Final report

1. Project details

Project title	Smart Photovoltaic Systems (SPVSYS)
Project identification (program abbrev. and file)	Energinet.dk ForskEl project no.10648
Name of the programme which has funded the project	ForskEL
Project managing company/institution (name and address)	Department of Energy Technology, Aalborg University Pontoppidanstræde 101, 9220 Aalborg
Project partners	Aalborg University Danfoss Solar Inverters A/S Gaia Solar A/S (replaced Sunsil A/S)
CVR (central business register)	29 10 23 84
Date for submission	14/12/15

2. Short description of project objective and results

English:

This project aims to support the higher penetration of PV systems into the electricity network by proposing new, more intelligent converters that are able to interact with the electrical environment at their point of connection – both towards the grid and the PV generator.

The project focused on new PV inverter functionalities and features that in one hand can actively support the grid that is connected to, and in the same time can assess the health state and detect performance degradation and faults in the PV generator. The key results of the project are within automatic PV array diagnostics and performance assessment, grid support functions with large PV plants and voltage support algorithms in small residential systems.

Dansk:

Dette projekt har til formål at støtte højere udbredelse af solcelleanlæg i el nettet ved at foreslå nye, mere intelligente omformere, der er i stand til at interagere med det elektriske miljø på deres punkt i forbindelse - både for siden af nettet og PV generator.

Projektet fokuserer på nye PV inverter funktionaliteter og funktioner, at der på den ene side aktivt kan støtte elnettet, der er tilsluttet, og på samme tid kan vurdere

de sundhedsmæssige tilstande og opdage ydeevne nedbrydning og fejl i PV-generatoren. De vigtigste resultater i projektet er inden for den automatiske PV array-diagnostik og resultatvurdering, el-net supportfunktioner med store PV anlæg og spændingssupport algoritmer i små boligområders systemer.

3. Executive summary

SPVSYS focused on increasing the penetration of PV power into the electricity mix by developing intelligent features of the PV inverter – the key component for converting and integrating the power generated by the PV panels into the existing electricity network.

Two main areas were targeted:

- On the *PV generator side*, diagnostic functions for early detection of faults and performance degradations, with focus on possible implementation in existing PV inverter hardware, were developed. With the increasing importance of the Operation and Maintenance (O&M) cost within the total lifetime cost of PV inverters, these functions can be very important since they support the reduction of O&M cost for PV plants. Furthermore, they help improving the system reliability and availability.
- On the *grid side*, grid integration and grid support features were targeted. With the increasing penetration of PV in the electricity network, this issue is becoming critical, and in response system operators impose increasingly stringent requirements for connected PV generators. In this project smart grid support functionalities for both low voltage distribution network and medium voltage network were developed.

The results of this project can be utilized in the next generation of PV inverters to implement online PV diagnostic and advanced grid support functions, but this project also paved the way to advanced diagnostic, failure detection and reliability and lifetime assessment of PV arrays.

4. Project objectives

4.1 Project description

According to the plan the project was structured into 4 major work packages, with the descriptions as below, reproduced from the project application document:

The goal of the project is to develop new diagnostic and condition monitoring functionalities as well as advanced control algorithms for the PV Power systems focusing on both grid and PV generator sides. All these functions can be implemented in the current platforms of the PV inverters on the market (for example Danfoss Solar Inverters, but could be licensed to other companies worldwide as well) and turn them in so-called Smart PV Inverters with more market value and increased grid integration potential.

In order to achieve the main goal of this project, four main work packages have been defined, which have been grouped under the framework of two PhD projects. Work Packages WP1 and WP2 will be carried out by the PhD project entitled “Advanced control techniques”, while WP3 and WP4 will be carried out by the PhD project entitled “Diagnostic and Condition Monitoring functions”.

WP.1- Advanced grid condition monitoring

Key parameters of the grid - like the grid impedance - indicate changes in the grid strength, islanding, presence of resonances, and type of faults. In this task, advanced grid monitoring algorithms, robust against line distortions, and able to estimate the characteristic parameters of the grid (impedance, open circuit voltage, short-circuit power), will be carried out. Different active methods based on P, Q variation, and harmonic injection will be developed and implemented in PV inverters. The target of this research activity is to provide improved solutions regarding islanding detection, grid-adaptive controller structure, and coordination between distributed PV systems. Focus will be put on development of new, more robust grid condition monitoring methods in presence of high PV penetration.

WP.2 – Advanced grid control

In this task an optimal controller, able to offer the best response in terms of accuracy, dynamic response and robustness will be developed.
The influence of the output filter parameters and grid impedance on the behaviour of the control system will be assessed. Grid integration of PV systems under different grid operating cases (normal and grid faults) as required by the recent grid codes worldwide will be considered in this task. For normal grid operating conditions, voltage support strategies by reactive power will be assessed in order to increase PV penetration more. Other ancillary services like primary frequency control, power factor correction for local loads and harmonic compensation will be developed. Under grid fault conditions multiple grid connected inverters which have low voltage ride-through (LVRT) feature can contribute on mitigation of voltage dips. In this task control strategies that will make the behaviour of PV systems to be close to conventional synchronous generators will be developed. Coordination of multiple PV generators connected to the grid in the sense of coupling with central power plants is required in order to balance consumption and generation regionally. Optimum decentralized controllers with minimum signal exchange between distributed PV generators or with autonomous operation will be investigated.

WP.3- Diagnostics and failure mitigation techniques for PV plants

New PV cell technologies, especially thin-film are gaining important shares in the PV market. In order to characterize PV-panels under different conditions, models of these new PV cells will be developed. These models will be the support for developing new diagnostic functionalities, aiming at early detection or prediction of faults or performance degradations.
Many types of faults in the PV system can be predicted by understanding their failure mechanisms and analysing the trends in their key characteristics. Moreover, by identifying the responsible stress factors (e.g. by diagnostic functions), and analysing ageing patterns, it is possible to design a failure mitigation mechanism. Thus, the operating conditions can online be adjusted for mitigating the fault, or warning message can be generated thus allowing for pre-emptive measures, avoiding the fault.

WP.4- Advanced PV plant monitoring and control

In this task high level software applications targeted for monitoring and processing essential information about the operation of PV plants will be developed, in order to improve the management and extend the useful life of the entire PV system. In this task, enhanced control methods for maximizing the yield in all conditions, based on the information regarding the operational and environmental conditions (partial shadow, fast clouding, mismatching cells, etc.) of the PV array, provided by the diagnostic functions, will be developed for applications in large PV power plants with and without Sun tracking.

4.2 Project implementation

The project has followed the general plan for implementation, and all the four major work packages have been carried out.
However, due to the increased attention towards and importance of PV grid integration, it has been decided to put a stronger focus on WP2, where advanced grid control have been addressed both for LVDN as well as for MV networks. Therefore, less effort has been spent on WP1 which is focused more on grid condition detection (in this respect the project has built on previous experience and results from earlier projects), due to the higher importance of WP2.
WP1 and WP2 has been centred in a full PhD project (*Grid Support in Large Scale PV Power Plants using Active Power Reserves*) focusing on grid support from large PV power plants (LPVPP) and a 1-year Postdoc project (*High PV Penetration in LV Distribution Networks*) focusing on advanced voltage support strategies for LVDN.
WP3 and WP4 have been carried out as planned, and they have been executed in the framework of a full PhD project (*Characterization and Diagnostics for Photovoltaic Modules and Arrays*).

While no major changes in the project plan was needed, a new project partner had to be found due to the bankruptcy of one of the industrial partners, Sunsil A/S (2012). Sunsil was involved in WP3 and WP4, and their role was focused on testing and implementation of results from these work packages, especially bringing in the end user perspective.
Due to the fact that these activities were concentrated mainly in the second half of the project, it was possible to invite another external partner, Gaia Solar A/S, a company with great experience in design of photovoltaic plants and Building Integrated Photovoltaics (BIPV).

5. Project results and dissemination of results

5.1 Main activities and results

The main activities in this project are carried out in conjunction with the two PhD programme and the 1-year Postdoc project.
In the following the key results of the project per work package are listed, and are based on the half-year reports submitted during the project.

5.1.1 WP.1&2- Advanced grid condition monitoring & Advanced grid control

5.1.1.1 Grid support with large PV power plants on the MV network

The increased penetration of PV within the electrical power system has led to stability issues of the entire grid in terms of its reliability, availability and security of the supply. As a consequence, large scale PV power plants (LPVPPs) operating in Maximum Power Point (MPP) are not supporting the electrical network. Several grid events and the increased number of downward regulation procedures have forced the European Network of Transmission System Operators for Electricity (ENTSO-E)

to continuously upgrade their Network Codes (NCs), imposing grid stabilization features to LPVPP.
Considering the technical challenges present in nowadays power systems, these work packages focused on frequency and power ramp control strategies provided by LPVPPs with internal generated Active Power Reserves (APRs), enabling LPVPPs to provide the following services, also detailed in Figure 1:

- *System management:* LPVPPs should perform security analysis for forecast improvement, availability analysis in power production and ancillary services; give information about temporary unavailability, to perform according to schedules.
- *Frequency stability:* LPVPPs should contribute to frequency stability with APRs.
- *Voltage stability:* To keep the voltage in the safety limits, LPVPPs should provide reactive power support.
- *System robustness:* LPVPPs have to have a robust operation during grid disturbances.
- *System restoration:* After a disturbance or even blackout LPVPPs have to restore the voltage or to control it if their implementation is technical feasible.

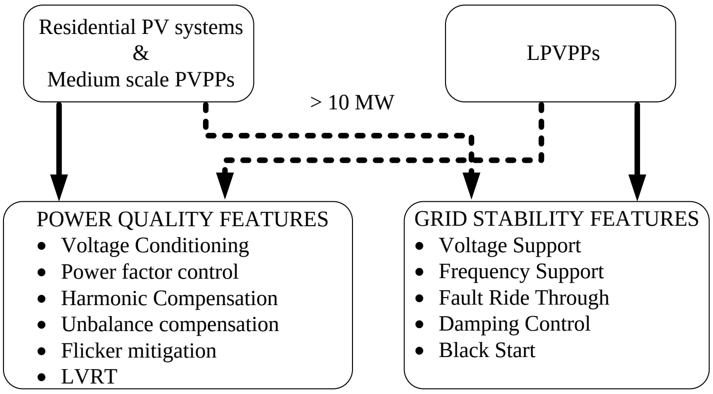


Figure 1: Functionalities of grid connected PV systems depending on their level of installed capacity

The main contributions of these work packages are listed below:

- A complete overview of most recent network codes (NC) focused on frequency stabilization features and power ramp capabilities; a detailed overview can be seen in publication I.
- Development of a new HV grid benchmark (generic IEEE 12 bus system) implemented over a real time framework (RTDS) with adaptable parameters (e.g. PREPA characteristics); a detailed overview can be seen in publication III and VI.
- Analysis of short-term and mid-term frequency stability based on real time domain and statistical studies of LPVPPs with Frequency Sensitive Mode (FSM) and Inertial Response (IR) considering different levels of penetration. The study is performed on a realistic Danish load profile with the n-1 contingency criteria included. The results show the necessity of FSM and IR, in the case of increased PV penetration, and highlight the advantages brought by these ancillary services;
- A control method for limiting power fluctuation in LPVPPs due to high irradiance changes has been proposed. The method smooths out the power mismatches, contributes to NC fulfilment and optimally uses the internal generated APRs; a detailed overview can be seen in publication VII

- Optimal sizing of APRs based on Power Ramp Limitation (PRL) methodology, presented in Figure 2, and prioritization of APR deployment between internal APRs and storage units; a detailed overview can be seen in publication VIII
- Analysis of APRs availability in LPVPPs provided by curtailment based on central inverter studies; a detailed overview can be seen in publication IV.
- Hardware implementation of FSM, IR and PRL control architecture on downscale Power Hardware-In-the-Loop (PHIL) 15 kW PV central inverters; a detailed overview can be seen in publication V.
- Real-time evaluation of PHIL LPVPPs with frequency support functions and PRL capabilities over a flexible AC grid test bench with generic IEEE 12 bus system characteristics. A detailed overview can be seen in Publication IX

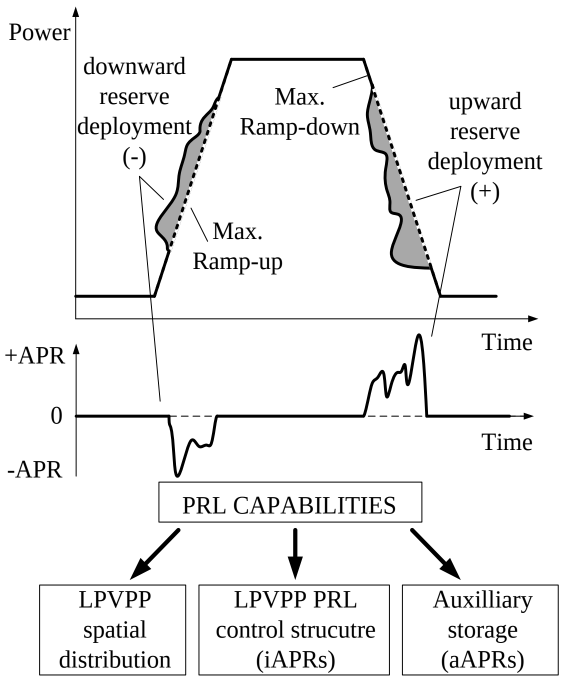


Figure 2: Power ramping obligation in LPVPPs

The chosen power system for these studies was the PREPA (Puerto Rico Electrical Power Authority), since the power level, nature of generation and layout (Western Loop, Central Loop and Eastern Loop) present similar characteristics with the generic IEEE 12 bus system, presented in Figure 3. Furthermore the PV plant was modelled, which is presented in Figure 4.

