AC-link based new microgrid system for research of local power flow management

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Abstract. This paper gives an overview of a distributed energy technology laboratory, where diverse approaches are studied to effectively integrate distributed generation into power systems. The laboratory is equipped with small-scale power generation devices including wind turbine (3.5 kW), PV array (2.5 kW), synthetic energy generator (3.6 kW) and also batteries, ultra capacitor, programmable load (6.2 kW), weather station, power flow and power quality control and monitoring system. The laboratory is used for researching and applying energy-management technics to control energy storage and increasing power reliability and power quality in small-scale generation units. On-site measured data of power consumption and production can be linked to the laboratory and simulated online with synthetic energy generator and programmable load. It is also possible to scale the measured data and model systems with variable sizes. As a result the stability of variable systems can be tested with different storage capacities and load management techniques.

Key words: renewable resources, energy management, power quality, research laboratory, hybrid energy system.

INTRODUCTION

The energy industry is transitioning from a traditional centralized energy generation network to a network with many additional dispersed generation units, also called distributed energy generation (DG). DG systems may include different technologies like photovoltaic, wind turbines, electrical generators and many more. Increasing proportions of DG devices connected to the grid can potentially affect the power quality of supplied energy. Some critical issues must be resolved in order to provide stable and cost competitive energy to consumers.

High penetration of renewables means that centralized power plants and distribution networks have increased requirements to adapt to the high stochastic nature of renewable power sources. One option to overcome this problem is to control the energy generation process, which in terms of renewables requires energy storage and power flow management. Another way is to use load management (LM) in accordance with energy production by shifting the use of appliances towards peak period of DG output.

Investigations on grid integration of DG can be done in a theoretical way by analysis or simulation. Practical measurements at real systems can be done with field tests or at downscaled systems in laboratories. The following provides an overview of Digital Electronics Laboratory located in Estonian University of Life Sciences Institute of Technology. Location of the laboratory: 58°23'19'' North, 26°41'37'' East, Elevation 76.5 m a.s.l., Tartu, Estonia.

Renewable energy sources like wind and solar have a stochastic nature and neither one is usable without special measures for reliable energy supply. Different approaches are used to mitigate the stochastic nature of these energy sources: grid connection, combining different energy sources, adding storage elements to micro grid, shifting loads (Annuk et al., 2013) etc. The main problem is the determination of the optimal mix of energy sources and control techniques with the focus on the economical optimization to maximize the proportion of the produced energy that is consumed on site (Atwa et al., 2010; Caralis et al., 2011). Fig. 1 presents a one day wind turbine and PV system power output measured in the laboratory on 14-th March 2014 to describe the variable nature of these energy sources.
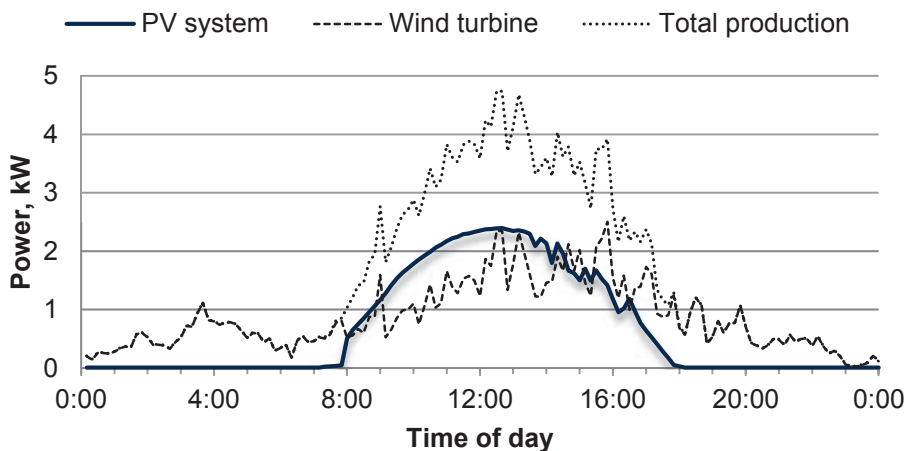
Figure 1. Laboratory PV system and wind turbine power output (14.03.2014).

