Final report

1.1 Project details

Project title	Micro-grid Technology, Research and Demonstration
Project identification (program abbrev. and file)	64013-0407
Name of the programme which has funded the project	EUDP - Systemintegration
Project managing company/institution (name and address)	Department of Energy Technology, Aalborg University Pontoppidanstræde 111, 9220 Aalborg East
Project partners	Aalborg University, Tsinghua University, Kamstrup A/S, Shanghai Solar Energy Science & Technology Co. Ltd
CVR (central business register)	29102384
Date for submission	19.01.2018

1.2 Short description of project objective and results

The project aimed to develop demonstrative, research-oriented platforms to ease the integration of Distributed Generation (DG) units with hierarchical (multilayer) control strategies for microgrids. Aalborg University, Kamstrup A/S, Tsinghua University, and Shanghai Solar Energy Ltd. have collaborated for this project. A 200kW microgrid pilot platform has been developed in Shanghai. A flexible microgrid energy management system (EMS), with ICT and coordinated control functionalities, was implemented and validated through laboratory-scale and pilot-site tests. A complete smart metering system was implemented in the laboratory. Furthermore, the technical achievements of the project were reported in 44 scientific papers including 12 journal articles.

Projektet har til formål at udvikle demonstrative, forskningsorienterede platforme for at lette integrationen af decentrale el-produktionssystemer med hierarkiske (multilayer) styringsstrategier for Microgrids. Aalborg Universitet, Kamstrup A/S, Tsinghua Universitet og Shanghai Solar Energy Ltd. har samarbejdet om dette projekt. En 200kW Mikrogrid pilot platform er blevet udviklet i Shanghai. Et fleksibelt Microgird styringssystem til styring af energibesparelser med IKT og koordinerede kontrolfunktioner blev implementeret og valideret gennem laboratorie- og pilot test. Et komplet smart målesystem blev implementeret i laboratoriet. Desuden blev de tekniske resultater af projektet rapporteret i 44 videnskabelige artikler inklusive 12 journalartikler.

1.3 Executive summary

The project dealt with research, development and demonstration of a full-scale microgrid (MG). The work has been carried out by two universities, Aalborg University (AAU), Denmark and Tsinghua University (TU), China, in cooperation with the companies Kamstrup A/S, Demark and Shanghai Solar Energy Science & Technology Co. Ltd (SSEC). In order to ensure project success and develop a fruitful and efficient collaboration, regular meetings have been arranged with project partners.
The MG is regulated by using a hierarchical (multilayer) control structure to provide optimized energy management with demand response feature and satisfactory power quality. Communication networks are applied in order to coordinate MG elements and send main system information to the MG central controller. Proper control of the power electronics interfaces of energy resources and the integration of smart metering system, which is also called advanced metering infrastructure (AMI), are considered as well.
The first project work package (WP1) was focused on the design of MG. The MG is modeled in different simulation scenarios have been run and experimentally tested in AAU MG lab. Based on this, the system layout as well as architecture and basic control of power electronic converters of photo-

voltaic (PV) systems, wind turbines (WTs) and battery energy storage were determined and the MG has been installed in Shanghai pilot site.
In WP2, a multilayer (hierarchical) control system has been designed and proper control methods are developed for compensation of harmonics and unbalance to ensure the desired power quality. An integrated hierarchical control system to improve power quality and enable Demand Side Management (DSM) and load control (including shifting and shedding) has been developed and tested in AAU MG Lab. Furthermore, the control algorithms have been implemented for PV arrays, WTs and battery energy storage in Shanghai site. In order to assess power quality and evaluate the effectiveness of the proposed compensation schemes, extensive measurements have been performed in the Lab and also the MG site by using both smart metering system and a power quality analyzer (Fluke 437-II).
In WP3, MG communication and SCADA system have been developed. Both wired (Ethernet-based) and wireless schemes as well as SCADA with EMS and smart metering system have been implemented in AAU MG Lab. Although Ethernet-based and other communication technologies can be applied in Shanghai site, RS-232 and RS-485 protocols form the basic communication in this site due to their high reliability and relative implementation simplicity.
WP4 was dedicated to development of energy management and optimization techniques for MGs. In this regard, both islanded and grid-connected operations are taken into account. In the islanded mode, the EMS was implemented to provide the reference signals for battery banks and Renewable Energy Sources, RESs (PV and WT) and to minimize the disconnection of the loads. In grid-connected operation, optimization is done to maximize the revenue of the MG considering energy purchase and sell prices while technical needs were also satisfied.
In WP5, an extensive effort has been done for exploiting all the features of AMI for smart grid applications. In this regard, EMS and AMI are integrated in a properly designed architecture. Furthermore, the final tests of all control, metering and communication systems are also performed in both MG Lab and Shanghai site.
To summarize, based on the technical achievements of the project, an integral solution has been proposed which can enhance the MGs implementation and commercialization in the context of smart grid. In other words, MGs are envisioned as building blocks of smart grids. In fact, the main aspects and concerns of smart grids with high penetration of RESs including energy management and optimization, demand response, smart metering, communication, power quality as well as control and architecture of power electronics interfaces are explored in this project.

1.4 Project objectives

The main objectives of the project can be summarized as below:

- Developing demonstrative MG platforms in both laboratory- and full-scale pilot site.
- Implementing control and energy management strategies as an integral solution for MGs based on a multi-layer structure and proper communication technologies to ease the integration of RESs and energy storage systems.

In order to achieve these objectives, the following milestones have been planned and accomplished during the project:

- M1 Microgrid structure implementation
- M2 Microgrid control systems
- M3 Communication networks for Microgrids
- M4 Energy management systems for Microgrids
- M5 Integral microgrid solution

To accomplish these milestones several tasks which are detailed in section 1.5 of the present report have been done and regular meetings were held with project partners. The main coordination meetings between AAU and partners are briefly listed below:

- <u>Meetings with Kamstrup A/S</u>
    - Meeting at AAU MG lab, Date: 12-08-2014
    - Meeting at Kamstrup A/S, Date: 04-09-2014
    - Meeting at Kamstrup A/S, Date: 01-04-2015
    - Meeting at AAU MG lab, Date: 11-06-2015
    - Meeting at AAU MG lab, Date: 09-02-2016

    - Meeting at Kamstrup A/S, Date: 10-02-2017

- Meetings with TU
    - Meeting at IEEE ECCE 2014 conference in Pittsburgh, PA, USA, Date: 15-09-2014
    - Meeting with TU and SSEC in Shanghai MG site, Date: 17-11-2014
    - Meeting at PES General Meeting in Denver, USA, Date: 27-07-2015
    - Meeting at AAU, Date: 11-10-2016
    - Meeting at AAU, Date: 17-07-2017

- Meetings with SSEC
    - Meeting with TU and SSEC in Shanghai MG site, Date: 17-11-2014.
    - Meeting in Shanghai MG site, Date: 27-05-2016.
    - Meeting at AAU, Date: 19-07-2017.

In addition to the above meetings, a postdoc contracted by TU and started from 01-03-2015 has been working in AAU and TU in continuous contact with Shanghai MG site owned by SSEC. In addition, to strengthen the coordination between AAU and Chinese partners, a professor from TU stayed in AAU for two months starting from mid of July 2015.
It is also noteworthy that AAU has been in continuous contact with Kamstrup A/S through emails and phone calls to fully implement the features of smart metering system in AAU MG lab.
Furthermore, the project activities have been coordinated by weekly internal meetings in AAU.
The main challenge in the project was adapting the developed lab-tested models and control algorithms in AAU side to the requirements and practical limitations of Shanghai pilot site. It was due to the fact that communication protocols and control possibilities were different between a Danish lab and a Chinese industrial environment. This issue as the main risk for pilot site implementation has been resolved through continuous contacts and technical meetings with Chinese partners.
Generally, the project progressed well based on the Gantt chart and no noticeable deviation and unexpected problem occurred.

1.5 Project results and dissemination of results

The project achieved its milestones and objectives and an integral MG control solution has been proposed, tested in the laboratory and demonstrated in a pilot site. The results and technical activities of the project are detailed below in the order of WPs.
It should be noted that following the fruitful collaboration with the project partners, cooperation for future projects is planned and in the following months the efforts will be focused on preparing project applications based on the upcoming funding opportunities. It is expected that such collaborations lead to new services, products and employment possibilities in Denmark.