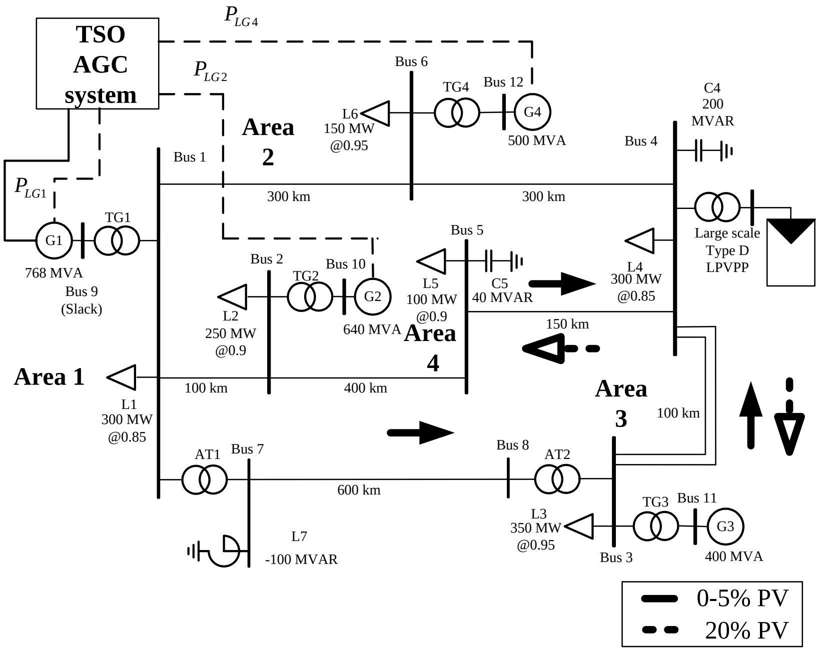


Figure 3: Adaptation of the generic IEEE 12 bus system to PREPA power system (single line view)

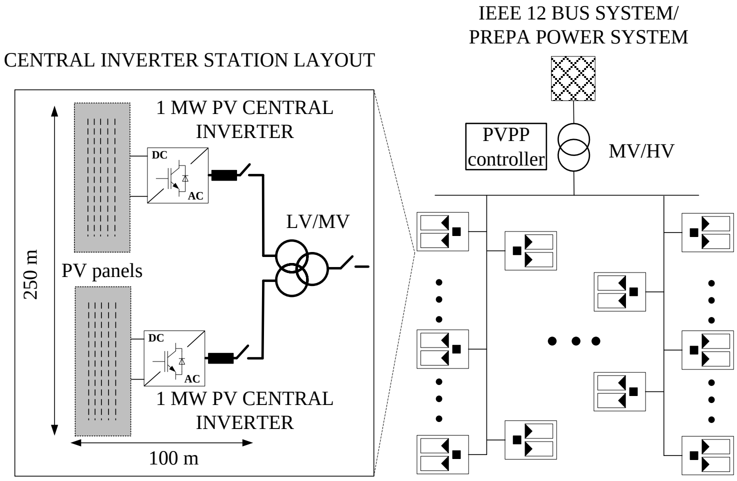


Figure 4: Layout of LPVPPs with central inverter stations (single line diagram)

Depending on the MPPT algorithm used to extract the maximum power (P_{MPP}) by controlling the DC voltage at the input of the converter (V_{MPP}), the PV panels produce a power directly proportional with the present condition of irradiance and temperature.

To provide APR demanded by ENTSO-E NCs (between 1.5%-10% from P_{max}/P_{MPP}) for ancillary services such as the FSM, without involving any other auxiliary storage devices, the LPVPP system operator has to generate them internally by dividing the total APR requirements among the total number of central inverters in the plant. The internal APR (iAPR) can be produced in two ways:

- To set the DC voltage reference of the central inverter *below* the MPP voltage of the PV panels (V_1). The set DC voltage forces the PV arrays to act as a current source with the major disadvantage that during high slope irradiance changes, the produced current and the deployment of APR for different ancillary services (FSM and PRL) can cause the DC voltage to experience large fluctuations and even converter tripping.
- To set the DC voltage reference of the central inverter *above* the MPP voltage

of the PV panels (V_2). The set DC voltage reference gives the opportunity to operate the PV arrays as voltage sources without inducing large fluctuations in the DC voltage during APR deployment. Operating at higher voltages than the V_{MPP} opens the possibility of controlling the arrays directly in power and in this case the DC voltage becomes an intrinsic characteristic.

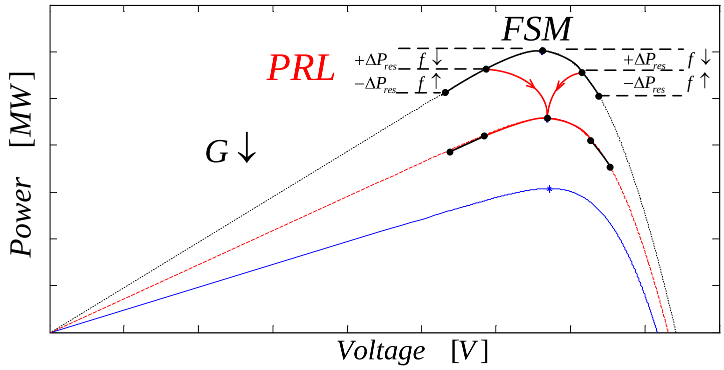


Figure 5: P-V characteristics and APR deployment of central inverters during frequency changes (FSM) and high irradiance slopes (PRL)

The synthetic frequency generated by the proposed power system benchmark model is subject to LPVPPs which can provide synthetic governor functions. To provide these functions, the central inverters in the LPVPP have to consider the time response during the supply of these services. Giving the fact that frequency support functions are placed in the seconds range, the contribution of the LPVPP to these services is realized in the outer loop control architecture of the central PV inverter used in the plant (see Figure 6). Thus, the central inverter outer loop control architecture can be summarized as:

The active power produced by the PV arrays is highly dependent on the meteorological conditions along with the amount of APRs that have to be supplied from curtailment, the downward regulation power imposed by the TSO, as well as the start-up procedures imposed by the plant operator.

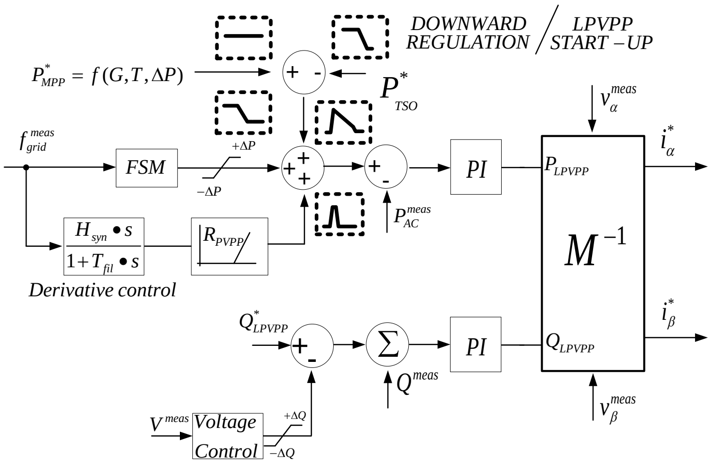


Figure 6: LPVPP central inverter control architecture - frequency sensitive synthetic governor concept

To complete the FSM operation and to have a better iAPR usage, the IR is added to the central inverter control architecture. The control structure chosen for the IR in LPVPP is based on the derivative control, which has the purpose to determine the Rate of Change of Frequency (ROCOF) during normal operation and especially during event.

LPVPPs supplying mandatory FSM enhanced with high sensitivity IR have a direct impact also over the global indicators of frequency quality: decrease the standard deviation, percentiles and reduce the number of Standard frequency range (SRF) violations

Power ramp rate control of LPVPPs are a necessity in small power systems since the active power mismatches created by large power fluctuations of LPVPPs cannot be recovered by the generating plants in the system. To fulfil the ramping requirements with LPVPPs, it is necessary to combine the electrical characteristics with the size and spatial distribution deciding the minimum requirements of APRs.

The proposed PRL control strategy overcomes the challenges created by large output power fluctuations of LPVPPs and decides the minimum necessities of APRs. PRL services provide flexibility in terms of APR usage since the control architecture can be implemented in the production area at the central inverter station level but proves to have a better appliance at the plant level where the APR management is realized.

To validate the proposed services PHIL tests have been done. PHIL testing combines the features of both pure hardware and pure software methods by running a mathematical model of the well-known components of a system in pure software environment. In this way, the gap between software simulation and hardware testing is bridged, leading to novel advantages hardly seen in former simulation technologies. Consequently, the use of PHIL is no longer optional, but rather seen as a necessity giving the opportunity to develop new grid support concepts that can boost up the integration process of LPVPPs into the grid.

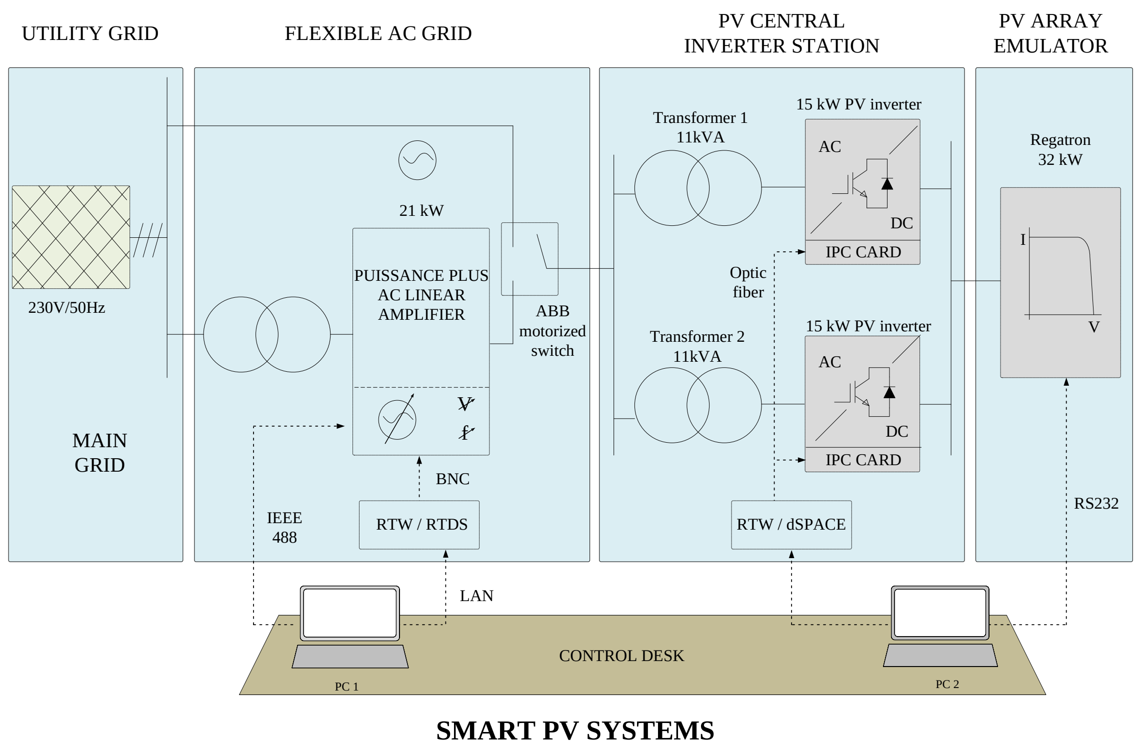


Figure 7: PHIL test setup used for experimental validation of the proposed services for LPVPPs

To successfully perform stable PHIL tests, interface algorithms (IA) are used to couple hardware and software environments. The IA contains different elements that enable the possibility to exchange different signals between the Hardware under Test (HuT) devices and the Real Time System (RTS) at the desired power level.