Taking into account network restricted capacity and decreasing support for renewables in future, it is reasonable to use the produced electricity on site: not to sell energy to the grid but cover a part of the consumption with energy produced on site. The actuality of the problem is, how to control energy flows in grid supported renewable based micro grids to use maximum energy on site by minimum storage capacity amounts and by maximum economic benefit. The topic is highlighted under subject B.2.6 in the Horizon 2020 Work Programme 2014–1015 of the European Union (Horizon, 2013): The realization of reliable, economically efficient and stable energy supply systems, including in the recent years the question of optimal integration of an increasing share of variable renewable energy.

BACKGROUND

Design Objectives

One of the main research fields at Estonian University of Life Sciences Department of Electrical Engineering is Integrated Energy Systems. It focuses on how power systems based on one or more renewable sources can be designed, controlled and integrated to existing grids, delivering a regulated reliable power supply. Three types of renewable energy sources are in the focus of the research: wind, solar and biogas. The fore mentioned research topics are also listed in the Horizon 2020 programme, along with other relevant topics for the laboratory, like electricity grids and energy storage (European Commission 2014). The research topics can be divided into five major groups:

- Energy conversion – evaluate the potential of renewable resources in local energy production.
- Energy storage – storing excess energy generated by renewable resources in peak time and using it when energy consumption exceeds energy production. Defining storage equipment and capacities for various conditions and different systems.
- Load management – balancing the supply of electricity on the network with consumption behaviour. Finding methods to engage consumers' attention in the power balancing process.
- Power quality – analysing the impact of DG in power quality.
- Production curve´s fitting – mitigation of sources power output fluctuations to increase the share of renewable´s on site and decrease battery capacity amounts.

The pilot scale biogas research and development laboratory was opened in 2009, but so far there weren't laboratories where wind and solar energy conversion processes could be researched. Department of Electrical Engineering is currently in the phase of introducing and testing of the `Digital Electronics Laboratory` (DEL), a state of art laboratory with small scale solar and wind energy hybrid system connected to the electricity grid and have possibilities to work autonomously. In the planning process following requirements for the laboratory were set:

1. The laboratory is aimed for teaching and research purposes in the field of renewable energy.
2. The laboratory should facilitate experiments on combining micro-sources (PV panels, wind turbine) and energy storage devices.
3. The design needs to be such that every energy source and conversion process can be tested separately.
4. The laboratory needed to have one synthetic energy generator (SEG) which can be controlled online based on power production measured on-site.
5. The laboratory must be connected to the public university AC network.
6. It must be possible to connect the energy sources to variable load banks and operate dependent on the experiment requirements in island regime (micro grid) or in on-grid regime.
7. Online controlling of variable load banks according to on-site measured consumption data.

8. Completely digitized and centralized monitoring system for all system variables including a weather station and database where the information is stored for research purposes.
9. Transmission of the laboratory parameters over the internet so that they can be used in lectures.

The laboratory will be used by researchers, professors, PhD students, and also by Master's level students conducting their thesis projects supervised by the afore-mentioned.

MATERIALS AND METHODS

System overview

The laboratory equipment was chosen among typical components available on the market, according to the design requirements. One objective was to provide maximum analysis capabilities of present day technologies of solar and wind energy conversion systems. The power ratings were kept in the scale of residential applications. Grid integration of commercial or industrial scale energy resources can be measured and analysed with downscaled parameters in the laboratory. This method is cost- and time saving compared to field tests. Table 1 provides the specifications of selected components.

Table 1. Laboratory main components

| Device	Specification
Battery-based grid inverter	SMA Sunny Island 6.0H
Horisontal axis wind turbine	3.5 kW PMSG passive yaw control
Polycrystalline PV Array	10 x (250 W, 30 V) PV module
Synthetic energy generator	Inverter SMA Windy Boy 3600TL
Ultra-capacitor	Maxwell BMOD0165 48.6 V DC, 165 F, 96 A
Batteries	8 x Deep Cycle AGM 220 Ah, 12 V
Resistive loads	Variable 0–2.2 kW and fixed 2 x 2 kW
Weather station	Vantage Pro2

The laboratory energy sources and consumers are connected to the output bus of a battery-based inverter system (SMA Sunny Island 6.0H), forming a one phase AC-coupled system. In stand-alone mode the inverter generates an AC voltage and frequency supply independent of grid AC source. Eight deep cycle AGM (Absorbent Glass Mat) VRLA (Valve Regulated Lead Acid) batteries and one ultra-capacitor (Maxwell BMOD0165) are used for energy supply and storage in case of unbalances in energy consumption and production. In the on-grid mode excess power generation in laboratory can be exported to the utility.