Project Results

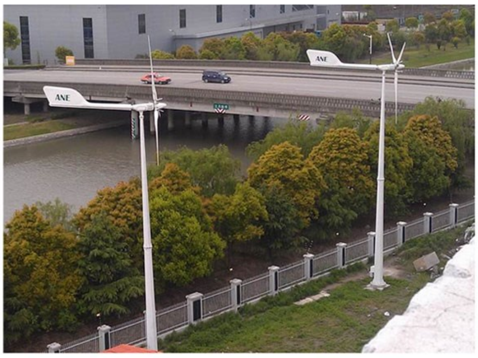
WP1 Microgrid design

The following tasks have been completed in this WP:
- *Task 1.1 Microgrid modeling and simulation*
- *Task 1.2 Design of power electronics microgrid architecture*
- *Task 1.3 Research and development of energy storage systems*
- *Task 1.4 Development of battery management system*
- *Task 1.5 Implementation of wind-PV-battery based microgrids*

The models and algorithms were firstly tested in AAU MG Lab and the resultant findings and experiences were applied for implementation in Shanghai MG site. Fig. 1 shows the MG lab setups. The photovoltaic/wind/battery MG system implemented in Shanghai site can be seen in Fig. 2.

Fig. 1. Setups in AAU MG Lab

Rooftop building photovoltaic installation



2x10 wind turbine system

Battery energy storage system, power electronics and control

Fig. 2. MG implementation in Shanghai site

<u>WP2 Microgrid control and power quality</u>

Task 2.1 Multilayer control design

A multilayer (Hierarchical) control scheme has been designed and validated by means of simulation studies and experiments in AAU MG Lab. This control architecture consists of primary, secondary and tertiary layers.

The hierarchical control addresses voltage and frequency restoration, energy management and optimization as well as power quality enhancement. Centralized as well as distributed schemes for hierarchical control have been designed and validated. A general scheme of the control architecture is depicted in Fig. 3.

Task 2.2 Microgrid harmonic and unbalance compensation

Based on the hierarchical architecture designed in Task 2.1, control of power electronic converters in microgrids to compensate voltage harmonics and unbalance is designed and validated through simulations and experiments. The goal of compensation is to provide desirable voltage quality for the sensitive loads inside the microgrid.

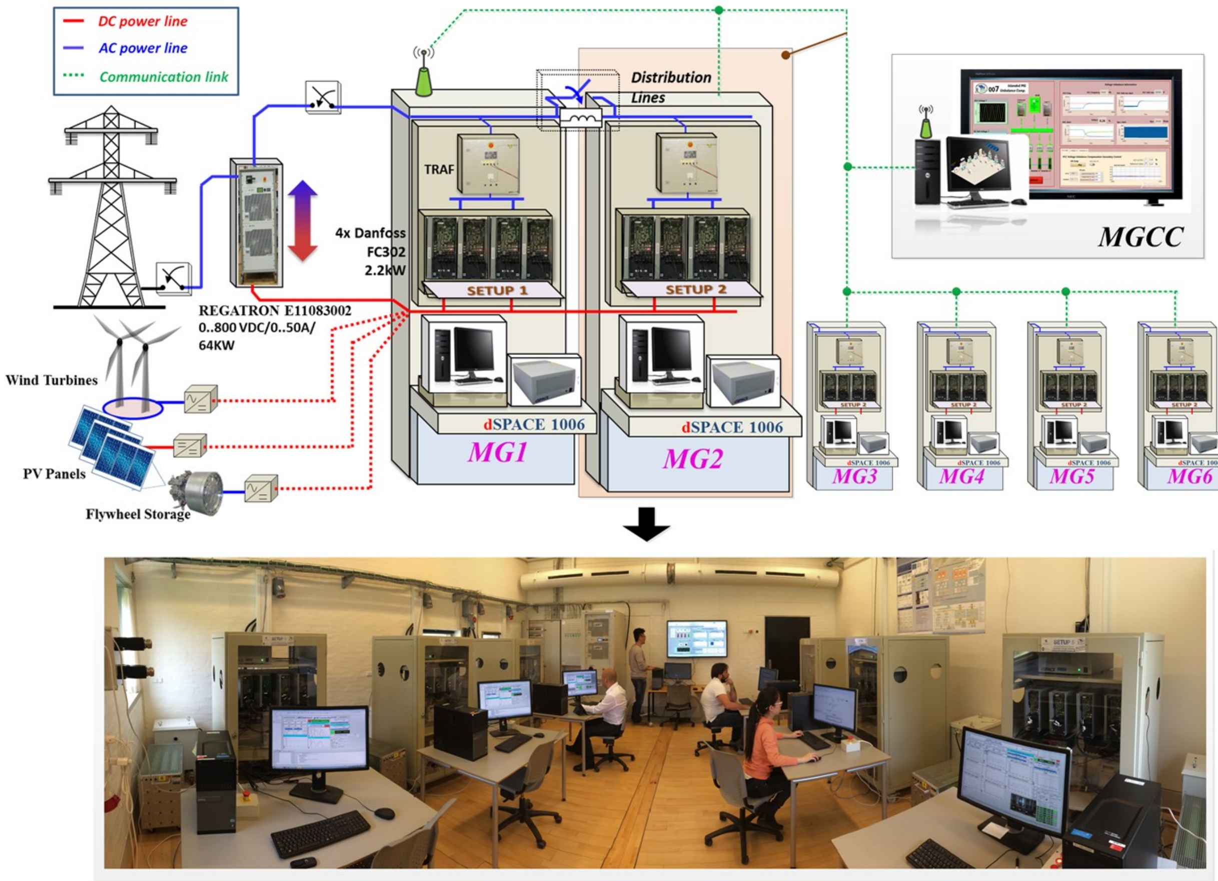
Moreover, extensive work has been done for implementing smart metering system in AAU MG Lab. All of the Lab setups were equipped with the new smart meters from Kamstrup (2 meters per setup as can be seen in Fig. 4).

In addition, these smart meters are integrated in a smart grid platform from Kamstrup (OMNIA Suite) in the Lab. As it can be seen in Fig. 5, data recorded in the smart meters are transmitted by mean of radio mesh communication to a data concentrator (OMNICON) and then to a central PC database for analysis and reporting. EMS and DSM functions are integrated in this PC. In addition, software tools, namely Utilidriver and Visionair are installed to integrate smart meters and facilitate data reporting and analysis.

OMNIA Smart metering installation is also in line with the following tasks:

- *Task 5.1. Integration of smart meters and smart-grid ready technologies*
- *Task 2.2 Microgrid harmonic and unbalance compensation*
- *Task 2.5 Power quality assessment under real-case scenarios*

In fact, smart meters are able to record power quality events like voltage variations and interruptions as well as voltage distortions like harmonics. These recordings are sent to the central PC for reporting and analysis. Thus, the smart metering system can be used to assess the effectiveness of the developed control approaches for compensation of power quality problems.



