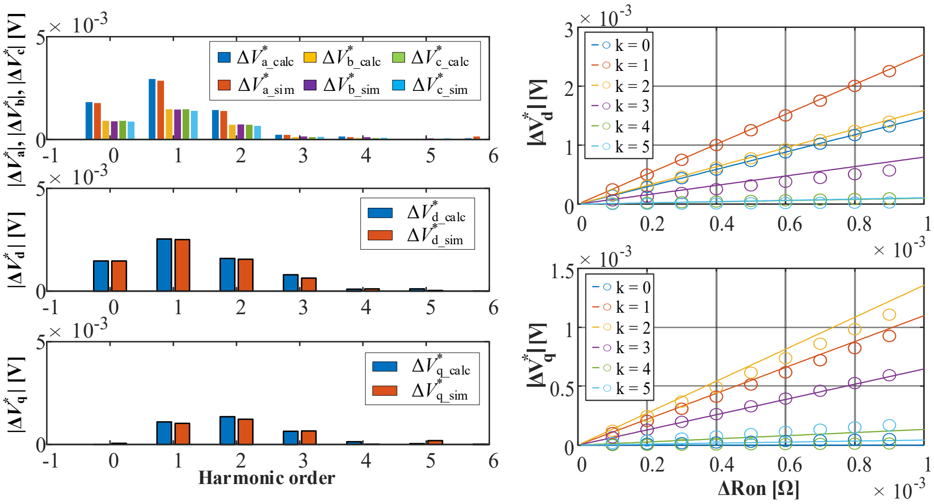


Fig. 4: (a) Comparison of harmonics magnitude between calculation and simulation. The increased on-state resistance of S_1 is ΔR_{on}=1 mΩ. (b) Comparison of harmonics between calculation (solid lines) and simulations (circles). ΔR_{on} of S_1 varies from 0 to 1 mΩ, and the harmonic order k varies from 0 to 5.

Summary

This report explains the importance of the condition monitoring method in a power electronic-based converter system. The gap between the previous research work and the industry applications is analysed. To develop a condition monitoring method that is non-invasive, online monitoring, and free from extra measure circuits, this report studies the possibility of using harmonics in control variables to estimate the on-state resistances of power semiconductor devices. The effects of the on-state resistances to the circuit in both time domain and frequency domain are analysed in detail. The controller response is studied and modelled. The main research outcome is a model between the health precursor of power semiconductor devices and the controller variable.

3.4.3. Contribution to the WP objectives

One of the objectives of WP2 is objective 2: "developing models to describe/predict the behaviour of PV and wind generators and to design the best and safest ways to integrate their generation into existing grids to improve reliability and efficiency". Health status is one of the key behaviours for distributed generation systems. Knowing the health status can help to manage the distributed energy resources in a safe and efficient manner.

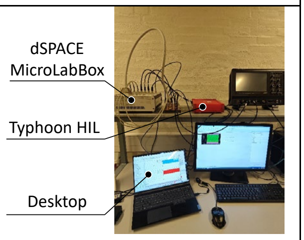
In a distributed generation system, inverters are critical and fragile devices; inside the inverter, power semiconductor devices are causing high maintenance costs. Thus, condition monitoring techniques are required to estimate the health status of power semiconductor devices in inverters. Previous works provided methods to measure the health precursor of power semiconductor devices in an accurate way. However, some previous works are impractical because they are invasive, off-line measurement methods, and require extra measurement circuits.

This work uses the harmonics in control variables as a health precursor of power semiconductor devices, which has the advantages of non-invasive, online measurement, and avoiding extra measurement circuits. The model between the harmonics in control variables and the health precursor on-state resistance is built. Then, it is validated through PLECS simulation.

The main contribution of this work is investigating the possibility of using control variables to monitor the health status of power semiconductor devices. It is a practical condition monitoring method, and it has the potential to be applied to different converters. Monitoring the health status of distributed energy resources based on this research work helps to optimize the maintenance plan, improve system reliability, save waste material, and reduce costs. Consequently, the system is operating in a reliable and efficient manner.

3.4.4. Scientific achievements

Experimental prototypes

#	Name	Description	Status (designed, assembled, tested)	Photo
	Hardware-in-the-loop (HIL) test setup	Test target: validate the model estimating increased on-state resistances via harmonics in control variables. Test setup: plant is built in Typhoon HIL and the controller is built in dSPACE MicroLabBox.	Assembled and testing.	

Publications

#	Title, incl. citation information	Type (Conference, journal, book chapter)	Status (Submitted, accepted, published)	DOI
	S. Ou, A Sangwongwanich, S Sahoo, F Blaabjerg, "Semiconductor Devices Condition Monitoring Using Harmonics in Inverter Control Variables, ".	EPE'23 ECCE Europe	Accepted	

4. Conclusions

Overall, the contributions are within the scope of the corresponding tasks. Scientific results obtained by every WP2 Partner allow us to ensure that the project is on the right track to achieve all its goals. Two ESRs did some experimental validation with the Hardware in the Loop (HIL) technique, in which it is possible to run and verify a target control platform for the prototypes without having actual hardware in the setup.

As for the following goals, ESR01 will continue his research by extending the simulation model to include two parallel-operated converters with detailed performance metrics, such as power losses, harmonic behavior, and redundant operation. He will also focus on implementing the experimental model of the abovementioned converters, including actual power electronics components, control hardware, and grid simulation equipment.

ESR02 plans, based on the research so far, to develop a new energy management control algorithm, for which he will extend his model to include a standalone mode of operation and gain the possibility of fetching and interpreting weather forecast data. He is also in the process of developing a hardware prototype interfacing PV, ES, grid simulator, and local loads.

ESR03 will focus his attention on the family of optimization algorithms for VPP, covering specific constraints and modes of operations. His attention will also be put on the Prototype of the Virtual Control Plant with the control capabilities already developed and able to interface with EMS, local load, and the grid.

ESR04, based on his results, will try to improve the monitoring method in terms of resiliency and reliability. This will lead to the development of the first version of a software tool for the condition monitoring system aiming to enhance the resilience of converters.

As research conducted in all four tasks aims to achieve the same WP2 objectives, it is expected to achieve more collaboration between WP2 Partners, resulting in more joint publications, but even now, there are already some of them

Finally, based on scientific outcomes, all ESRs were able to conduct topic-specific research and develop a working model for testing different solutions. Based on oral and written communication with supervisors and co-supervisors, all four ESRs have been evaluated as highly devoted, responsible, and open-minded researchers.

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