The configuration of the PHIL PV plant was made up of two grid connected converters which were responsible to process the produced PV power and to inject it into the flexible PHIL AC grid.

Both grid connected PV inverters were controlled by a dSPACE RTS at a switching frequency of 10 kHz. The dSPACE RTS was responsible for the data acquisition, converter control and PWM generation.

The control architecture used by the dSPACE RTS had a double loop configuration. The inner loop is realized in the stationary reference frame controlling the current injected into the grid while the outer loop is responsible with the control of the active and reactive power delivered by the PHIL PV plant.

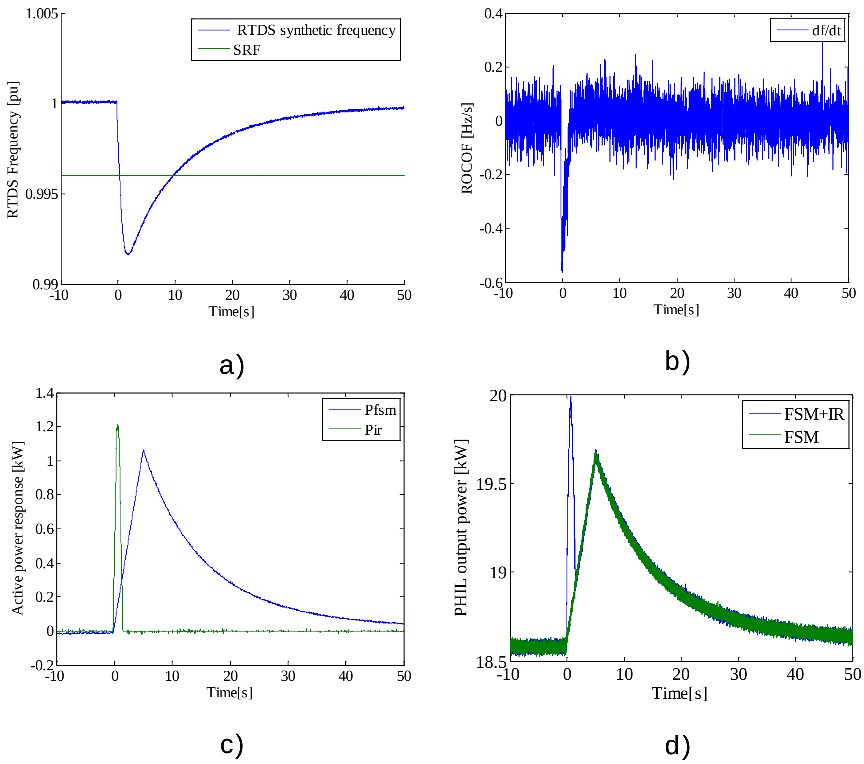


Figure 8: Frequency support in PHIL PV plants: a) RTDS generated synthetic frequency b) Measured ROCOF c) iAPR deployment during IR and FSM d) PHIL PV plant response with FSM and FSM+IR

Having the entire laboratory test bench linked together with the flexible PHIL AC grid, the possibility of testing the proposed synthetic governor functions delivered by PHIL PV plants was done.

For this purpose the generic IEEE 12 bus system was subject to a frequency event meaning the loss of 2 p.u. of generation which determined the frequency to deviate from its rated parameters and to exceed the SFR as shown in Figure 8a. During the frequency disturbance, the measured ROCOF (see Figure 8b) enabled the synthetic inertia modelled in the PHIL PV plant and caused the inverters to react by means of their iAPR which for this study case the amount of iAPRs were considered to be in the range of 10% at STC power production (see Figure 8c). The dynamic character of the proposed PRL method was observed in Figure 8d where the time constant was dynamically changed during high power ramp rates which means adapting the iAPR needs to the imposed ramp-rate requirements.

Short-term and mid-term frequency stability analysis, based on time domain and statistical evaluation studies, demonstrated the LPVPPs ability to improve the frequency stability during transients and their participation in the regulation process of overall frequency quality parameters. Furthermore, the analysis proved that LPVPPs can become active players in the power system, along with the conventional generation, and can share part of the stabilizing responsibilities and consequently can allow higher PV penetrations.

5.1.1.2 Grid support with residential PV on the low voltage distribution network

Several technical problems limiting the number of PV system connections and caused by interaction between PV inverters and the grid were identified as following:

- Voltage rise problem due to high P injections from PV generating plants. The cross-section of distribution cables and feeder length have also considerable impact on the grid voltage elevation.
- Overload limits of network components such as cables and transformers can be major barriers against high PV penetration. Use of actual dynamic thermal limit may allow overloading these components for certain periods without degrading their lifetime.
- Harmonic emissions of PV inverters, background distortion of grid voltage, output filter impedance of PV inverters, cable impedance can easily form a parallel resonance in the distribution network,
- Normal operation of individual PV inverters can be affected by background voltage distortions existing in the network if grid synchronization and current controllers are sensitive to the grid voltage. It may result in unwanted inverter trips and accordingly, less energy yield.
- Voltage dips may prevent normal operation of PV inverters if their controller structures are not properly designed. Some reported problems related to voltage dips have been outlined such as fast disconnection from the grid, current controller sensitivity to voltage dips, the effect on MPPT operation and low voltage ride-through.

The key results with regard to developing load flow tool are listed below:

- After evaluation of different load flow solvers, it was determined that forward sweep method is more suitable for distribution networks.
- An automatic node and branch numbering technique adopted from several references was achieved. Thus, providing a branch list in a random order, the nodes and branches can be arranged in a sequence starting from the root node towards end nodes.
- Modelling of 3-phase underground cables and overhead lines were completed. The model and load flow tool was also tailored to investigate neutral-to-earth voltage elevations.
- Various 3-phase loads (constant power, constant current, 1-phase, etc.) and shunt capacitors were modelled.
- Modelling of 2-winding 3-phase transformers were completed.

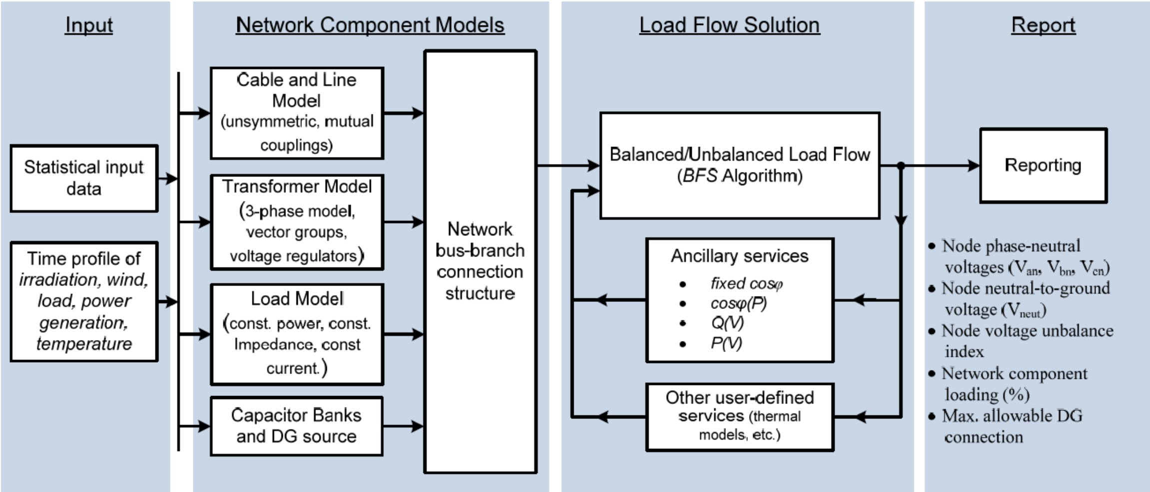


Figure 9: Functional block diagram of the load flow calculation tool for three-phase distribution networks developed in Matlab

Appropriate load flow solution techniques special for distribution networks were investigated and established during this period. Owing to Matlab®'s powerful computational performance and ready-to-use functions, the tool became flexible by allowing users to develop their own special model functions (thermal model of components, ancillary services, detailed generating plant models, etc.) and any special network analysis (statistical load flow, yearly energy yield and loss analysis, etc.). The tool, thus, can be practised on the reference networks developed during this project phase in order to estimate their maximum PV penetration level with different unbalanced scenarios. The test results obtained by the developed load flow simulation were compared with the results acquired from Radial Distribution Analysis Package (RDAP):

- Overall voltage mismatches took place in the acceptable level of 0.1-2% for IEEE 13-bus test network
- Since neutral and ground return currents can be computed, phase-to-neutral and phase-to-ground voltages at each node were also determined.

Other results with regard to employing static Q methods and P curtailment in PV inverters were also achieved as listed below:

- In case of cosφ-based Q methods, generated Q reference is only proportional to the P output of the PV inverter. Therefore, under the same rated power, Q reference is uniformly dispatched among distributed PV inverters along a radial feeder regardless of their distance to the MV/LV power transformer. As a result, power losses caused by additional Q support will be similar in all PV inverters. However, these cosφ-based Q methods assume that the grid voltage level increases with produced P from the PV inverters without taking into consideration of load variation in the neighbourhood. When the high irradiance level coincides with the peak power demand, then the voltage rise may not reach to the critical value. Q consumption at that moment will be unnecessary.
- Q(V) method directly uses local voltage information that is a consequence of the power production and consumption in the neighbourhood. The advantage of this method is that Q is not unnecessarily consumed by the PV inverters. However, it results in unequal Q sharing among PV inverters due to having different grid voltage elevations along the feeder. In a reverse power flow case, the inverters at the end of feeder will be exposed to higher grid voltage

levels so higher amount of Q absorption is forced by Q(V) curve. In result, this strategy introduces different amount of extra power losses on the inverters based on their locations.

- New Q method, cosφ(P,V), was proposed to inherit the previous advantages from the standard Q methods and combine them in one method without requiring communication infrastructure.
- Inverter loss evaluation was carried out using average loss modelling coupled with the load flow analysis. Extra power losses in the PV inverters due to Q support were computed for various Q methods and the resultant losses became a basis for the operational cost of PV inverters.

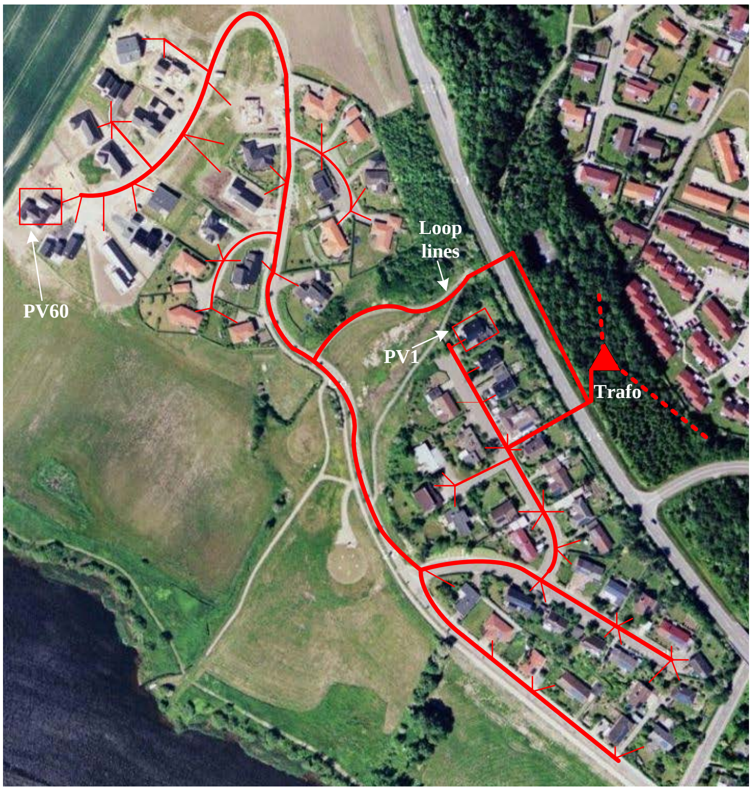


Figure 10: Example network for calculating PV hosting capacity and calculating extra inverter losses due to the various reactive power support strategies

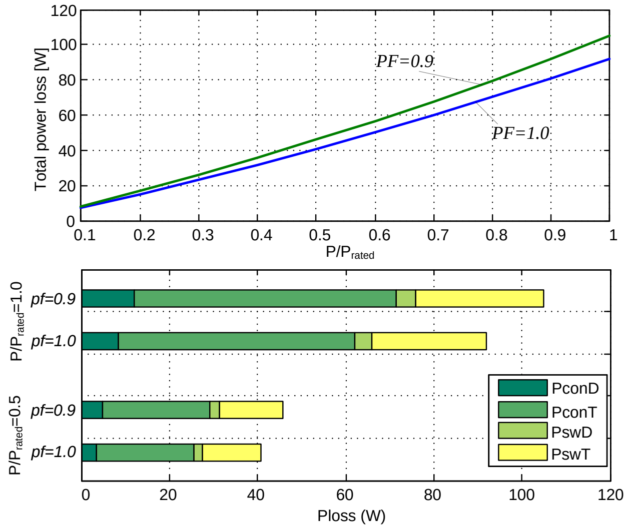


Figure 11: Total power loss in the PV inverter vs output power at different power factors (PF) (top graph) and loss evaluation in the PV inverter switches at different power levels (100% and 50% of rated power) and different power factors (0.9 and 1) bottom graph)

- For the suburban reference network, if the PV inverters were not allowed to absorb Q, maximum 5.3kW/house power injection could be achieved without deteriorating network normal operation. Q(V) and cosφ(P,V) methods perform similar PV capacities (7kW/house) with 100% transformer overloading limit. But less voltage rise was identified at the end of feeder when cosφ(P,V) method was employed. If transformer overload limit is allowed to be higher for certain period, then higher PV capacity can be achieved by cosφ(P,V) method.