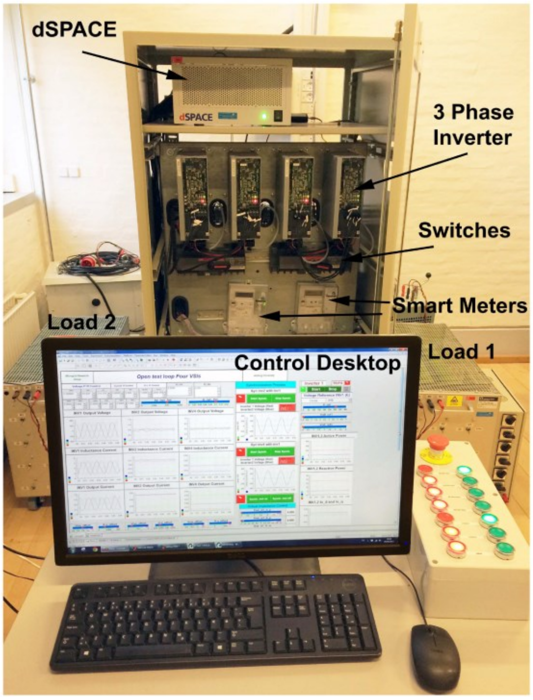


Fig. 4. Smart meters installed in setups of MG Lab

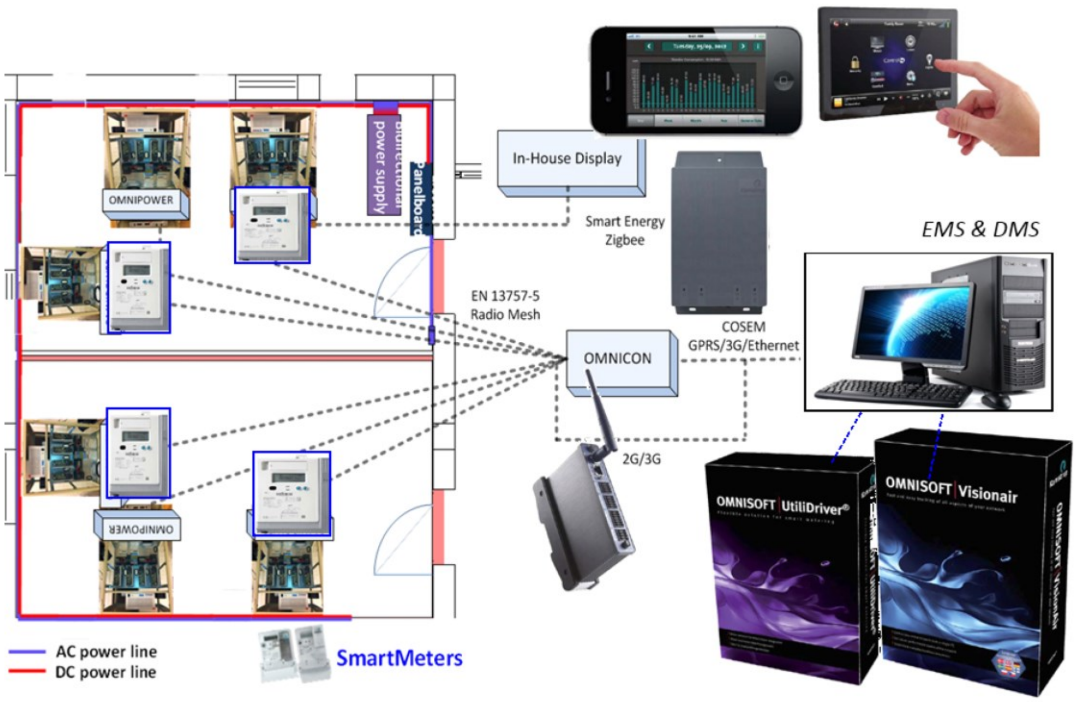


Fig. 5. Schematic diagram of OMNIA system implementation at Microgrid Lab.

Task 2.3 Integration of microgrid control unit

Task 2.4 Demand side management and load shedding control

The main focus in Tasks 2.3 and 2.4 has been on developing, testing and implementing an integrated hierarchical control system for microgrids to improve power quality and enable DSM and load control (including shifting and shedding). It should be mentioned that DSM and load control are two of the EMS functions. Thus, although, a full EMS is designed and implemented in WP4, its general design, features and control architecture are also studied in Tasks 2.3 and 2.4.

The integrated hierarchical system has been developed and tested in AAU MG Lab. Fig. 6 depicts the implemented control architecture. As it can be seen in this figure, the control system consists of primary, secondary and tertiary levels. The primary control is in charge of local voltage and current control of DGs while the secondary level takes care of microgrid power quality (PQ). In Fig. 6, restoration of voltage and frequency and also voltage unbalance compensation have been illustrated in

this regard; however, harmonic compensation is implemented in a manner similar to unbalance. Tertiary control is mainly in charge of EMS and optimized operation. A communication link which will be explained later transmits control signals and data between control levels.
As mentioned before, DSM and load shedding are two EMS functions which are covered by Task 2.4. Fig. 7 shows the details of the laboratory implementation by emulating a system similar to the microgrid implemented in Shanghai site. As it can be observed in this figure, the tested system consists of some DG converters with LCL filters which interface loads, storage systems and generators. There are two types of loads: Non-controllable (non-shiftable/non-shedable) which cannot contribute to Demand Response (DR) and shiftable loads which can be considered for DR. One important point about this figure is that EMS and its database and communication system are integrated with smart metering system.
This fact has been better shown in Fig. 8(a) where four Lab setups (Set.1 to Set. 4) have been tested with integrating EMS and smart metering system. As it can be seen, each setup has two smart meters. Several features are measured by the meters such as bidirectional active and reactive energies (four-quadrant energy flow), harmonic and unbalance indices and power factor. In addition, over/under-voltages and voltage sags and swells can be recorded. Different communication protocols are used to transfer the information between devices which will be explained later in this report. The EMS is formed by a database system and several modules with different functions such as acquiring and storing the data, monitoring, optimizing and forecasting which are implemented in LabVIEW. Fig. 8(b) shows a sample measurement in LabVIEW. The database is developed in MySQL environment.

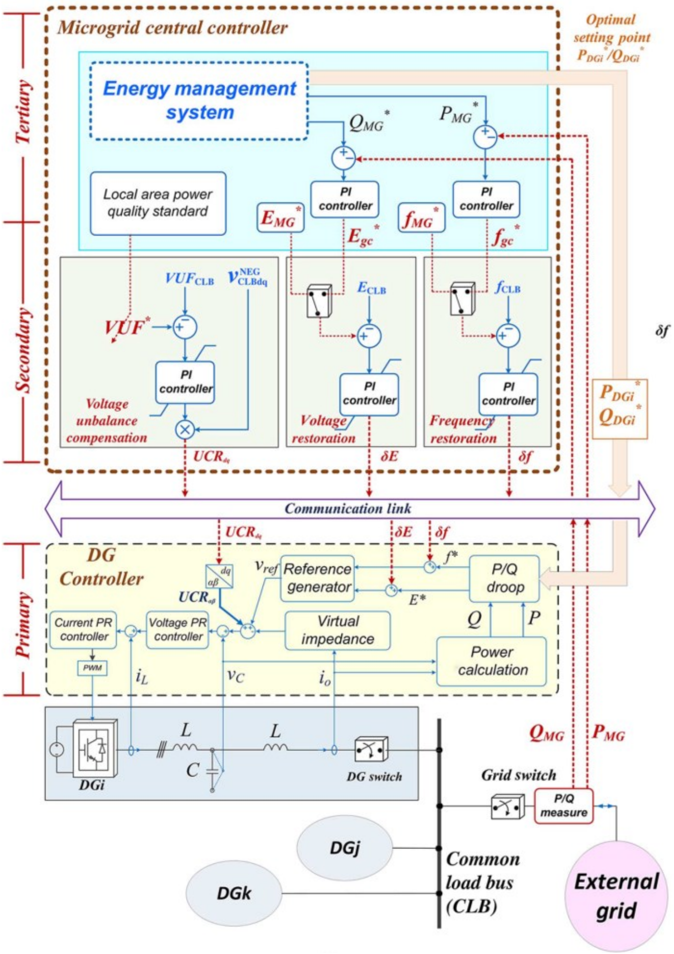


Fig. 6. Hierarchical control structure in AAU Lab.

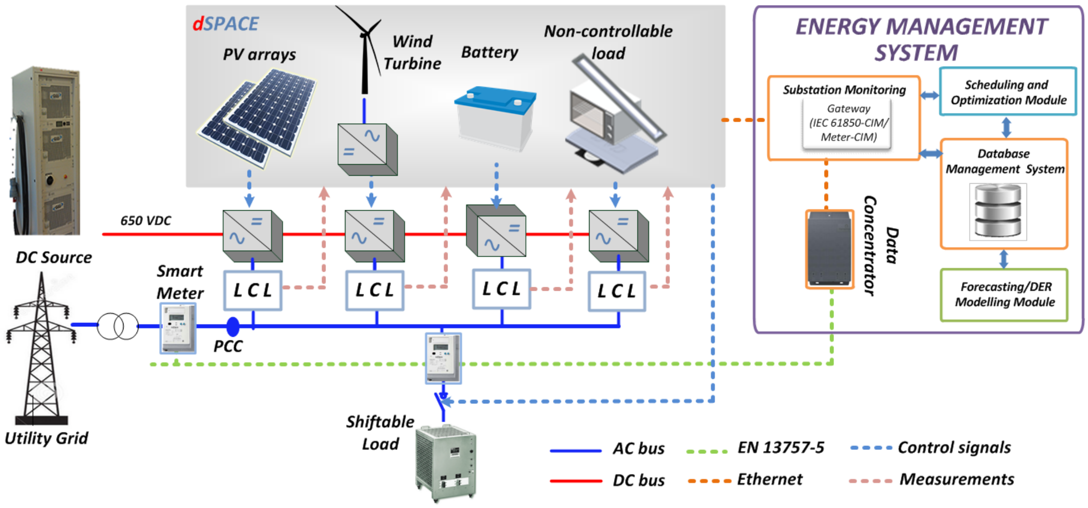
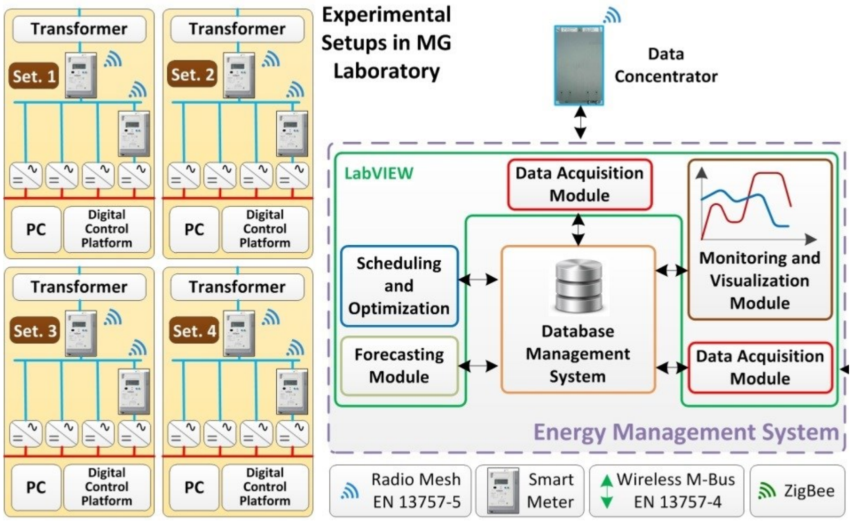
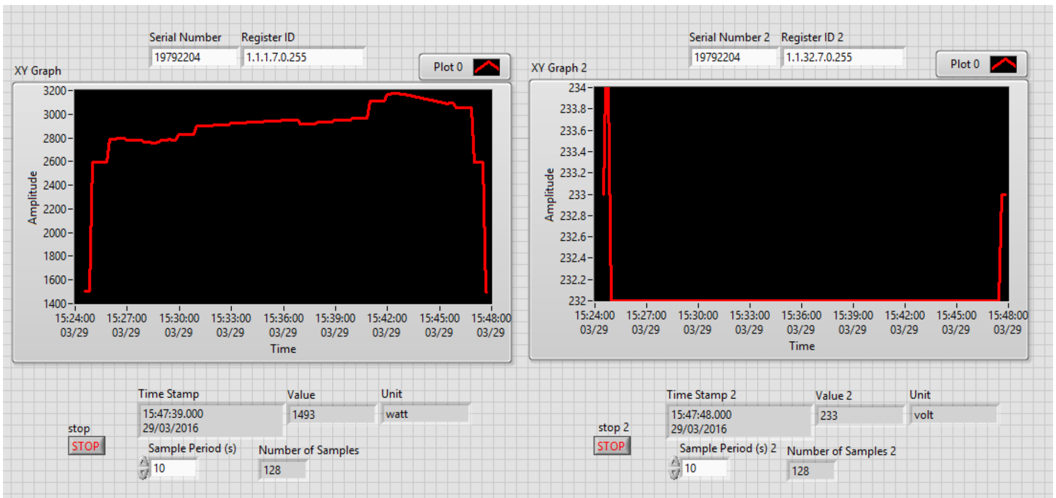


