DERri
Distributed Energy Resources
Research Infrastructures

User-Project Proposal:

Use-Project Acronym	SPVSYS
User-Project Title	Smart Photovoltaic Systems
Main-scientific field	Power electronics
Specific-Discipline	Photovoltaic power systems

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(Repeat for all Users)

Date of submission	31.10.2011
Re-submission	YES________ NO________
Proposed Host TA Facility	IWES
Starting date (proposed)	01.04.2012

Summary of proposed research (about ½ page)

Every year more and more Photovoltaic (PV) power is integrated into the grid, making PV energy one of the fastest growing renewable energy technologies in the world. Until recently, standard PV systems were equipped with limited functionalities where the main focus was only on the power production and in any abnormal situation to disconnect. The trend changed and PV systems, mainly the involved power electronics, started to gain more and more intelligence.

From the power production point of view, PV systems skilled with elevated diagnostic algorithms should provide in any condition the state of health of the production plant.

Another goal of this research project is to make PV systems react like conventional power plants in such a way that they should provide support to the grid when the Distribution System Operator (DSO) requests it, especially during faulty conditions. Furthermore, the integration of PV systems has to be made on a basis that it has to be compatible with the future concept of smart grid where one vital element is the communication among the generating units.

PV systems equipped with smart control functionalities have the potential to become one of the future technologies which can replace the conventional ways of producing electricity and the involved power electronics are the key of success.

State-of-the-Art (about 1 ½ page)

Solar energy proves to have an intermittent and non-dispatchable character being strongly influenced by meteorological conditions. Traditionally, PV systems were operating only in maximum power point tracking (MPPT) mode in order to capture as much energy as possible from the sun without any other services included. Another drawback was that in case of faulty grid, PV systems were required to disconnect. The trend changed and today most PV systems beside the MPPT mode should provide ancillary services like voltage and frequency support, improved power quality and in this way to enforce the stability and reliability of the grid [1].

High PV penetration into the grid made system operators consider strict regulations regarding their interconnection. The most important requirements are: EN 50160 - Public Distribution Voltage Quality, IEEE 1547 - Interconnection of Distributed Generation, IEC 61727 - Characteristics of Utility Interface, VDE 0126 Safety - It provides over/undervoltage and frequency detection and test procedures, IEC 61000 - Electromagnetic Compatibility [2-5]

Several interconnected PV systems in a decentralized electric power system start to become a reality all over the world. As a consequence such systems are no longer seen as ‘negative loads’ due to their significant installed power and they are considered in the planning and operation of the grid. From this point on the communication between the DSO and the PV systems is needed for a proper interaction between them[6, 7]

The trend focuses on the new generation of protocols based on ‘object’ transmitting technology such as IEC 61850. This standard is preferred over the well-known legacy protocols (Distributed Network Protocol (DNP3), Modbus, RS232, CAN etc.) due to their following drawbacks: Low system integration, Low interoperability, difficulties in operabilities interoperability, limited expendability and flexibility[7].

PV systems equipped with specialised communication features like IEC 61850 – 90 – 7 are becoming ‘smart’ and can perform autonomously according to pre-established settings. Such systems can ‘sense’ local conditions like voltage level, frequency deviation, power quality and can receive and broadcast emergency signals which can modify in real time their active and reactive power output. These Intelligent Electronic Devices (IEDs) can perform according to schedules, can consider prizing signals and can respond at any DSO request[8].

Taking into consideration the grid connection, PV systems can roughly be split into distributed generation or PV plant. In both cases they have to ensure two main functionalities: stability and quality. In case of large PV plants, grid stabilization features are used while power quality capabilities are ensured and applicable for smaller PV applications.

References

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[2] EN 50160, "Voltage characteristics of electricity supplied by public distribution systems", 2010.
[3] Anonymous "IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems", IEEE Std 1547. 2-2008, pp. 1-207, 2009.
[4] International Electrotechnical Commission, "IEC 61000 - Electromagnetic compatibility (EMC)", 2008.
[5] International Electrotechnical Commission, "IEC 61727 - Photovoltaic (PV) systems – Characteristics of the utility interface", 2004.
[6] EPRI. Implementation of international Electrotechnical commission (IEC) 61850 - A coherent

approach to substation and smart grid. EPRI. Pato Alto CA, USA. [December 2010]. Available: www.epri.com.
[7] P. Esslinger and R. Witzmann, "Increasing grid transmission capacity and power quality by a new solar inverter concept and inbuilt data communication", in Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES, 2010, pp. 1-8.
[8] International Electrotechnical Commission, "IEC 61850 - Communication networks and systems in substations", 2011.