According to thermal model of oil-immersed distribution transformers, 130% loading will not degrade the transformer lifetime. Therefore, 130% loading should be considered for the more accurate estimation of maximum allowable PV capacity.

An MSc project has also contributed to this work package, the work is entitled: "Control of grid connected PV systems with grid support functions" and the goal was to analyse and improve the voltage regulation methods for grid connected PV inverters proposed by the new German grid code. The support strategies based on reactive power (cosφ(P) and Q(U)) were modelled and simulated by performing load flow analysis on a typical LV distribution network. An optimized voltage regulation method was proposed which minimized the reactive power consumption using coordinated control. The Ethernet communication IEC 61850 based on server/ client architecture was used to exchange information between PVs and master controller. A laboratory setup has been developed for the experimental validation of IEC 61850, which is detailed in Figure 12 and Figure 13.

At the end of this activity, it has been demonstrated that using the communication concept, critical information can be exchanged between inverters (Client) and master controller (Server) with the purpose of synchronizing the behaviour of the PV generators. The reference has being successfully sent and wrote to the dSPACE through IEC 61850 and CLIB library. A local droop function has been implemented in the Client application, which calculated the optimum reactive power for each inverter based on the received voltage measurements. Despite the fact that the droop function can be implemented locally without the use of IEC 61850, its main purpose was to decide a real new reference of reactive power without using user input values. Due to the ICD Designer software and time limitations, the optimized algorithm could not be experimentally validated in the laboratory. On the other hand, the communication standard IEC 61850 has been successfully implemented and validated, showing that inverters can share local data for the minimization of network losses and better distribution of reactive power.

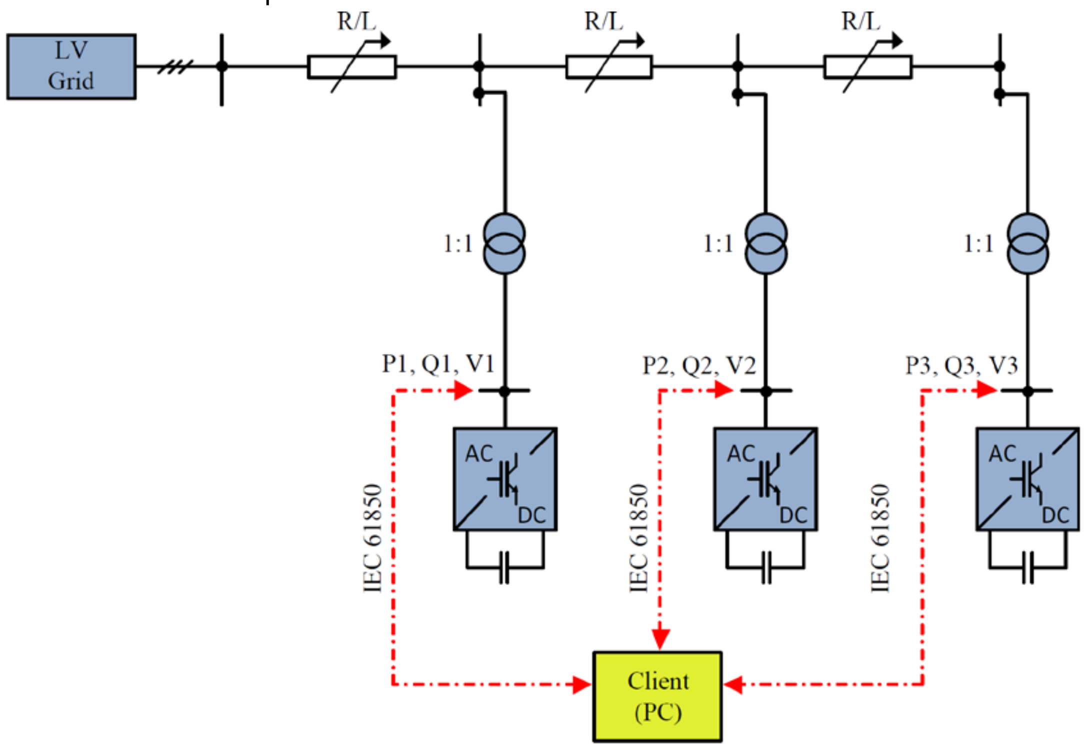


Figure 12: Single line diagram of the experimental setup used for the proposed voltage regulation method

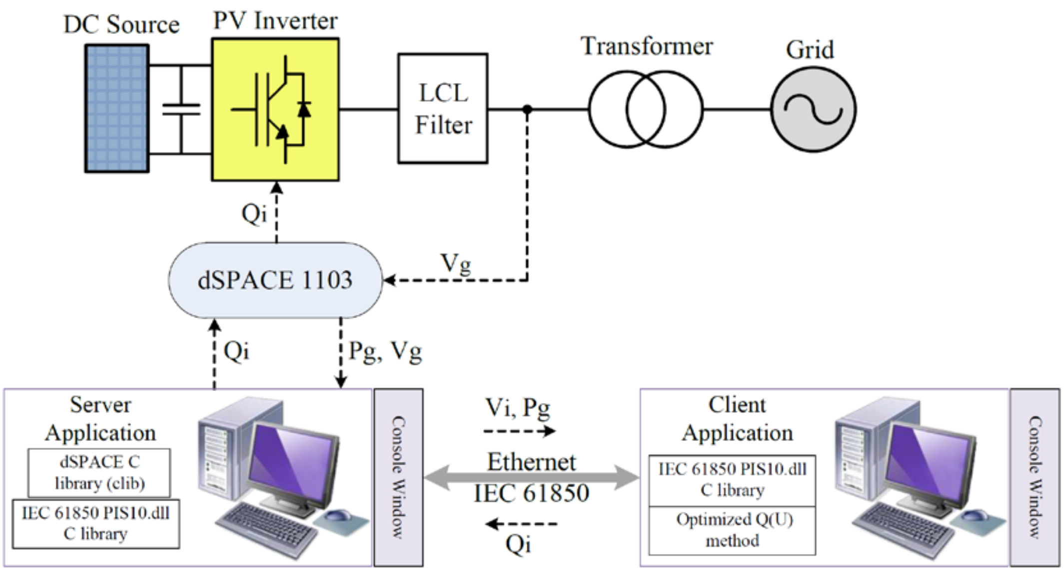


Figure 13: Experimental test setup showing the control and communication architecture used for the setup presented in Figure 12

5.1.2 WP 3 - Diagnostics and failure mitigation techniques for PV plants and WP4 - Advanced PV plant monitoring and control

These two work packages focused on the PV generator side of the PV system, and are included within the PhD programme *Characterization and Diagnostics for Photovoltaic Modules and Arrays.*

- ***Graphical User Interface for accessing and analysing weather measurements acquired at Aalborg University.***

A Matlab Graphical User Interface (GUI) was developed, shown in Figure 14 , for exploring, visualizing and exporting measurement data acquired by weather sensors deployed at the Department of Energy Technology. The main purpose of the software is to facilitate easy access to the Aalborg University students and staff, to high-resolution and long-term weather data, for use in their own research and/or student projects. The software was made available on the PV systems research group website and is accessible through the AAU IT system at www.pv-systems.et.aau.dk

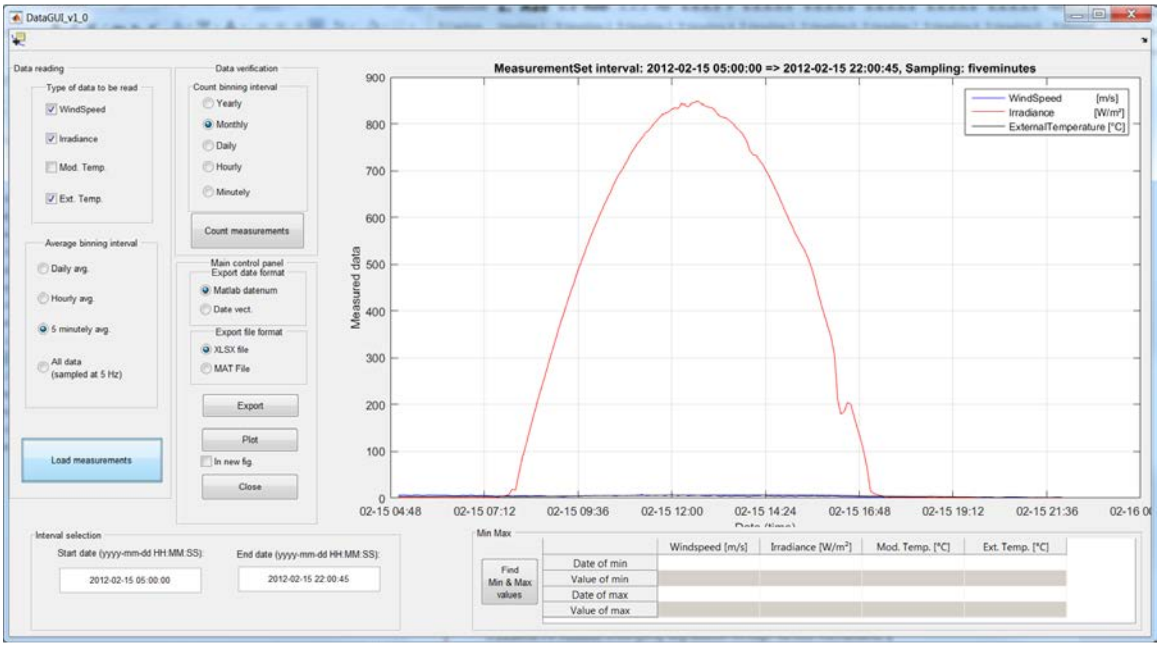


Figure 14. Screenshot of the DataGUI Matlab software, developed for analyzing and accessing weather measurements acquired by meteorological sensors at Aalborg University. The main purpose of the software is to facilitate easy access to the Aalborg University students and staff, to high-resolution and long-term weather data.

- ***PV module and array measurement analysis framework in Matlab***

A software framework has been developed (a screenshot is shown in Figure 15), for supporting the analysis of PV modules and arrays I-V measurements. This software tool is used to analyse the experimental I-V curve measurements, acquired on module level in the laboratory with the Flash Sun Simulator, and outdoor with an I-V tracer and/or PV inverter. This tool was used as to support the development the I-V diagnostic methods for modules and arrays, within this project.