Fig. 7. Demand response and load control in AAU Lab.



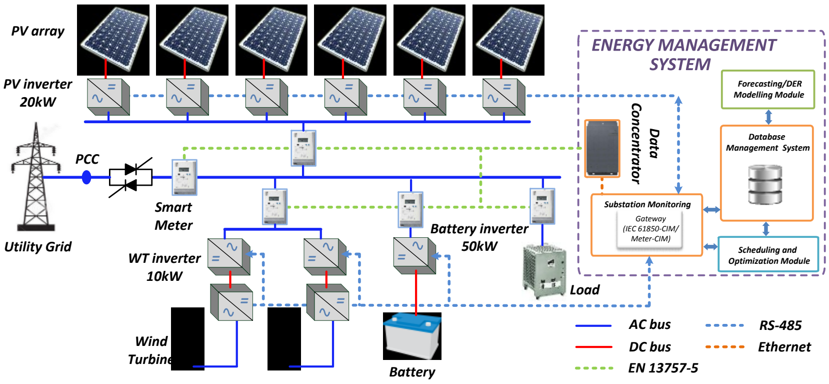
(a)



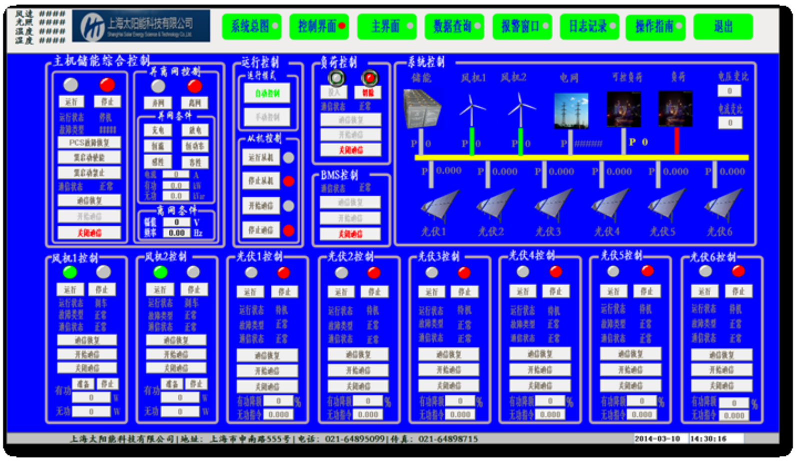
(b)

Fig. 8. (a) Overview of the smart metering system in AAU Lab
(b) Measurements in LabVIEW (left: active power, right: rms phase voltage)

Regarding the real implementation, Fig. 9(a) shows a general diagram of the microgrid installed in Shanghai site. The control algorithms have been implemented for PV arrays, WTs and battery energy storage. Fig. 9(b) illustrates the system user interface.



(a)



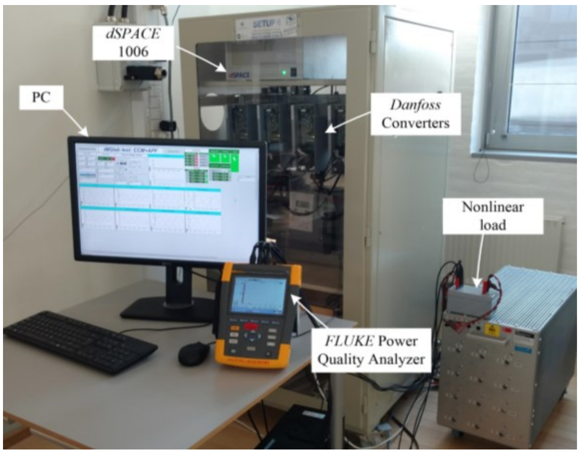
(b)

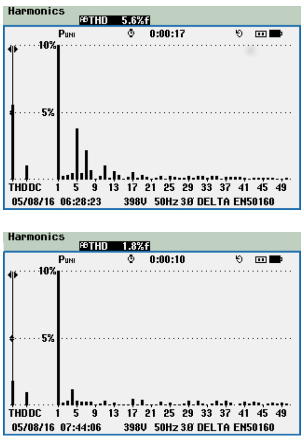
Fig. 9. Microgrid system in Shanghai: (a) general scheme, (b) user interface.

Task 2.5 Power quality assessment under real-case scenarios

In order to assess PQ and evaluate the effectiveness of the proposed compensation schemes, extensive measurements have been performed in the Lab and also the MG site. As mentioned before, the implemented smart metering system is able to record various PQ features including frequency variations, voltage deviations, power outages, rapid voltage changes, power factor as well as voltage and current unbalance factors and Total Harmonic Distortion (THD). Various tests demonstrated that these feaures can be effectively recorded and stored in the deveopled database shown in Fig. 8(a). To this aim, both VisionAir (data management software from Kamstrup) and LabVIEW have been applied.

In addition, a powerful PQ analyzer (Fluke 437-II) has been purchased and used for exact PQ measurement. Fig. 10(a) shows the setup for a labrotary test regarding harmonic compensation by using this peice of equipment. Comparing the voltage harmonic spectrums in Fig. 10(b) shows that the harmonics are effectively compensated which is also observed as THD decrease from 5.6% to 1.8%.





(a) (b)

Fig. 10. (a) Test setup for harmonic compensation, (b) Harmonic spectrums (top: before, bottom: after compensation)

WP3 Microgrid communications and SCADA systems

Task 3.1 Definition of the communications network

Task 3.2 Integration of communication systems

Task 3.3 Design of nondeterministic models

Task 3.4 Communication delays and uncertainties compensation

Task 3.5 Integration of ICT and microgrid SCADA system

Regarding Microgrids communications and SCADA systems both wired (Ethernet-based) and wireless schemes have been implemented in AAU microgrid laboratory. Fig. 11 gives a general view of the communication and SCADA with EMS and smart metering system in the Lab. As it can be seen, a central computer sends and receives the control commands and data from multiple lab setups. Many aspects regarding communication delays, interruptions, reliability and uncertainties have been studied.