Detailed Description of proposed project : Objectives – Expected Outcome – Fundamental Scientific and Technical value and interest (2-3 pages)

Purpose:

This project aims to support the integration of PV systems into the electrical power systems by proposing new, more intelligent converters that are able to interact with the electrical environment at their point of connection. This project addresses this goal by focusing on:

- Smart control of PV systems, by employing new functionalities that prepare PV inverters for the integration into the smart grids of the future, and help comply with the ever more stringent grid requirements in an environment where many other PV systems are connected to the same grid.
- Condition Monitoring and Diagnostics functionalities that monitor the state of the entire PV power system including the PV array, inverter and grid, and feature effective measures to maximize availability and reduce maintenance.

This project will contribute to PV systems with higher stability and availability, resulting in higher energy yield and life-time, allowing lower cost for energy generated by photovoltaics. It is expected that this project will bring important contribution to enabling mass penetration of PV generation.

At the end of this project new diagnostic and prognostic functions will be provided to the PV industry that will effectively increase long-term yields of PV installations. Intelligent software features implemented in PV inverters will provide grid support, higher stability against grid disturbances, and lower maintenance cost for PV systems. The outcome of this project is expected to directly benefit the Danish PV industry as the obtained results can be implemented in commercial PV inverters, making an improvement of the presently available products in the range of PV inverters. Clearly, the expected findings of the project are as following:

- By utilizing new smart functions for the commercial PV inverters, more PV systems can be connected to the available electric grid.
- PV systems will be more robust than the state-of-the-art PV systems against distorted and faulty grid conditions.

Organization

The project coordinator is Aalborg University, Department of Energy Technology, by Professor Remus Teodorescu. Professor Teodorescu managed and coordinated over 20 research projects in the area of power electronics for wind and PV power including the Vestas Power Program, 10 PhD research cooperation projects between Vestas and Aalborg University in the field of grid integration of wind power (2008 - 2013).

Project description

Photovoltaic energy generation is becoming increasingly significant in providing sustainable energy for the ever-increasing needs of the society, and it will play a key role in the world energy scenario.

Mass penetration of PV generation requires not only that the entire PV installation meets performance, reliability and availability requirements, but prerequisites new solutions to improve yield, availability, stability and robustness for seamless integration into the electricity network. Our aim 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.

The state-of-art projects have focused more on highly efficient, low cost PV systems including solar module installation and grid-connected inverters, gaining experiences for PV in all categories of buildings, PV modules with integrated inverters. On the other hand grid interaction of these systems especially with high penetration levels has not been investigated in details so far. 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 Smart Photovoltaic Systems (SPVSYS) (ForskEL – 10648) 17.09.2010 4 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 behavior 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 behavior 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 analyzing the trends in their key characteristics. Moreover, by identifying the responsible stress factors (e.g. by diagnostic functions), and analyzing 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 preemptive 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.

Relevance
By the end of 2010 the cumulative PV installations should reach more than 30 GW worldwide, experiencing an important growth despite the financial crisis. This shows that the need for renewable energy is a strategic issue due to the climatic impact, sustainability and high development rates in China and India. Denmark has a leading position in renewable energy, specially related to wind power. In PV industry, Denmark is increasing the market shares where companies like Danfoss Solar Inverters are currently supplying 3-4% of the worldwide PV inverter market and new companies in the PV module manufacturing industry are emerging (SunSil). Smart Photovoltaic Systems (SPVSYS) (ForskEL – 10648) 17.09.2010 5 The European Strategic Energy Plan estates a binding target to ensure 20% of renewable energy sources in the EU energy mix by 2020. This will strengthen the implementation of renewable generation technologies, such as wind and PV. The large penetration of PV inverters especially in low voltage networks related to residential/commercial PV plants stability issues are becoming challenging. New, more stringent grid requirements are expected to emerge following the path of wind power with global goal of turning renewable energy power plants in "virtual" power plants. As PV penetration is growing, the impact on grid stability is becoming important. New demands like voltage ride-through, voltage regulation and island operation are emerging. The current application also follows the Danish strategy detailed in "Solceller – Dansk strategi for forskning, udvikling, demonstration og udbredelse", where in subsections 3.4C and 3.4D it is stated that grid connected photovoltaic systems will have to take an active role within the electrical power system. Grid connected photovoltaic systems in Denmark are expected to keep their decentralized position also in the near future; therefore it is a must that the future systems manage the local consumption and the electrical grid both under normal and faulty conditions.