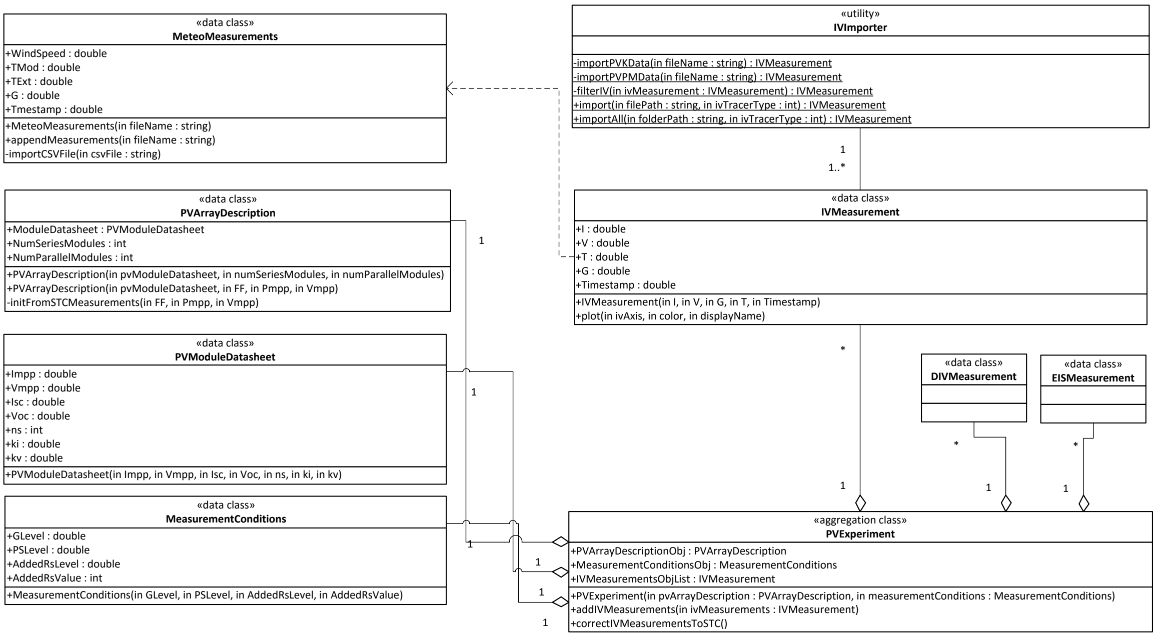
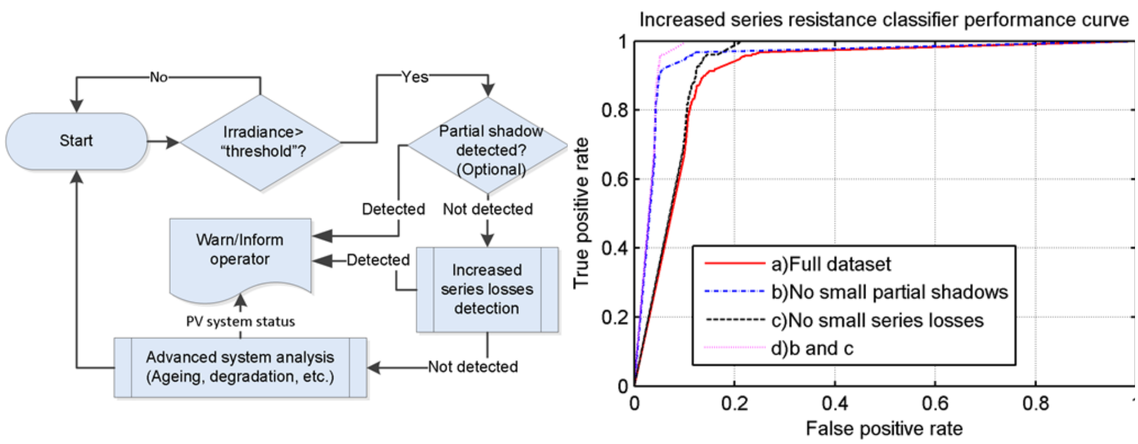


Figure 15. Class diagram of the PV measurement data objects, used for importing, storing, and analyzing I-V measurements of PV modules or strings.

- ***Method for detection of increased series resistance in PV strings***

An experimental study was performed on the PV system located at Aalborg University, for investigating practical methods for detecting increased series resistance type degradation in crystalline silicon based PV strings. The results of this study led to the development of a diagnostic method based on I-V curve analysis, depicted in Figure 16-a. The method showed a high fault detection accuracy, shown in Figure 16-b, and results were published in Publication XIX.



a) b)

Figure 16. Method for detecting increased series resistance in PV strings based on I-V curve analysis. a) Fault detection concept; b) Fault detection performance of the diagnostic method.

- ***Flexible PV inverter laboratory setup***

A PV inverter hardware test setup has been developed, consisting of two fully programmable solar inverters, and PV simulator, shown in Figure 17. The purpose of the setup was to facilitate the test and validation of the PV inverter control and diagnostic functions developed within this project, as well as to support master level student projects. Within the duration of this project, the PV inverter setup was used to support two publications on PV inverter MPPT control strategies (Publication XXII) and optimized MPPT operation in partial shading conditions (Publication XXI), as well as an MSc student project.

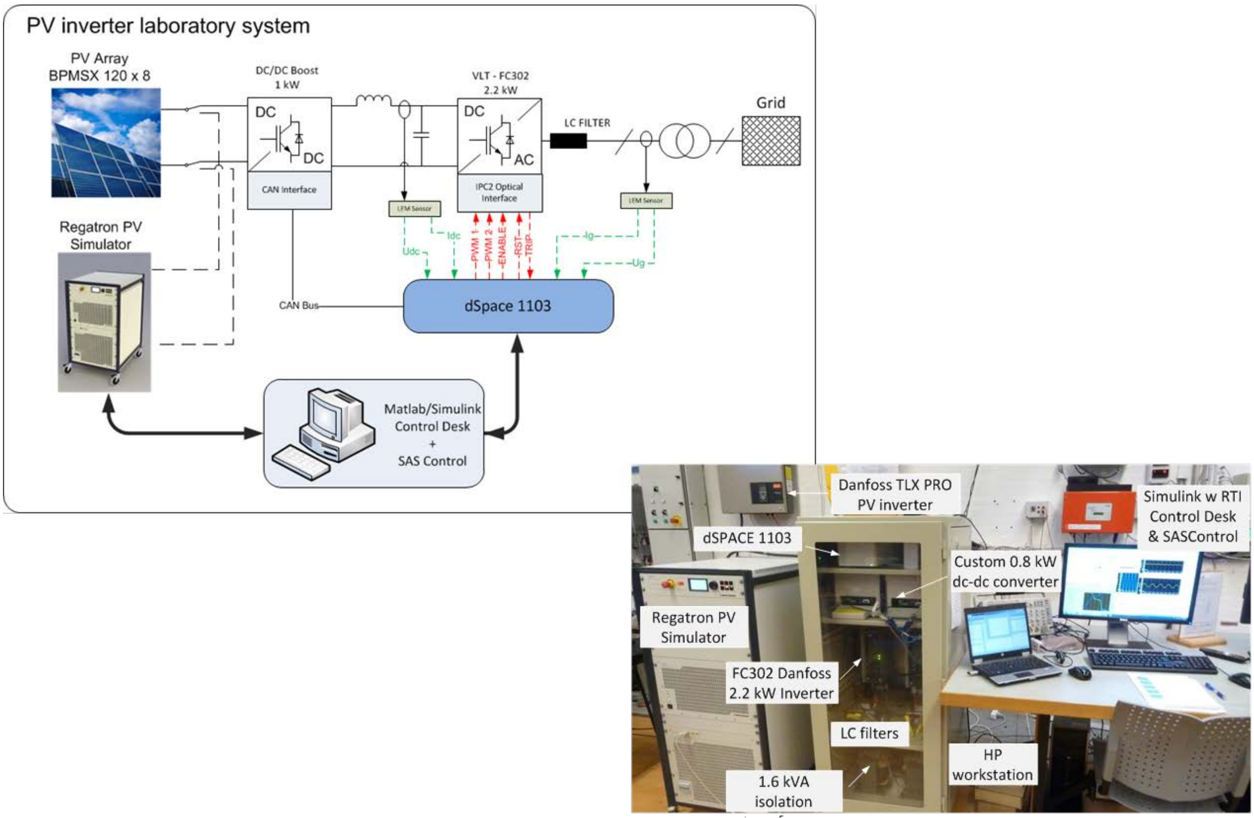


Figure 17. Flexible PV inverter laboratory setup, for implementing and testing PV inverter control and diagnostic functions.

- ***IEC 61850 test platform***

Developed a hardware-in-the-loop test platform for developing applications based on the IEC 61850 communication protocol. The platform, shown in Figure 18, was implemented on the dSPACE real time system and using the CLib and the SystemCorp IEC 61850 API, for communication through the IEC 61850 protocol between two or more inverter setups (based on Danfoss VLTs and dSPACE) and a central management PC. The purpose of this platform was to enable smart grid and smart PV inverter applications based on the IEC 61850 communication protocol, which is currently being developed as a standard for electrical substation automation. This platform was used to support two MSc student projects.

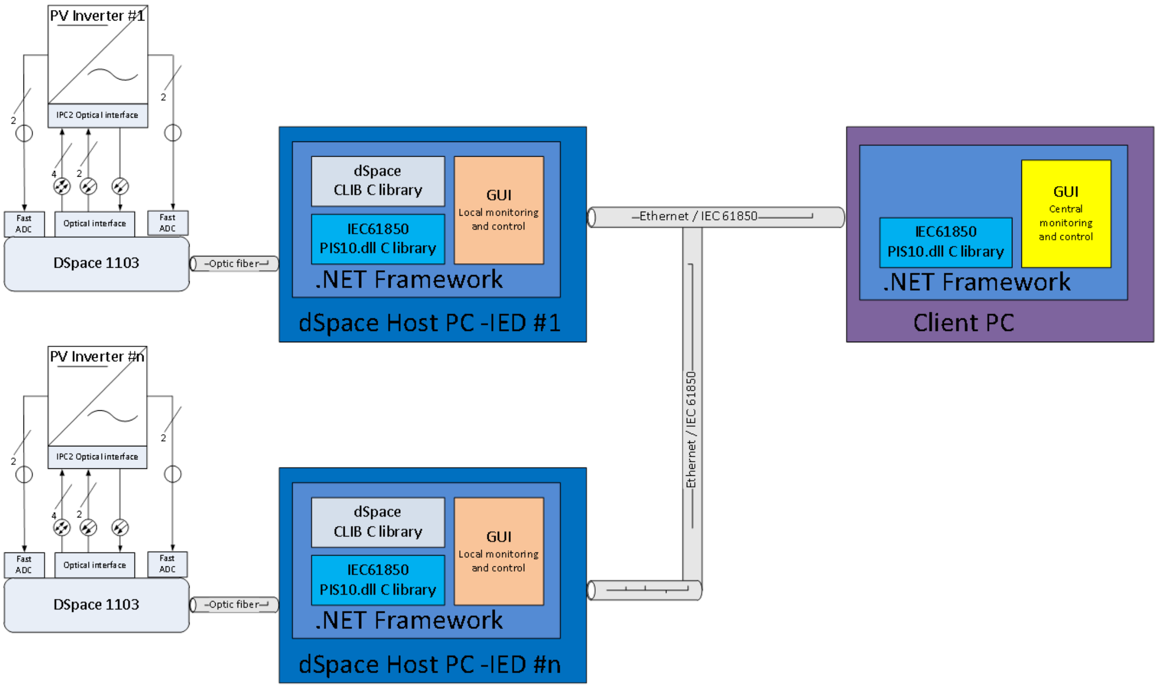
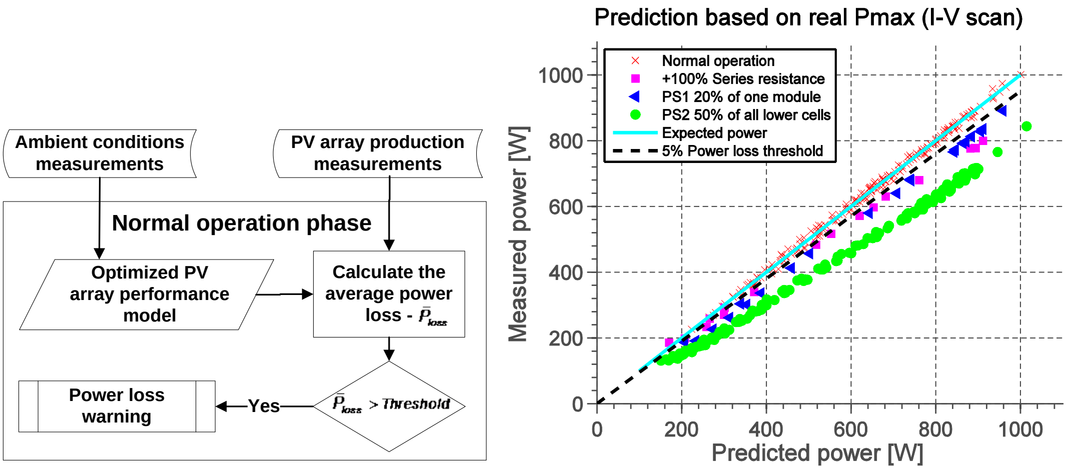


Figure 18. IEC 61850 hardware in the loop test platform concept, for developing smart gird applications.