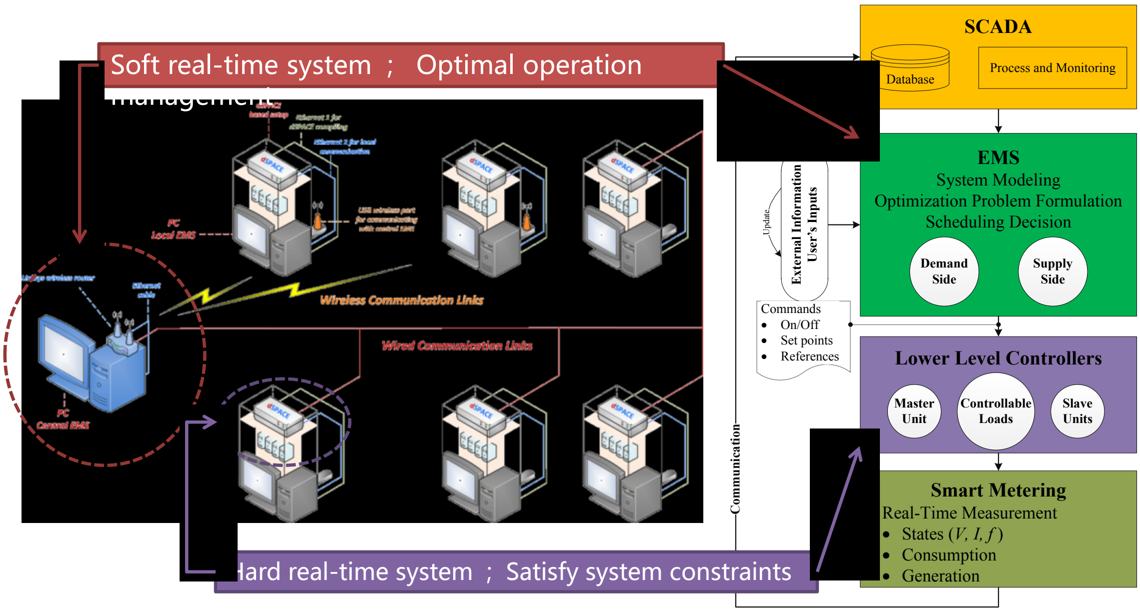


Fig. 11. Overview of SCADA and communication system in the Lab.

Furthermore, as it can be seen in Fig. 8(a), different communication schemes have been applied in the smart metering system. Smart meters communicate with the data concentrator by means of a radio mesh topology, based on the standard EN 13757. The data concentrator receives all the information and transfers the data packets to the acquisition system, using Ethernet, although, GPRS or 3G communications are also available. In addition, ZigBee technology can be used for wireless communication between smart meters and so called in-home-displays. The data shown on the display may help the user (in real world, electricity customer) to optimize his/her consumption behavior.

Fig. 12 illustrates the communication system implemented in Shanghai microgrid site. It should be mentioned that although Ethernet-based and other communication technologies can also be applied as shown in Fig. 9(a), RS-232 and RS-485 protocols form the basic communication in this microgrid site due to their high reliability and relative implementation simplicity.

WP4 Microgrid energy management system

Task 4.1 Research on energy management systems

Task 4.2 Development of power flow optimization techniques

Task 4.3 Implementation of energy management systems

In this WP, energy management and optimization techniques have been developed for microgrids. Both islanded and grid-connected operations are taken into account. In what follows, some details on implemented EMSs are presented.

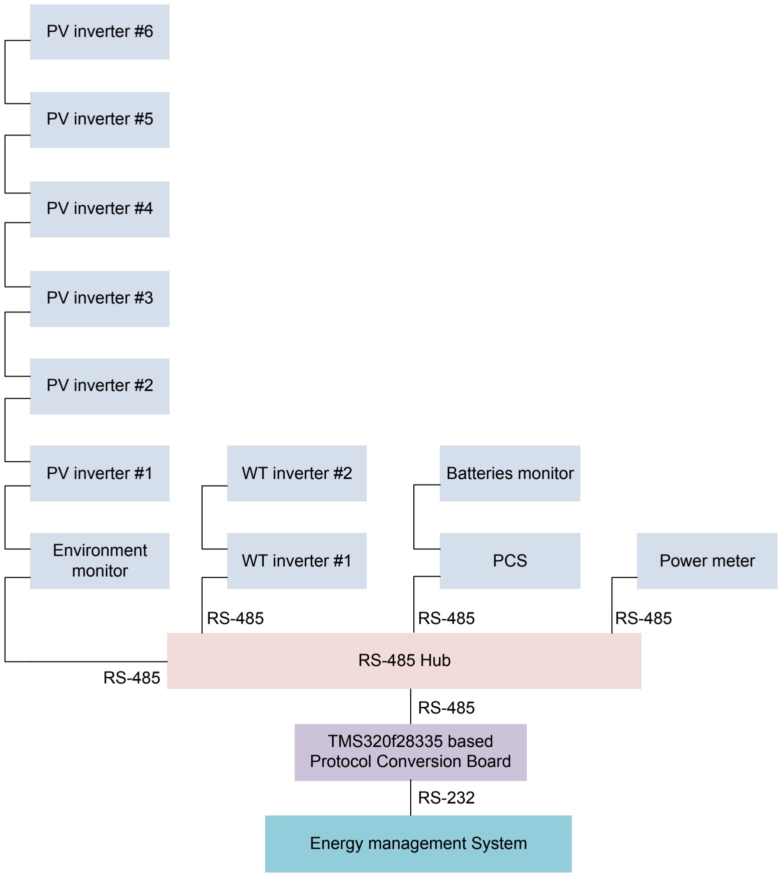


Fig. 12. Communication scheme in Shanghai site.

Islanded operation

Fig. 13 depicts the model and general structure of the EMS developed for islanded operation of the Shanghai Microgrid site. As the case study, the microgrid is supplying a resistive load which can be disconnected to ensure a safe operation range of battery bank as the Energy Storage System (ESS). Note that the models of Distributed Energy Resources (DERs) namely battery bank and RESs are included in the EMS.

In this microgrid, the inverters of RESs including PV arrays and WTs operate as constant power sources following the power references given by maximum power point tracking (MPPT) algorithm or derived from the optimization procedure.

The EMS is implemented to provide the references of the RESs and to manage the disconnection of the load, and it is composed of several modules as can be seen in Fig. 13. The modules are connected by means of a Database Management System in order to avoid bottlenecks due to processing times.

The optimization has been developed as a Mixed Integer Linear Programming (MILP) problem to minimize the disconnection of the loads in this islanded RES-based microgrid.

Grid-connected operation

In order to emulate the microgrid site installed in Shanghai for grid-connected operation, the model shown in Fig. 14 has been implemented in the laboratory. The power references for the Supervisory Control are provided by EMS which is composed of four modules, Optimization, Data Processing, User Interface, and Data Storage.

The optimization model is implemented in the module Optimization by means of an Algebraic Modeling Language (AML) that automatically translates the problem so that the Solver can understand and solve it. The input and output data is structured by the Data Processing model and stored in the Data Storage which is a collection of files accessible by the User Interface and Supervisory Control.

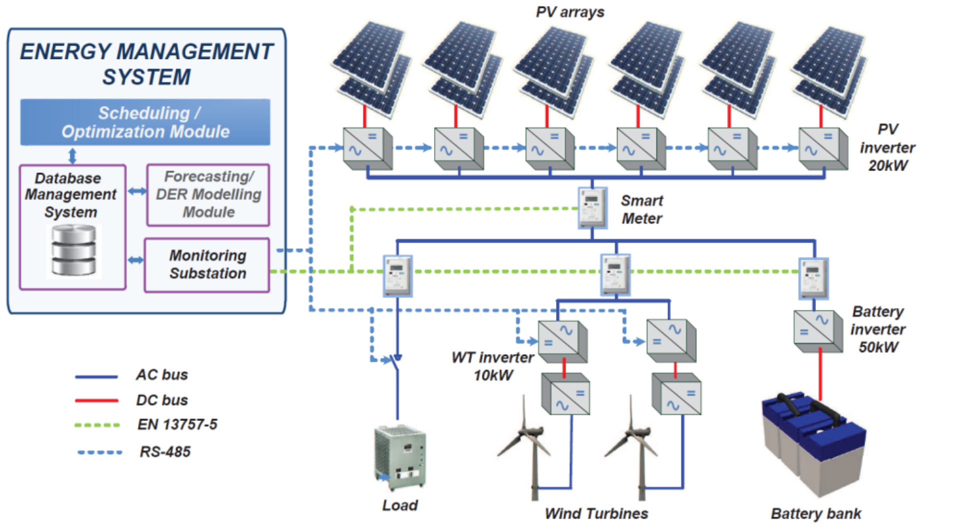


Fig. 13. EMS and general scheme of the microgrid in Shanghai in islanded mode.