R&D Strategy

One of the main interests of the Department of Energy Technology (DET) is on renewable energy technologies, focusing on wind and photovoltaic applications that are interfacing the electrical grid. During the last decade DET has established a solid experience base in the field of photovoltaic inverters, including development of grid connected inverters (module inverters, new transformerless inverter topologies), Maximum Power Point Tracking (MPPT) for PV systems, modeling and diagnostics of PV modules, as well as advanced grid control of PV inverters including grid condition monitoring, anti-islanding, control strategies under distorted grid, and more. DET carried out a large number of PhD/ industrial projects and produced an extensive publication list, in the above-mentioned topics.

Originality and Innovation of proposed research – Broader Impact (1-2 pages)

The main objectives of this project are to develop control strategies for grid support, monitoring and coordination between distributed PV systems. Another direction is to improve the existing control strategies applied for PV inverters in coordinated control operation.

The target is to integrate PV systems into the grid and to comply with the requirements imposed by the grid operator. In normal operation and especially under fault conditions, PV systems have to provide the grid with voltage support, frequency support and in this way to start behaving as a conventional power plant In future PV installations, trends show that PV inverters equipped with smart capabilities are preferred over the standard options due to their obvious technical and economic advantages.

These new characteristics added to the PV systems and to the power electronics involved should meet the requirements and should facilitate the integration of such systems into the future smart grids. In the upcoming revolutionary idea and concept of smart grid, PV systems equipped with elevated communication protocols and smart control techniques should play an important role in integrating solar energy into the grid. Ancillary services from the system operator's point of view are considered mandatory even for medium and low voltage applications. In any given condition PV systems consisting of smart PV inverters should comply with future grid codes and in the same time improve the stability of the grid. The developed techniques will be implemented in commercial PV inverters therefore contributing to higher PV penetration.

In parallel, diagnostic functionalities for the PV generator should be studied and implemented in the new smart PV inverters, that are able to detect PV performance decreasing factors, such as partial shadows, dust, increased series resistance due to bad contacts or PV module degradation. The functionalities should be developed based on experimental study of the PV system, and extrapolated as much as possible to different operating conditions of the PV system.

Furthermore, reliability and ageing data of old and new PV technologies should be collected and processed with the goal of estimating lifetime models for the different PV panel technologies. Such lifetime information would be invaluable in supporting the continuous integration and installation of PV systems and improve the diagnostic and condition monitoring process of PV systems.

Proposed Host TA Infrastructure/Installation – Justification (about one page)

PVMG group would like to use the test facilities provided by **Fraunhofer IWES** institute in Kassel. PV power systems should provide ancillary services to the grid but also to perform detailed measurements (yield, IV curves, dark IV, IR imaging, electrochemical impedance spectroscopy) of the PV arrays/modules installed in order to characterize their state of health,to develop diagnostic functions and collect reliability/ageing data. These systems are usually connected to low and medium voltage networks and the grid simulator (10 kV) is an adequate tool to test the applicability of the grid support function in term of voltage and frequency implemented in smart PV inverters.

From the smart grid perspective, one important feature is the communication. PV systems skilled with communication abilities will be tested in order to determine energy yield, test the health of PV models and last but least integrate PV power into the grid. All these steps will be carried out using the facilities provided by IWES-Systec test center.

Synergy with ongoing research (about ½ page)

Institution: Electric Power Research Institute(EPRI)

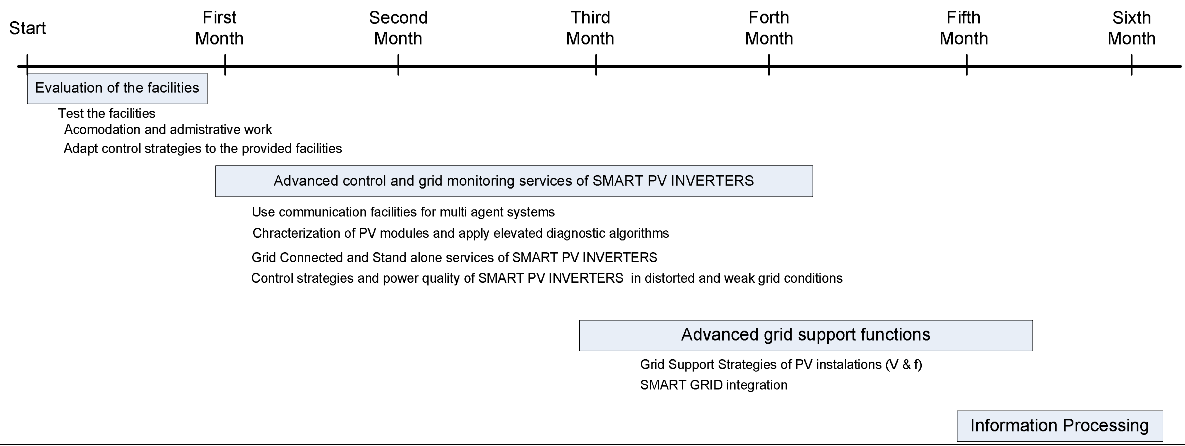
Project: Demonstration of Photovoltaic Inverters with Smart-Grid Functionality
Source: www.epri.com