- ***Condition monitoring method for PV systems***

Developed a condition monitoring method for PV systems based on the online regression of a PV array performance model. The method can be implemented in an inverter and can use either measurements extracted from the I-V curve of the PV array or averaged production data, to calculate online (using regression modelling) the parameters of a performance model for the PV array in question. This model is then used to monitor the condition and power production of the PV array, as shown in Figure 19-a. Experimental results yielded a power loss detection accuracy of 5%, shown in Figure 19-b. More details can be found in Publication XVII.



a) *b)*

Figure 19. PV system condition monitoring: a) algorithm of the condition monitoring during normal operation; b) experimental results showing measured and predicted PV string power during normal operation and various fault conditions. Deviations from the 5% power loss threshold will yield a power loss warning.

- ***PV module diagnostic method based on light and dark IV curve analysis***

Developed a diagnostic method for identifying degradation/failure type in crystalline silicone PV modules based on analyzing the light and dark I-V characteristics of the PV module. Four types of degradation were investigated: optical losses and degradation, degradation of the electrical circuit, mechanical degradation, and potential-induced degradation of the PV modules.

The method is based on monitoring certain parameters of the light and dark I-V characteristic curves, as shown in Figure 20. The method was tested and experimentally validated using modules that were subjected to accelerated stress under controlled conditions, leading to various extents of degradation. The results showed good detection sensitivity foe detecting even incipient module degradation and were published at a conference and an extended version in a journal paper (Publication XV).

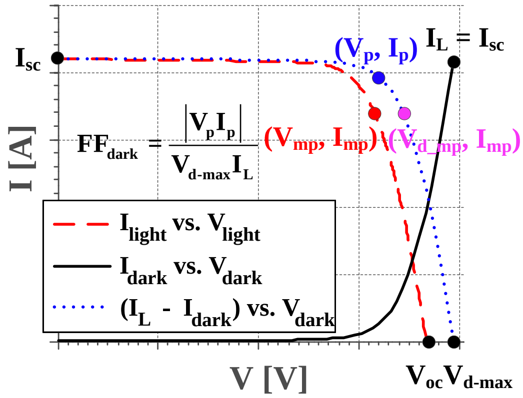


Figure 20. Diagnostic parameters calculated from the light and dark I-V curves.

- ***PV DAQ – PV Data Acquisition and Diagnostic System***

Developed a PV System monitoring application, shown in Figure 21, which takes advantage of the inverters own I-V curve and production measurement functions, to monitor the PV system remotely, and log the measurements to a central database hosted at AAU. More details about the operation were published in Publication XVI.

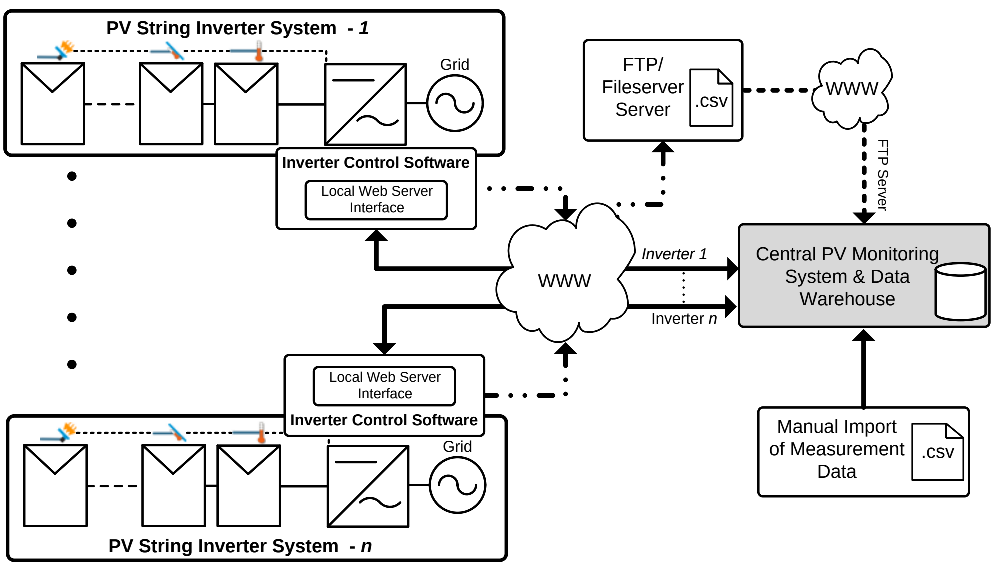


Figure 21. Overview of the PVDAQ software application remote monitoring of PV systems.

In addition to the data acquisition functionality, a GUI was implemented, shown in Figure 22, for exploring, visualizing and exporting the PV data, and facilitating access to the data to other students or staff. The main purpose of the software was to become a field test platform for implementing and validating the PV condition monitoring and diagnostic methods developed through this project, on a real PV system.
Using this software, a collaboration agreement was made with Aalborg Havn A/S for long term monitoring of their PV systems, and further development and field testing of the software. A similar agreement was made with Gaia Solar A/S that extends beyond the time frame of the current project.

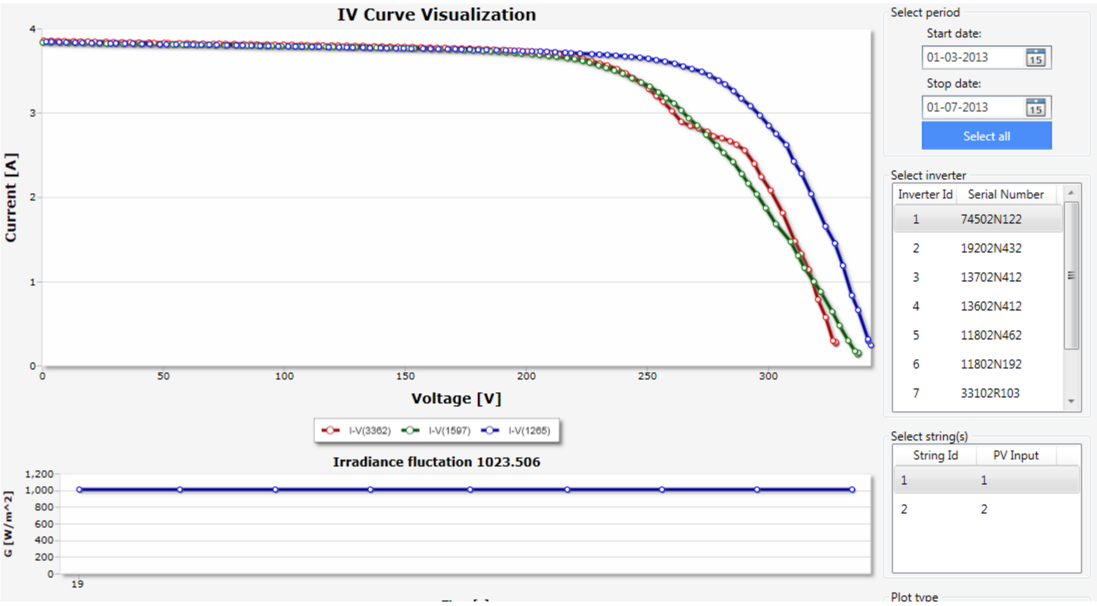


Figure 22. Graphical user interface of the PVDAQ software for visualizing and exporting the PV string I-V curve measurements acquired by the PVDAQ.

- ***Method of in-situ performance degradation estimation for modules undergoing PID***

  An *in-situ dark I-V measurement setup* was developed in collaboration with the US based National Renewable Energy Laboratory (NREL) researchers, shown in Figure 23, for measuring the dark I-V characteristic curve, module temperature and leakage current of PV modules undergoing accelerated stress testing and damp-heat controlled chambers.

The setup was used to study the d*ark I-V characteristic of PV modules undergoing potential induced degradation* (by damp-heat + high voltage), shown in Figure 24, and *increased series resistance type degradation* (by mechanical damage to the modules and thermal cycling).
These results were used to develop a new method for estimating the module power loss for modules undergoing PID stress testing, from in-situ dark I-V measurements performed at the stress temperature. The method and results were published in collaboration with NREL in three publications (Publication X, XI and XXIII).
The test setup and in-situ power loss estimation method are useful for studying the degradation characteristic of PV modules undergoing PID, and to develop lifetime and reliability models. They are currently being used by the PV reliability research group at NREL in the research and development of standards for module PID testing.

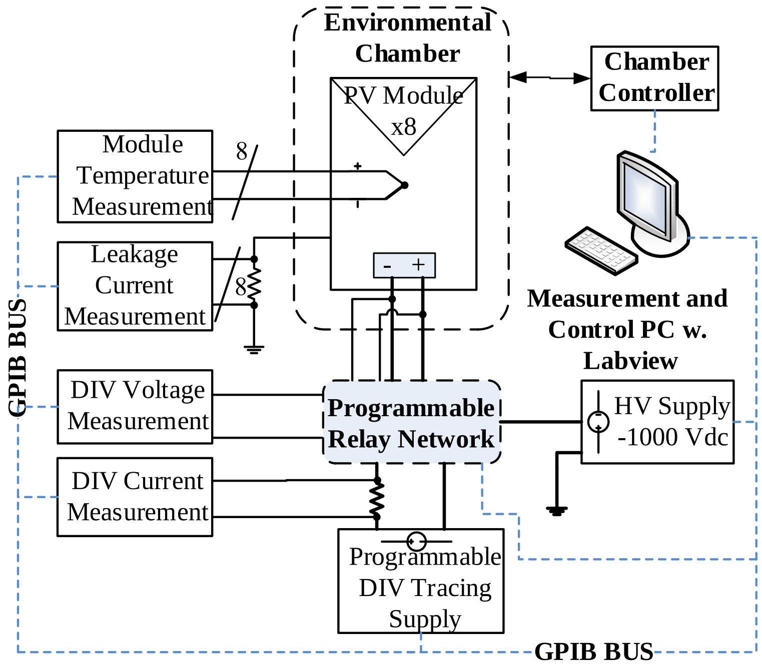


Figure 23. Fully automated experiment setup for performing potential-induced degradation stress testing on photovoltaic modules.

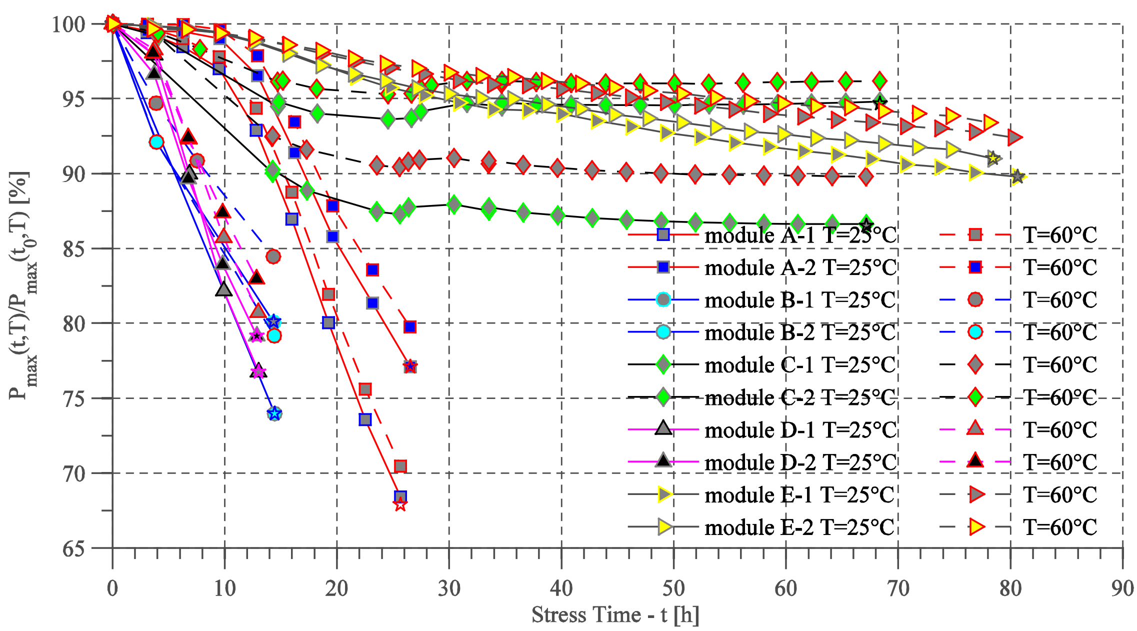
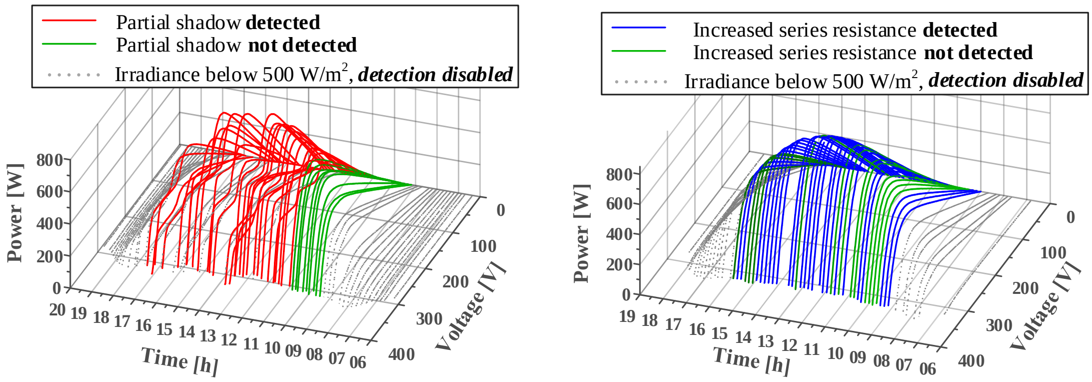


Figure 24. Maximum power (P_{max}) degradation curves calculated from the dark I–V measurements at 25 °C, solid lines; and 60 °C, dashed lines, for PV modules undergoing PID stress testing, and acquired with the in-situ test setup.