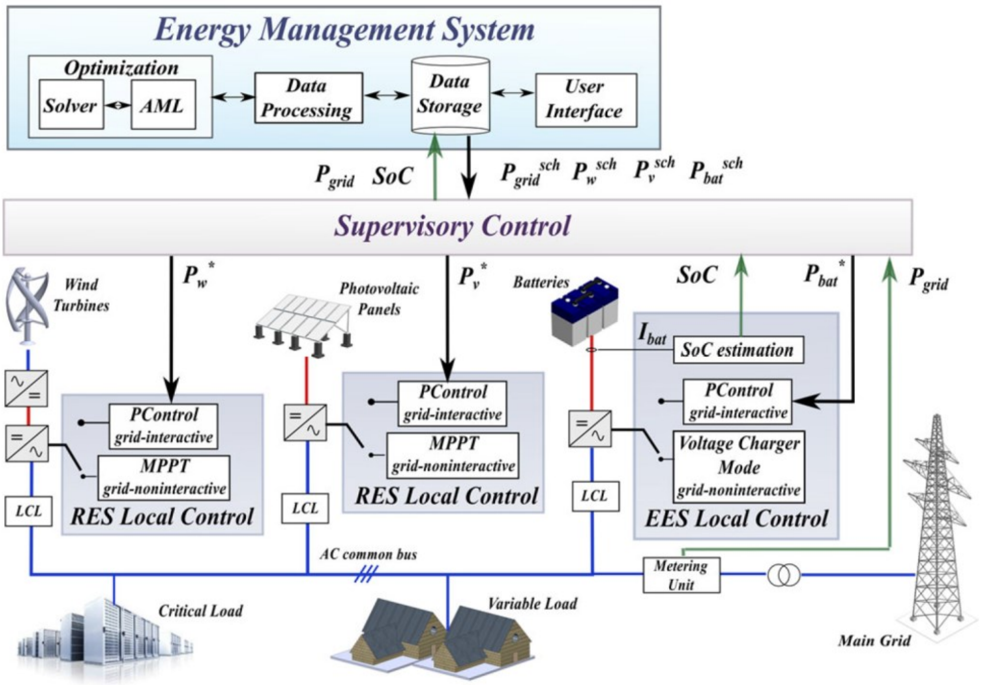


Fig. 14. EMS for the microgrid grid-connected operation.

<u>WP5 Microgrid test bench, implementation and validation</u>

Task 5.1 Integration of smart meters and smart-grid ready technologies

Task 5.1 has been concentrated on exploiting all the features of AMI for smart grid applications. In this task, the integration of AMI and EMS in the context of smart grid has been investigated. Furthermore, power quality monitoring based on AMI is explained. In what follows, the details regarding the implementation in a laboratory-scale application, as well as some obtained results are provided. This activities form a part of the final tests of Task 5.2.
As it can be seen in Fig. 15, the system consists of three main logical blocks, which are the AMI, composed of the physical devices, as well as the software for obtaining the measurements, the Meter Data Management System (MDMS), and the EMS.

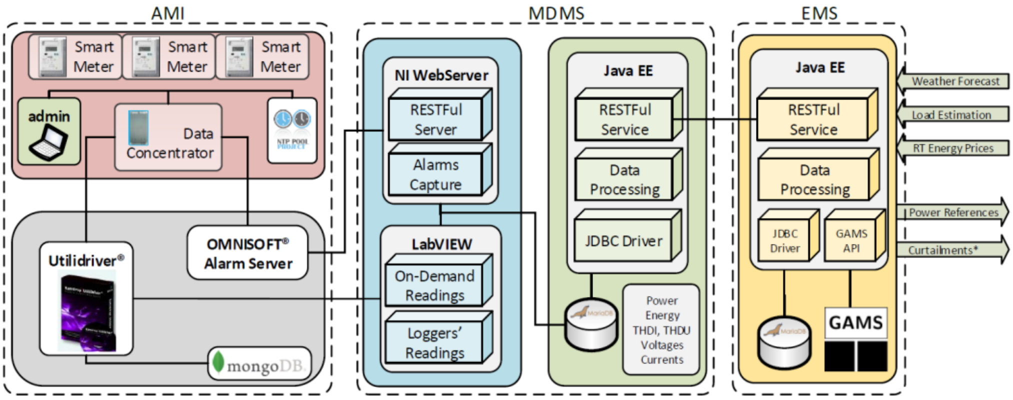


Fig. 15. Logical architecture of integrating EMS and AMI.

The AMI is divided into two levels. In the first layer, the AMI physical Network can be found (red block). This part comprises all the physical smart meters (SMs), as well as the Data Concentrator that collects SMs measurements periodically, and it is permanently connected to a Network Time Protocol (NTP) server to synchronize the timestamps. The communication between the SMs and the Data Concentrator is based on the standard EN 13757-5 that implements a radio mesh topology. Moreover, they are in compliance with the IEC 62056, the international standard of the DLMS/COSEM specification (Device Language Message Specification /Companion Specification for Energy Metering).

Regarding the electrical measurements, all SM models that have been used (3-phase meters, single-phase meters and CT-Meters), belonging to the Kamstrup OMNIA Suite, are in compliance with international standards. They measure active positive energy (EN 50470-1 and EN 50470-3), reactive energy, and active negative energy (IEC 62052-11, IEC 62053-21 and IEC 62053-23), as well as power quality (PQ) parameters according to EN 50160.

The second layer (gray block) integrates the logical software provided by the manufacturer to ensure efficient interoperability with the AMI network. This software communicates over Ethernet with the Data Concentrator and implements all the back-end processes that are necessary to configure the system, perform on-demand operation readings and capture the periodic records. In parallel with this, the Data Concentrator is also able to forward the alarms produced with the AMI network. For that aim, a service is constantly listening and capturing these events that can subsequently be sent by email or posted to a web service.

The MDMS block is responsible for capturing the data, store them and make them accessible. Therefore, it is the key connection point between the AMI and additional features to be implemented. It is composed of two layers. The first one is the management unit (blue block). This software was implemented using the LabVIEW visual programming language and is composed of two main systems. On one hand, a RESTFul server was built using the NI WebServer in order to capture the Alarms that are forwarded by the Alarm Server. The information contained in these alarms, sent as an XML packet, is read by the LabVIEW program and subsequently stored. On the other hand, a desktop application with a Graphical User Interface (GUI) was developed for performing two tasks: to query on-demand readings from the AMI Network and to read the periodic measurements stored in the SMs' loggers.

It should be pointed out that although the head-end software is connected to a local MongoDB database, it is a temporal storage with a maximum deep of 3 days and with a fixed structure that cannot be modified. Moreover, the alarms triggered in the system are not recorded by this database. Thus, the second layer of the MDMS is the storage system (green block), implemented using the database engine MariaDB. This database is structured in a flexible way, so new meters and types of measurements can be added. Furthermore, it is not limited to a specific manufacturer, since the measured variables are defined by their standard OBIS codes (IEC 62056).

On top of this, the JAVA application implements a RESTful service for reading the data with various layers of security for the measurements, allowing a simple communication using the HTTPS protocol and JSON or XML format. This makes the system compatible with any other third-party software.

Finally, the EMS (yellow block) queries the necessary measurements from the SMs to the data management system and together with additional information such as weather forecast, real-time energy prices or load estimation generates the power references that can be used by the converters.

Another JAVA EE server is used for this task, connected to GAMS software for running the optimization process. Regarding the PQ supervision, the MDMS is able to record global indicators such as current and voltage THD (THDI, THDU) and power factor, as well as different PQ events (voltage variations, unbalances, etc.).
The test bench for the experiments as well as the central system and data concentrator for the AMI (block in the top-right corner) are shown in Fig. 16. This setup is implemented in AAU MG Lab.

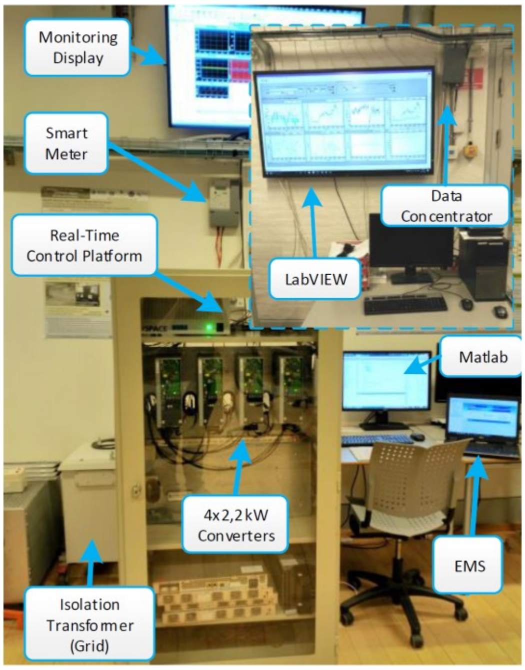


Fig. 16. Hardware setup for the test in MG Lab.

Task 5.2 Final tests
In this task, the final tests of the whole control system are performed both AAU MG laboratory and MG site in Shanghai. Photos presented in Fig. 17 are taken during a test in MG site.


Fig. 17. Test in Shanghai MG site: batteries, power electronic converters and measurement display

Dissemination Activities

The website has been regularly updated: http://www.meter.et.aau.dk

The outcomes of the project have been presented in the form of scientific papers and presentations which are posted to the project webpage, too. See the report's Annex for list of publications extracted from the project.