PVMG group proposed project entitled 'Smart PV Systems' has the purpose of providing grid connected PV systems with elevated diagnostic tools for PV panels and with improved control algorithms for a better integration of PV power into the grid.

Dissemination – Exploitation of results (about ½ page)

The results obtained from the collaboration with DERri and Fraunhofer IWES Institute will be published in prestigious conferences like Energy Conversion Congress and Exposition (ECCE), Annual Conference of Industrial Electronics (IECON) organized by IEEE, and International Energy Agency Photovoltaic Power System Programme (IE-PVPS).

Time schedule (about ½ page)



Description of the proposing team (as long as needed)

Remus Teodorescu received the Dipl.Ing. degree in electrical engineering from Polytechnic University of Bucharest, Romania in 1989, and PhD. degree in power electronics from University of Galati, Romania, in 1994. In 1998, he joined Aalborg University, Department of Energy Technology, power electronics section where he currently works as a professor He has more than 180 papers published, 1 book (Grid Converters for Photovoltaic and Wind Power Systems, ISBN-10: 0-470-05751-3 – Wiley) and 4 patents. He is a Senior Member of IEEE, Past Associate Editor for IEEE Trans on Power Electronics and chair of IEEE Danish joint IES/PELS/IAS chapter. He is the founder and coordinator of the Green Power Laboratory at Aalborg University focusing on the development and testing of grid converters for renewable energy systems. He is the coordinator of Vestas Power Program, involving 10 PhD students, 2 Post Doc and guest professors in the areas of power electronics, power systems and energy storage. His areas of interests are: design and control of power converters used in photovoltaics and wind power systems, grid integration with wind power, medium-voltage converters, HVDC/FACTS, energy storage.

Dezso Sera received his B.Sc. and M.Sc. degrees in Electrical Engineering from the Technical University of Cluj, Romania in 2001 and 2002, respectively.

In 2005, he graduated from the M.Sc. program at Aalborg University, Denmark, in the Department of Energy Technology (DET) and in 2008 he received his PhD degree from the same department, where he currently works as Associate Professor. Since 2009 he has been the coordinator of the Photovoltaic Systems and Microgrids Research Programme at DET.

His current research activities are in photovoltaic power systems in general, specifically in the modelling, characterisation, diagnostics and maximum power point tracking (MPPT) of PV systems, and, also in the grid integration of PV power.

Tamas Kerekes obtained his Electrical Engineer diploma in 2002 from Technical University of Cluj-Napoca, Romania, with specialization in Electric Drives and Robots. In 2005, he graduated the Master of Science program at Aalborg University, Department of Energy Technology in the field of Power Electronics and Drives. In 2009 he received his PhD degree from Aalborg

University. Currently he is working as an Assistant Professor at the same Department. Since he started his PhD at the Department of Energy Technology his main interest is on PV inverter modeling, control and topologies as well as modulation techniques with focus on transformerless PV inverter systems.

Sergiu Spataru - received his B.Sc. degree in Automation and Applied Informatics from “Politehnica” University of Timisoara in 2009 and in 2011 he received his M.Sc. diploma in Wind Power Systems at Aalborg University, Department of Energy Technology. Currently his PhD student at Aalborg University and part of Photovoltaic Systems and Micro Grids Research Group.

Bogdan-Ionut Craciun received his B.Sc. degree in Power Electronics and Drives from Technical University of Cluj-Napoca in 2009 and in 2011 he received his M.Sc. diploma in Power Electronics and Drives at Aalborg University, Department of Energy Technology. Currently his PhD student at Aalborg University and part of Photovoltaic Systems and Micro Grids Research Group.