- ***Fault detection based on I-V curve analysis***

  We expanded our previous research on PV system diagnostic methods based on I-V curve analysis and developed and diagnostic system that integrates partial shading detection, increased series resistance detection, and PID detection.
The diagnostic system was field tested on a real PV system based on the Danfoss TLX Pro inverter. Figure 25 shows experimental results of the fields test, for detection shading of the PV system, and increased series resistance of the PV string. The method and results were published in Publication XX.



a) b)

Figure 25. Fault detection in a PV system by monitoring and analysing the I-V curves of the PV string periodically: a) a PV string affected by partial shading, red curves show when the shading has been detected by the diagnostic system; b) a PV string degraded through increase in its series resistance - the blue curves show the instances when the fault is detected.

- ***Method for quantifying solar cell cracks in PV modules by electroluminescence imaging***

  A method was developed for identifying the type and quantifying the extent of solar cell cracks present in crystalline silicon PV modules from EL images.
The method requires that the PV module is EL images at both a low (10% I_{sc}) and high (100% I_{sc}) current bias in a dark chamber. Afterwards the EL images are processed and used to calculate the luminesce distribution of the entire PV module, as well as for each cell. These distribution allow for determining the proportion of cracked cell areas, as exemplified in Figure 26.
The method is suitable for automatic analysis and assessment of PV module health, after manufacturing, transportation or installation. The method and results were published in Publication XXIII.

Moreover, the method has been included in the current draft of the IEC TS 60904-13 "Photovoltaic devices - Part 13: Electroluminescence of PV modules", which is being developed as an international standard for electroluminescence images of PV modules.

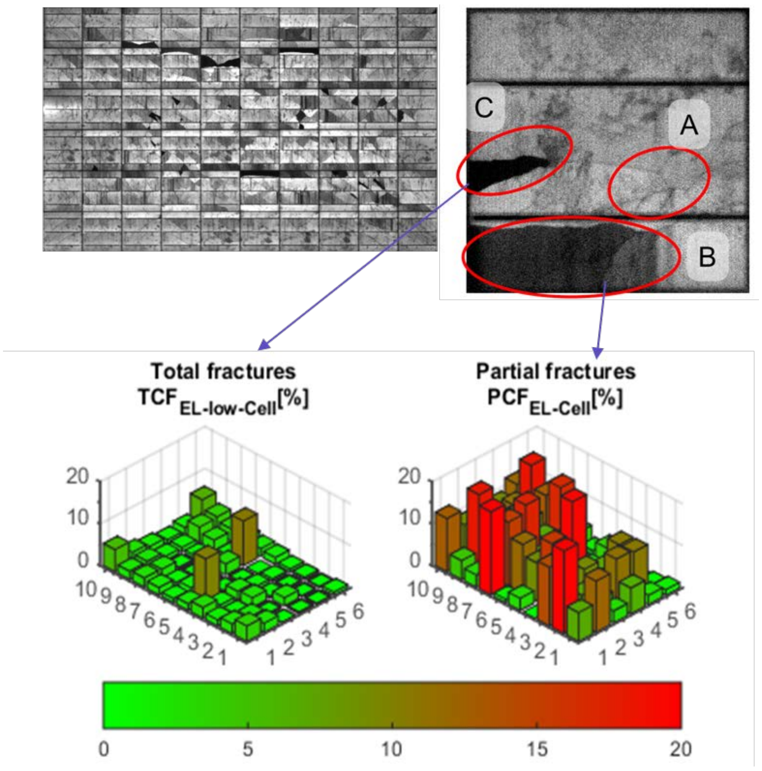


Figure 26. Example EL image of a conventional crystalline silicon PV module with different types of solar cell cracks. The type of the cell crack is determined by imaging the modules at 10% and 100% I_{sc} current bias. Afterwards, the EL images are processed and use to calculate the area of the cracks for each solar cell.

5.2 Dissemination

5.2.1 Publications

The results of the project has been published in a number of international peer-reviewed journal and conference publications, most of them within the two PhD programmes. In the following the list of publications are presented per PhD programmes:

PhD A: *Grid Support in Large Scale PV Power Plants using Active Power Reserves*

I. B-I Craciun, T. Kerekes, D. Sera, R. Teodorescu: **Overview of recent Grid Codes for PV power integration**; *Proceedings* of 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), 2012 Page(s): 959 – 965
II. B-I Craciun, E. Man, V. Muresan T. Kerekes, D. Sera, R. Teodorescu: **Improved voltage regulation strategies by PV inverters in LV rural networks**; Proceedings of 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2012, Page(s): 775 - 781
III. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Adrian Timbus: **Benchmark Networks for grid integration impact studies of large PV plants**, Proceedings of 2nd International Workshop on Integration of Solar into Power Systems, 2012

IV. B-I Craciun, S. Spataru, T. Kerekes, D. Sera, R. Teodorescu: **Power ramp limitation and frequency support in large scale PVPPs without storage**, Proceedings of IEEE 39th Photovoltaic Specialists Conference (PVSC), 2013, Page(s): 2354 – 2359

V. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, R. Brandl, T. Degner, D. Geibel, H. Hernandez, **Grid integration of PV power based on PHIL testing using different interface algorithms**, Proceedings of 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013, Page(s): 5380 – 5385

VI. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Adrian Timbus, **Benchmark Networks for grid integration impact studies of large PV plants**, Proceedings of IEEE PowerTech (POWERTECH), 2013, Page(s): 1 - 6

VII. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage, **Active power reserves evaluation in large scale PVPPs** Proceedings of 3rd International Workshop on Integration of Solar into Power Systems, 2013

VIII. B-I Craciun, Sergiu Spataru; Tamas Kerekes; Dezso Sera; Remus Teodorescu, **Internal active power reserve management in Large scale PV Power Plants**; 4th International Workshop on Integration of Solar into Power Systems, Berlin, Germany, 2014.

IX. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage, **Frequency support functions in Large PV Power Plants with Active Power Reserves**, IEEE Journal of Emerging and Selected Topics in Power Electronics Special Issue on Modeling and Control of Power Electronics for Renewable Energy and Power Systems, 2014

PhD B: *Characterization and Diagnostics for Photovoltaic Modules and Arrays*

X. S. Spataru, P. Hacke, D. Sera, C. Packard, T. Kerekes and R. Teodorescu. "**Temperature-Dependency Analysis and Correction Methods of in-Situ Power-Loss Estimation for Crystalline Silicon Modules Undergoing Potential-Induced Degradation Stress Testing**." Progress in Photovoltaics: Research and Applications, 2015, DOI: 10.1002/pip.2587.

XI. P. Hacke and S. Spataru. "**Automated Data Collection for Determining Statistical Distributions of Module Power Undergoing Potential-Induced Degradation**." Presented at 24th Workshop on Crystalline Silicon Solar Cells & Modules: Materials and Processes, Breckenridge, Colorado, United States, 2014.

XII. S. Spataru, D. Sera, T. Kerekes, R. Teodorescu, P. A. Cotfas and D. T. Cotfas. "**Experiment Based Teaching of Solar Cell Operation and Characterization Using the Solarlab Platform**." In proc. of Proceedings of the 7th International Workshop on Teaching in Photovoltaics, vol. 7, 2014.

XIII. S. Spataru, D. Sera, T. Kerekes and R. Teodorescu. "**Teaching Photovoltaic Array Modelling and Characterization Using a Graphical User Interface and a Flash Solar Simulator**." In proc. of Proceedings of the 6th International Workshop on Teaching in Photovoltaics, vol. 6, pp. 36-44, 2012.

XIV. S. Spataru, P. Cernek and D. Sera. "**Characterization of a Crystalline Silicon Photovoltaic System after 15 Years of Operation in Northern Denmark.**" In proc. of 29th European Photovoltaic Solar Energy Conference and

Exhibition, pp. 2680 - 2688, 2014, DOI: 10.4229/EUPVSEC20142014-5BV.1.31.

XV. S. Spataru, D. Sera, P. Hacke, T. Kerekes and R. Teodorescu. "**Fault Identification in Crystalline Silicon PV Modules by Complementary Analysis of the Light and Dark Current-Voltage Characteristics**." Progress in Photovoltaics: Research and Applications, 2015, DOI: 10.1002/pip.2571.

XVI. C. Kopacz, S. Spataru, D. Sera and T. Kerekes. "**Remote and Centralized Monitoring of PV Power Plants**." In proc. of Optimization of Electrical and Electronic Equipment (OPTIM), 2014 International Conference on, pp. 721-728, 2014, DOI: 10.1109/OPTIM.2014.6851005.

XVII. S. Spataru, D. Sera, T. Kerekes and T. Teodorescu. "**Photovoltaic Array Condition Monitoring Based on Online Regression of Performance Model**." In proc. of 39th IEEE Photovoltaic Specialists Conference pp. 0815 - 0820, 2013, DOI: 10.1109/PVSC.2013.6744271.

XVIII. D. Sera, S. Spataru, L. Mathe, T. Kerekes and R. Teodorescu. "**Sensorless PV Array Diagnostic Method for Residential PV Systems**." In proc. of 26th European Photovoltaic Solar Energy Conference and Exhibition, pp. 3776 - 3782, 2011, DOI: 10.4229/26thEUPVSEC2011-4AV.3.37.

XIX. S. Spataru, D. Sera, T. Kerekes and R. Teodorescu. "**Detection of Increased Series Losses in PV Arrays Using Fuzzy Inference Systems**." In proc. of Photovoltaic Specialists Conference (PVSC), 2012 38th IEEE, pp. 464-469, 2012, DOI: 10.1109/PVSC.2012.6317658.

XX. S. Spataru, D. Sera, T. Kerekes and R. Teodorescu. "**Diagnostic Method for Photovoltaic Systems Based on Light I-V Measurements.**" Solar Energy, (second round of review, 2015)

XXI. S. Spataru, A. Amoiridis, R. N. Beres, C. I. Ciontea, T. Klein and D. Sera. "**Development of an Intelligent Maximum Power Point Tracker Using an Advanced PV System Test Platform**." In proc. of Photovoltaic Specialists Conference (PVSC), 2013 IEEE 39th, pp. 2953-2958, 2013, DOI: 10.1109/PVSC.2013.6745084.

Further publications resulted from the project:

XXII. D. Sera, L. Mathe, T. Kerekes, S. Spataru and R. Teodorescu. "**On the Perturb-and-Observe and Incremental Conductance MPPT Methods for PV Systems**." IEEE Journal of Photovoltaics 3, no. 3 (2013): pp. 1070-1078, DOI: 10.1109/ JPHOTOV.2013.2261118.

XXIII. Spataru, S, Hacke, P, Sera, D, Glick, S, Kerekes, T, and Teodorescu, R, **Quantifying Solar Cell Cracks in Photovoltaic Modules by Electroluminescence Imaging,** in *42nd IEEE Photovoltaic Specialist Conference*. 2015, IEEE: New Orleans. p. 8.

XXIV. Hacke, P, Spataru, S, Terwilliger, K, Perrin, G, Glick, S, Kurtz, S, and Wohlgemuth, J, **Accelerated Testing and Modeling of Potential-Induced Degradation as a Function of Temperature and Relative Humidity**. *Photovoltaics, IEEE Journal of*, 2015. **5**(6): p. 1549-1553 DOI: 10.1109/JPHOTOV.2015.2466463.

XXV. E. Demirok, S. B. Kjaer, D. Sera, and R. Teodorescu, **Three-Phase Unbalanced Load Flow Tool for Distribution Networks**, in 2nd International Workshop on Integration of Solar Power Systems, Lisbon, Portugal, 2012.