The research activities of the project have been presented in:

- First SUNSEED Workshop on Advanced Control, Communications and Algorithms for the Smart Grid
  Aalborg University, 25th March 2015
  http://www.archive.es.aau.dk/sections/apnet/sunseed-workshop/
  Invited Presentation: Smart Metering System for Microgrids

- 9th International Conference on Power Electronics – ECCE Asia: ICPE 2015-ECCE Asia
  Seoul, Korea, 1st June 2015
  https://www.ieee.org/conferences_events/conferences/conferencedetails/index.html?Conf_ID=33862
  Tutorial: Microgrids – State of the Art and Challenges

- 23rd International Symposium on Power Electronics, Electric Drives, Automation and Motion (SPEEDAM)
  22-24 June 2016, Capri, Italy
  http://www.speedam.org/
  Tutorial: Advanced Control Architectures for AC and DC Microgrids

- PhD/Industrial Course on Power Quality in Microgrids
  18-19 April 2016, AAU, Aalborg
  Lecture: Smart Metering System for Microgrid Power Quality Evaluation

- IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA)
  31 May-2 June 2017, Bogota, Colombia
  http://www.pepqa.com.co/
  Keynote Speech: AC and DC Microgrids

- 8th Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2017)
  14-16 February 2017, Mashhad, Iran
  http://pedstc2017.um.ac.ir/
  Tutorial: Power Quality in Microgrids

- 43rd Ann. Conf. of the IEEE Ind. Electron. Society (IECON 2017)
  29 Oct.-1 Nov. 2017, Beijing, China
  IECON 2017, Oct. 2017, China.
  http://iecon2017.csp.escience.cn
  Tutorial: The Internet of Energy - The Building Block for the Future Smart Grids

1.6 Utilization of project results

The developed integral solution for microgrids will be used for education and research purposes in AAU. More specifically, integrated EMS and AMI system can be the base for several research activities in future and current projects in AAU. Since complete testing of Kamstrup AMI system (OMNIA) has been performed in AAU Lab, the company has gained enough information about system performance to improve the products and provide smart-grid-ready solutions. The microgrid site developed in Shanghai can be utilized mainly by Chinese partners (TU and SSEC) as a tool for future projects and research activities. Furthermore, they have registered 2 Chinese patents based on the project.

Regarding energy policy objectives, the proposed microgrid solution will facilitate the integration of RESs in electrical energy networks which leads to increased RESs penetration, reduced fossil fuel consumption and more carbon-free electricity production.

1.7 Project conclusion and perspective

It has been demonstrated in the project that multi-layer (hierarchical) control can provide a proper architecture to control RES-based microgrids and ensure high power quality and optimized operation in both islanded and grid-connected operations. In this regard, efficient energy management and demand response algorithms are required. Effective communication protocols and database technologies should be applied to facilitate an integral solution for microgrids.

Integration of smart metering systems (also called Advance Metering Infrastructure-AMI) with control and management of microgrid will provide a lot of value, since AMI can provide additional features such as power quality monitoring and the collected information could be transmitted through AMI reliable communication protocols. Furthermore, AMI system can facilitate implementation of demand response algorithms.

The outcomes of this project can facilitate high integration of renewable energies in electrical systems which will contribute towards reduction of fossil-fuel-based electricity production. Furthermore, the project findings can be applied in future research and providing better products and services in control of RES-based systems and implementation of AMI.

Annex

The project research activities and results have been reflected in the regularly updated home page www.meter.et.aau.dk .

List of the paper extracted from the project is provided below. The hyperlinks are provided to the pages with full information of the papers.

JOURNAL PAPERS

- ***Capacitor Current Feedback-Based Active Resonance Damping Strategies for Digitally-Controlled LCL-Filtered Grid-Connected Inverters***, Lorzadeh, I., Askarian Abyaneh, H., Savaghebi, M., Bakhshai, A., Guerrero, J. M., *Energies*, 2016.

- ***Mixed-Integer-Linear-Programming based Energy Management System for Hybrid PV-wind-battery Microgrids: Modeling, Design and Experimental Verification***, A. C. Luna; N. L. Diaz Aldana; M. Graells; J. C. Vasquez; J. M. Guerrero, *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp.2769-2783, April 2017.

- ***Flexible System Integration and Advanced Hierarchical Control Architectures in the Microgrid Research Laboratory of Aalborg University***, L. Meng, Meng, Lexuan; Hernández, Adriana Carolina Luna; Diaz, Enrique Rodriguez; Sun, Bo; Dragicevic, Tomislav; Savaghebi, Mehdi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Graells, Moises; Andrade, Fabio*, IEEE Transactions on Industry Applications*, vol. 52, no. 2, pp. 1736-1749, March-April 2016.

- ***Low-Voltage Ride-Through Operation of Power Converters in Grid-Interactive Microgrids by Using Negative-Sequence Droop Control,*** Zhao, Xin; Guerrero, Josep M.; Savaghebi, Mehdi; Wu, Xiaohua; Sun, Kai. *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp.3128-3142, April 2017.

- ***Energy Management System based on Fuzzy Fractional Order PID Controller for Transient Stability Improvement in Microgrids with Energy Storage***, Moafi, Milad, Marzband, Mousa, Savaghebi, Mehdi, Guerrero, Josep M. *International Transactions on Electrical Energy Systems*, 2050-7038, 2016.

- ***Tertiary Control of Voltage Unbalance Compensation for Optimal Power Quality in Islanded Microgrids***, L. Meng, F. Tang, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 802-815, Dec. 2014.

- ***Distributed Voltage Unbalance Compensation in Islanded Microgrids by Using Dynamic Consensus-Algorithm***, L. Meng, X. Zhao, F. Tang, M. Savaghebi, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, *IEEE Transactions on Power Electronic*, vol. 31, no. 1, pp.827-838, January 2016.

- ***An Optimal Energy Management System for Islanded Microgrids based on Multi-Period Artificial Bee Colony Combined with Markov Chain***, M. Marzband, F. Azarinejadian, M. Savaghebi, and J. M. Guerrero, *IEEE Systems Journal*, vol. 11, no. 3, pp. 1712-1722, Sept. 2017, DOI: 10.1109/JSYST.2015.2422253.

- ***Autonomous Active Power Control for Islanded AC Microgrids With Photovoltaic Generation and Energy Storage System***, D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp.882-892, Dec. 2014.

- ***A Control Architecture to Coordinate Renewable Energy Sources and Energy Storage Systems in Islanded Microgrids***, D. Wu, F. Tang, T. Dragicevic, J. C. Vasquez, and J. M. Guerrero, *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1156-1166, May 2015.

- ***Distributed Smart Decision-Making for a Multi-Microgrid System Based on a Hierarchical Interactive Architecture***, M. Marzband, N. Parhizi, M. Savaghebi, and J. M. Guerrero, *IEEE Transactions on Energy Conversion*, 2016.

- ***A Control Architecture to Coordinate Distributed Generators and Active Power Filters Coexisting in a Microgrid****,* M. M. Hashempour, M. Savaghebi, Juan C. Vasquez, and Josep M. Guerrero, *IEEE Transactions on Smart Grid*, vol. 7, no. 5, pp.2325-2336, September 2016.

CONFERENCE PAPERS

- ***Generation and Demand Scheduling for a Grid-Connected Hybrid Microgrid Considering Price-based Incentives***, A. C. Luna, N. L. Diaz, M. Savaghebi, W. Feng, K. Sun, J. C. Vasquez, and J. M. Guerrero, *43rd Annual Conference of the IEEE Industrial Electronics Society (IECON 2017)*, 29 October-1 November 2017, Beijing, China.

- ***Using Smart Meters Data for Energy Management Operations and Power Quality Monitoring in a Microgrid,*** E. J. Palacios-Garcia, E. R. Diaz, A. Anvari-Moghaddam, M. Savaghebi, J. C. Vasquez, J. M. Guerrero, and A. Moreno-Munoz, *26th IEEE International Symposium on Industrial Electronics (ISIE 2017)*, 19-21 June 2017, Edinburgh, UK.

- ***A Dynamic Consensus Algorithm based Hierarchical Control for Low Voltage Ride-Through Operation of Power Converters in Grid-Connected Microgrids***, X. Zhao, L. Meng, M. Savaghebi, J. C. Vasquez, J. M. Guerrero and X. Wu, *42nd Ann. Conf. of the IEEE Ind. Electron. Society (IECON)*, 24-27 Oct. 2016, Florence, Italy.

- ***Voltage Unbalance and Harmonic Compensation in Microgrids by Cooperation of Distributed Generators and Active Power Filters***, M. M. Hashempour, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, *7th Power Electronics, Drive Systems and Technologies Conference (PEDSTC 2016)*, 16-18 Feb. 2016, Tehran, Iran.