XXVI. Erhan Demirok, Dezso Sera, Remus Teodorescu: **Investigation of extra power loss sharing among PV inverters caused by reactive power management in distribution networks**, IEEE Energy Conversion Congress and Exhibition ECCE 2014

5.2.2 Conferences and presentations

As shown above, the results in this project have been published through a number of journal publications, but also at a large number of international conferences were attended, where beside a paper in the conference proceedings, oral or poster presentations have been done.

A list of the key conferences that have been attended and results within this project were disseminated is shown below:

- 2011
  - 26th European Photovoltaic Solar Energy Conference and Exhibition
  - 37th IEEE Annual Conference of Industrial Electronics Society
  - 1st International Workshop on Integration of Solar Power into Power Systems
- 2012
  - 38th IEEE Photovoltaic Specialist Conference
  - 6th International Workshop on Teaching Photovoltaics
  - 2nd International Workshop on Integration of Solar Power into Power Systems
  - 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems
  - 21st IEEE International Symposium on Industrial Electronics
  - 13th International Conference on Optimization of Electrical and Electronic Equipment
  - IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES 2012)
- 2013
  - 39th IEEE Photovoltaic Specialist Conference – **Best poster award** for Sergiu Spataru for the paper 'Development of an intelligent MPPT using an advanced PV system test platform'
  - IEEE Energy Conversion Congress and Exposition (ECCE 2013)
  - 3rd International Workshop on Integration of Solar Power into Power Systems
  - IEEE Grenoble PowerTech (POWERTECH 2013)
  - 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013
- 2014
  - 29th European Photovoltaic Solar Energy Conference and Exhibition
  - 24th Workshop on Crystalline Silicon Solar Cells & Modules
  - 7th International Workshop on Teaching in Photovoltaics
  - 4th International Workshop on Integration of Solar into Power Systems
  - 14th International Conference on Optimization of Electrical and Electronic Equipment
  - PV Days Workshop
  - Intersolar 2014

While both PhD projects as well as the Postdoc project were finished by 2014, some of the results from the project were still published in 2015 as well.

- 2015
    - 42nd IEEE Photovoltaic Specialist Conference
    - 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG2015)

Figure 27: Best poster award for Sergiu Spataru at the IEEE PVSC 2013 conference

5.2.3 Other dissemination activities

The project was disseminated also at local events such as the Danish Smart Grid Event, November 2011 (Figure 28), as well as the university webpage.

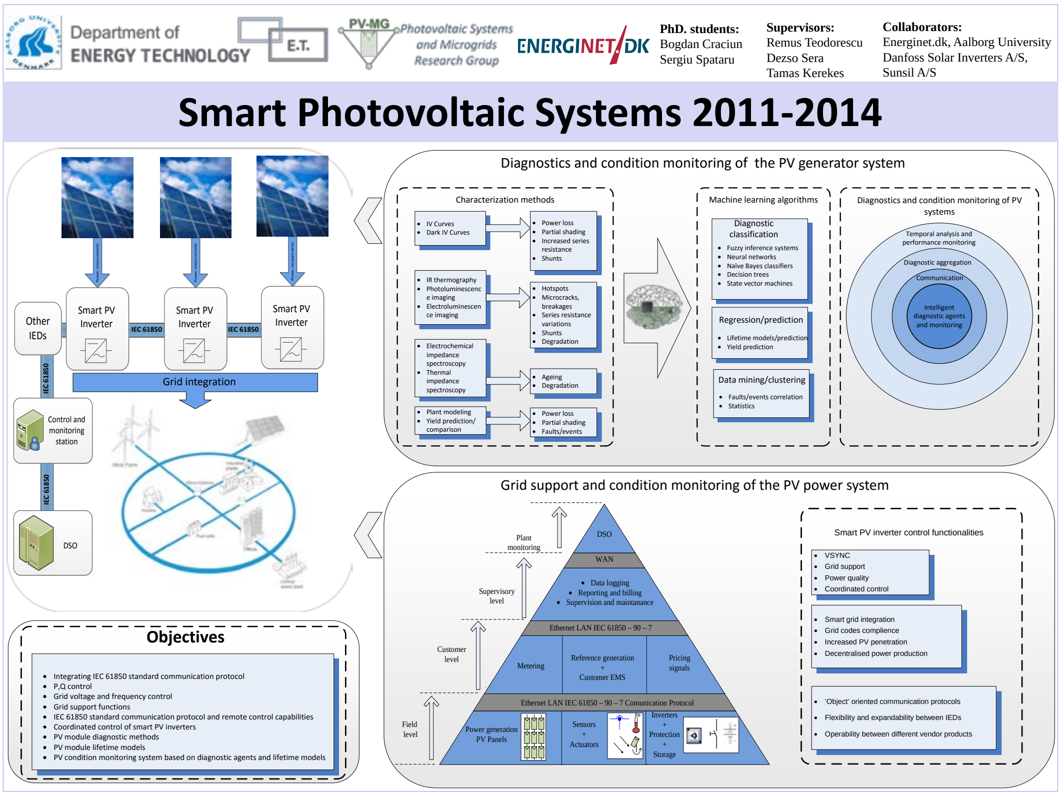


Figure 28: Poster presenting the Smart Photovoltaic Systems project at the Danish Smart Grid Event in November 2011

The project has also been made visible at the AAU webpage, which provides a platform of high visibility.

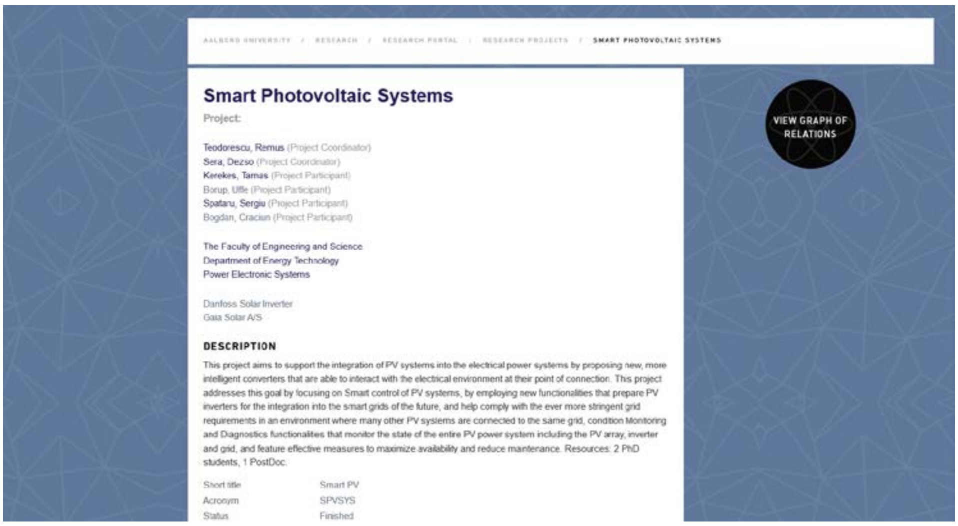


Figure 29: Screen dumps of the project description at the AAU webpage, and the link on the Photovoltaic Systems Research Group webpage

6. Utilization of project results

The platform developed for PV plant monitoring and diagnostics (PVDAQ) has been applied in another EUDP project entitled Energy Optimization of Solar Panels using Intelligent Controls (EOSPIC, 01.2012-07.2014) together with our industrial partner Gaia Solar A/S, and an agreement has been made with Gaia Solar A/S for further use of the platform.
Due to the change of ownership of Danfoss Solar Inverters A/S in the second period of the project, there is no direct utilisation from their side.

Furthermore, the project results contribute to a new standard for EL measurements of PV panels. The method for quantifying solar cell cracks from EL measurements been included in the current draft of the IEC TS 60904-13 “Photovoltaic devices - Part 13: Electroluminescence of PV modules”, which is currently being developed an international standard for electroluminescence images of PV modules.

The project has strongly contributed to teaching within photovoltaic systems at the Department of Energy technology, AAU. Apart from the research education of two successful PhD candidates, the results and know-how accumulated in the project have been disseminated towards education in a large number of MSc and BSc projects (mainly MSc), as well as courses at PhD and MSc level. Furthermore, the results were disseminated at international conferences and tutorials with audience from the world-wide research and industrial community, as listed below.

6.1 PhD education

6.1.1 New PhD graduates and postdoc

- Bogdan-Ionut Craciun, PhD thesis title: *Grid Support in Large Scale PV Power Plants Using Active Power Reserves*
- Sergiu Spataru, PhD thesis title *Characterization and Diagnostics for Photovoltaic Modules and Arrays*
- Erhan Demirok, Postdoc (1 year). *High PV Penetration in LV Distribution Networks*

6.1.2 Contribution to PhD / Industrial courses

The results of the project have been used directly in the following PhD courses, with attendance from academia from Denmark and international, as well as industry.

- Power Electronics for Renewable Energy Systems – in theory and practice PERES. (2011, 2012, 2013, 2014)
- Photovoltaic Power Systems – in theory and practice (PVPS) (2011, 2012, 2013, 2014, 2015)

6.2 MSC and BSc education

In the following the list of Masters and Bachelor semester projects and courses at the department of Energy Technology that benefitted from and contributed to SPVSYS as well as international tutorials are listed:

6.2.1 MSc and BSc projects

- Design and implementation of a solar cell stress testing setup MSc INTRO/7th sem
- Determining Maximum Photovoltaic Hosting Capacity of Low Voltage Distribution Networks BSc 5th sem
- High Efficiency Residential Photovoltaic system MSc 10th sem PED
- Characterization and Diagnostics of Photovoltaic Modules
- Impact of Large Penetration of PV and Wind Power into LV Distribution Network, Msc 8 Sem
- Challenges of PV integration in the MV electricity grid, MSc 10 Sem.
- Advanced control and condition monitoring for PV systems, Msc 10 Sem
- Design and Construction of a Solar Cell I-V Curve Tracer, BSc 6th sem
- High efficiency Residential Photovoltaic System; Msc 10 sem
- Control of Grid Connected PV Systems with Grid Support Functions; Msc 10 sem
- Photovoltaic power plant prepared for smart grid, Msc 10 Sem
- Multiterminal HVDC transmission MSc 10 sem

6.2.2 Contribution to MSc courses

- Control of grid connected PV and Wind turbine systems (2012, 2013, 2014, 2015)

6.3 Contribution to Tutorials

- International Workshop on Integration of Solar Power into Power Systems (2011, 2012, 2013)
- IEEE Energy Conversion Congress and Exposition, ECCE-2013
- IEEE European Conference on Power Electronics and Applications, EPE-2013
- IEEE International Symposium on Power Electronics and Distributed Generation ,PEDG-2015

7. Project conclusion and perspective

The project has produced a large amount of technical results, in support of higher PV penetration into the energy mix. These results were widely disseminated by scientific publications, courses (PhD and MSc), MSc projects, expert tutorials at conferences, conference presentations and posters, and webpages.

Some of the results of the project have already been applied and further developed in other projects (EUDP, Innovationsfonden), and continue to be further developed for new research projects.

While the direct commercial application at the end of the project was limited to only one partner (Gaia Solar A/S) due to the change of ownership of the other industrial partner (Danfoss Solar A/S), the project results strongly support the Danish PV industry both directly (know-how, monitoring platform, PhD courses, available scientific publications) as well as indirectly, through the continued research collaborations for which this project paved the way.

With the increasing penetration of PV power into the electricity grid both at distribution (residential and rooftop) level as well as LPVPP (typically ground mounted) on the MV network, the voltage support, power curtailment and active power reserve management functions become increasingly relevant. It is expected that more countries will tighten their grid technical requirements towards PV.

Furthermore, as the PV industry is becoming a more mature industry, and with the decrease of initial investment cost for new PV plant, especially the O&M cost during lifetime is becoming more substantial, therefore optimized O&M is gaining more and more attention from industry. The automatic diagnostic and characterisation techniques for the PV array developed in this project become therefore more and more important. Currently many of the results and know-how accumulated in this project is being used in the project entitled Fully Automated Service Execution Platform (FASE) funded by Innovationsfonden.

8. Annex

Links to PhD theses:

- PhD Thesis: *Grid Support in Large Scale PV Power Plants using Active Power Reserves* (http://vbn.aau.dk/files/207334549/bogdan_ionut_craciun.pdf) by Bogdan Craciun
- PhD Thesis: *Characterization and Diagnostics for Photovoltaic Modules and Arrays* (http://vbn.aau.dk/files/223521354/sergiu_spataru.pdf) by Sergiu Spataru

Link to project webpage at AAU: http://vbn.aau.dk/da/projects/smart-photovoltaic-systems%2879beee67-64a3-49d1-97aa-76aec82d4853%29.html