- ***Optimal Power Scheduling for an Islanded Hybrid Microgrid***, A. Luna, N. Diaz, M. Savaghebi, and J. M. Guerrero, *8th International Power Electronics and Motion Control Conference - ECCE Asia (IPEMC 2016-ECCE Asia)*, 22-25 May 2016, Hefei, China

- ***An Embedded Voltage Harmonic Compensation Strategy for Current-Controlled DG Interfacing Converters***, X. Zhao, L. Meng, C. Xie, M. Savaghebi, J. C. Vasquez, J. M. Guerrero and X. Wu, *IEEE Energy Conv. Cong. and Expo, (ECCE 2016)*, 18-22 Sept. 2016, Milwaukee, US.

- ***Hierarchical Coordinated Control of Distributed Generators and Active Power Filters to Enhance Power Quality of Microgrids***, M. Savaghebi, M. M. Hashempour, and J. M. Guerrero, *55th Int. Scientific Conf. of Riga Tech. Uni. on Power and Elec. Eng. (RTUCON)*, 14-17 October 2014, Riga, Latvia.

- ***Microgrid Central Controller Development and Hierarchical Control Implementation in the Intelligent MicroGrid Lab of Aalborg University***, L. Meng, M. Savaghebi, F. Andrade, J. C. Vasquez, J. M. Guerrero, and M. Graells, *Applied Power Electron. Conf. and Expo. (APEC)*, 15-19 March 2015, Charlotte, NC, USA.

- ***Fuzzy Droop Control Loops Adjustment for Stored Energy Balance in Distributed Energy Storage System***, N. Diaz, D. Wu, T. Dragicevic, J. C. Vasquez and J. M. Guerrero, IEEE ECCE-ASIA, 1-5 June 2015, Seoul, Korea.

- ***Economic Power Dispatch of Distributed Generators in a Grid-Connected Microgrid***, A. C. Luna, N. Diaz, F. Andrade, M. Graells, J. M. Guerrero and J. C. Vasquez, *IEEE ECCE-ASIA*, 1-5 June 2015, Seoul, Korea.

- ***Coordinated Secondary Control for Balanced Discharge Rate of Energy Storage System in Islanded Microgrids***. Guan, Yajuan; Guerrero, Josep M.; Quintero, Juan Carlos Vasquez. *9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, IEEE Press, 2015, p. 475 - 481.

- ***A Direct Voltage Unbalance Compensation Strategy for Islanded Microgrids***. Zhao, Xin; Wu, Xiaohua; Meng, Lexuan; Guerrero, Josep M.; Vasquez, Juan Carlos. *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE Press, 2015. p. 3252 - 3259.

- ***Small-Signal Modeling, Analysis and Testing of Parallel Three-Phase-Inverters with A Novel Autonomous Current Sharing Controller.*** Guan, Yajuan; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Coelho, Ernane A. A. *30th Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2015.* IEEE Press, 2015. p. 571 – 578

- ***Autonomous Active and Reactive Power Distribution Strategy in Islanded Microgrids***. Wu, Dan; Tang, Fen; Guerrero, Josep M.; Vasquez, Juan Carlos; Chen, Guoliang; Sun, Libing. *29th Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2014*. IEEE Press, 2014. p. 2126-2131.

- ***Autonomous Control of Distributed Generation and Storage to Coordinate P/Q Sharing in Islanded Microgrids - An Approach beyond Droop Control.*** Wu, Dan; Tang, Fen; Guerrero, Josep M.; Vasquez, Juan Carlos. *2014 IEEE International Energy Conference (ENERGYCON)*, IEEE Press, 2014. p. 983-988.

- ***Control and Analysis of Droop and Reverse Droop Controllers for Distributed Generations***. Wu, Dan; Tang, Fen; Vasquez, Juan Carlos; Guerrero, Josep M. *11th International Multiconference on Systems, Signals & Devices, SDD 2014*, IEEE Press, 2014.

- ***A Simple Autonomous Current-Sharing Control Strategy for Fast Dynamic Response of Parallel Inverters in Islanded Microgrids***. Guan, Yajuan; Vasquez, Juan Carlos; Guerrero, Josep M. *2014 IEEE International Energy Conference (ENERGYCON)*, IEEE Press, 2014. p. 182-188.

- ***Online Energy Management System for Distributed Generators in a Grid-Connected Microgrid***. Hernández, Adriana Carolina Luna; Aldana, Nelson Leonardo Diaz; Graells, Moises; Quintero, Juan Carlos Vasquez; Guerrero, Josep M. *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, IEEE Press, 2015. p. 4616-4623.

- ***A Hierarchical Control Scheme for Reactive Power and Harmonic Current Sharing in Islanded Microgrids.*** Lorzadeh, Iman ; Savaghebi Mehdi; Askarian Abyaneh, Hossein; Guerrero, Josep M. *17th Conference on Power Electronics and Applications, EPE'15-ECCE Europe*, Geneva, Switzerland, IEEE Press, 2015.

- ***Dynamic Consensus Algorithm based Distributed Voltage Harmonic Compensation in Islanded Microgrids***. Meng, Lexuan; Tang, Fen; Savaghebi Mehdi; Dragicevic, Tomislav; Quintero, Juan Carlos Vasquez; Guerrero, Josep M. *17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)*, IEEE Press, 2015.

- ***Adaptive Virtual Impedance Scheme for Selective Compensation of Voltage Unbalance and Harmonics in Microgrids***. Savaghebi, Mehdi; Shafiee, Qobad; Vasquez, Juan Carlos; Guerrero, Josep *IEEE Power & Energy Society General Meeting, PES GM 2015*, IEEE, 2015.

- ***Dynamic Consensus Algorithm based Distributed Unbalance Compensation in Islanded Microgrids***. Meng, Lexuan; Zhao, Xin; Savaghebi Mehdi; Dragicevic, Tomislav; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Tang, Fen. *IEEE Power & Energy Society General Meeting, PES GM 2015*, IEEE Press, 2015.

- ***Hierarchical Control for Voltage Harmonics Compensation in Multi-Area Microgrids.*** Hashempour, Mohammad M.; Savaghebi Mehdi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M. *2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, IEEE Press, 2015.

- ***Active Damping Techniques for LCL-Filtered Inverters-Based Microgrids.*** Lorzadeh, Iman; Savaghebi Mehdi; Askarian Abyaneh, Hossein; Guerrero, Josep. *2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, IEEE Press, 2015.

- ***Control of a Multi-Functional Inverter for Grid Integration of PV and Battery Energy Storage System.*** Mousazadeh, Seyyed Yousef ; Li, Chendan; Beirami, A.; Jalilian, Alireza; Savaghebi Mehdi; Guerrero, Josep M, *IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives*, 2015.

- ***Voltage Harmonics Monitoring in a Microgrid Based on Advanced Metering Infrastructure (AMI).*** Savaghebi, Mehdi; Guan, Yajuan; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Nielsen, Carsten. *Seminario Anual de Automática, Electrónica Industrial e Instrumentación 2015 (SAAEI'15)*, 2015.

- ***Negative Sequence Droop Method based Hierarchical Control for Low Voltage Ride-Through in Grid-Interactive Microgrids***, Zhao, Xin; Savaghebi Mehdi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Sun, Kai; Wu, Xiaohua; Chen, Guoliang; Sun, Libing. *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, IEEE Press, 2015. p. 6896 - 6903.

- ***Advanced Smart Metering Infrastructure for Future Smart Homes***, Diaz, Enrique Rodriguez; Palacios-Garcia, Emilio; Savaghebi, Mehdi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Moreno-Munoz, Antonio. *5th IEEE International Conference on Consumer Electronics*, IEEE Press, 2015.

- ***Smart Metering System for Microgrids***, Palacios-Garcia, Emilio; Guan, Yajuan; Savaghebi, Mehdi; Quintero, Juan Carlos Vasquez; Guerrero, Josep M.; Moreno-Munoz, Antonio; Ipsen, Brian S. *IECON 2015*, Yokohama, Nov. 2015. IEEE Press, 2015.

- ***Distributed Low Voltage Ride-Through Operation of Power Converters in Grid-Connected Microgrids under Voltage Sags***, X. Zhao, L. Meng, T. Dragicevic, M. Savaghebi, J. M. Guerrero, J. C. Vasquez, and X. Wu, *41st Ann. Conf. of the IEEE Ind. Electron. Society (IECON)*, 9-12 Nov. 2015, Yokohama, Japan.

- ***Optimal Power Scheduling for a Grid-Connected Hybrid PV-Wind-Battery Microgrid System***, A. Luna, N. Diaz, M. Savaghebi, K. Sun, G. Chen, L. Sun, J. C. Vasquez, and J. M. Guerrero, *Applied Power Electron. Conf. and Expo. (APEC)*, 20-24 March 2016, California, USA.

- ***Development and Integration of a HEMS with an Advanced Smart Metering Infrastructure***, E. R. Diaz, E. J. Palacios-Garcia, M. Savaghebi, J. C. Vasquez, and J. M. Guerrero, *34th Int. Conf. on Consumer Electron. (ICCE)*, 8-11 Jan. 2016, Las Vegas, USA.