Three different energy production units are used. Solar energy is integrated to the system with 2.5 kW PV array (DelSolar 250 W D6P250B3A), positioned to South at adjustable tilt to the horizon. A current-source 2.75 kW inverter (SOLIVIA 2.5 EU G3) is used for converting DC to AC. Wind energy is present with a 3-blade horizontal wind turbine (Windspot 3.5), with a 3.5 kW permanent magnet synchronous generator. For

controlled generation of energy a synthetic energy generator (SEG) is added to the system with a maximum power output of 3.6 kW.

The SEG consists of a frequency drive, rectifier and a grid-direct inverter. SEG draws power from the utility network and transfers it to the laboratory AC system. The power output can be a fixed variable, controlled by a predefined time based power curve or linked to an online variable measured on-site, that can be scaled if needed. The SEG can be used as balancing power source for smoothing solar and wind energy conversion power outputs.

A programmable load bank (PLB) is connected to the system to simulate consumer loads. The PLB is composed of one controllable and two discrete switching resistive loads with a total power variation of 0–6.2 kW. The PLB can be controlled in a same way as the SEG. An overview of the system architecture is presented in Fig. 2.
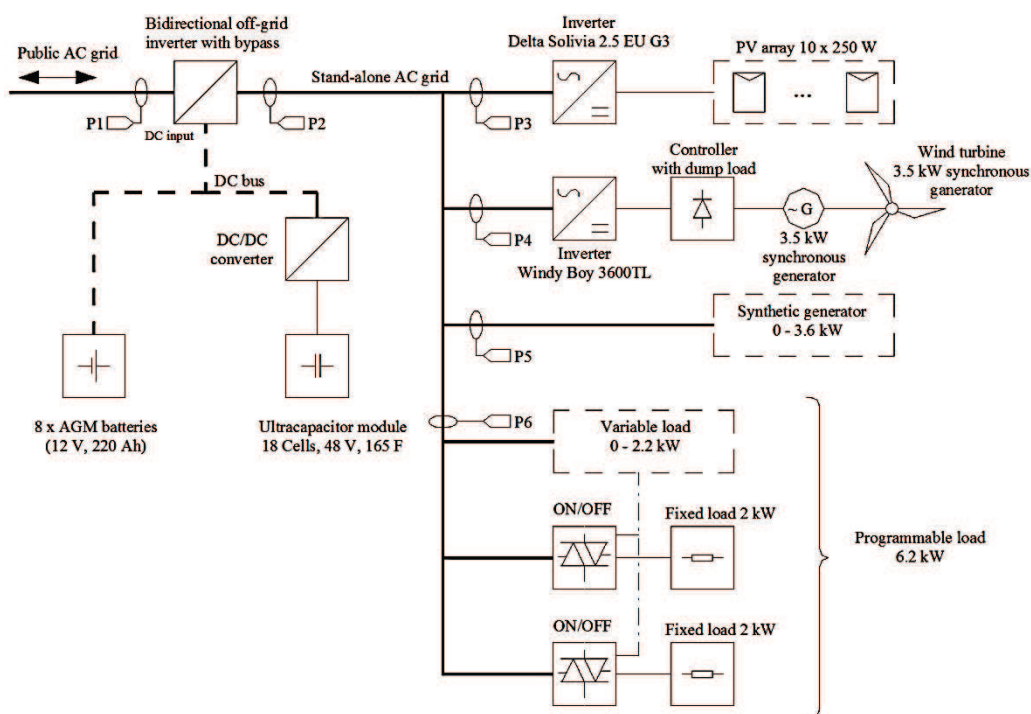
Figure 2. Main architecture of the system (*P1- P6* power flow and quality measuring points).

Control, measuring and storage devices are arranged in one enclosure (Fig. 3), which is placed in the control room. Inverters and loads are installed to the same room (Fig. 4). Energy emitted by loads is used for room heating.

Figure 3. Laboratory main switchboard.   **Figure 4.** Laboratory control room.

Outdoor components (wind turbine, weather station and solar panels) are installed on the rooftop of Institute of Technology. The placement is shown on Fig 5.

Figure 5. Equipment on rooftop.

Data acquisition and control system

All measurement results collected from sensors and devices are stored in the laboratory server, which is also connected to the university network and to the internet. Overview of data flow architecture is presented on Fig. 6.
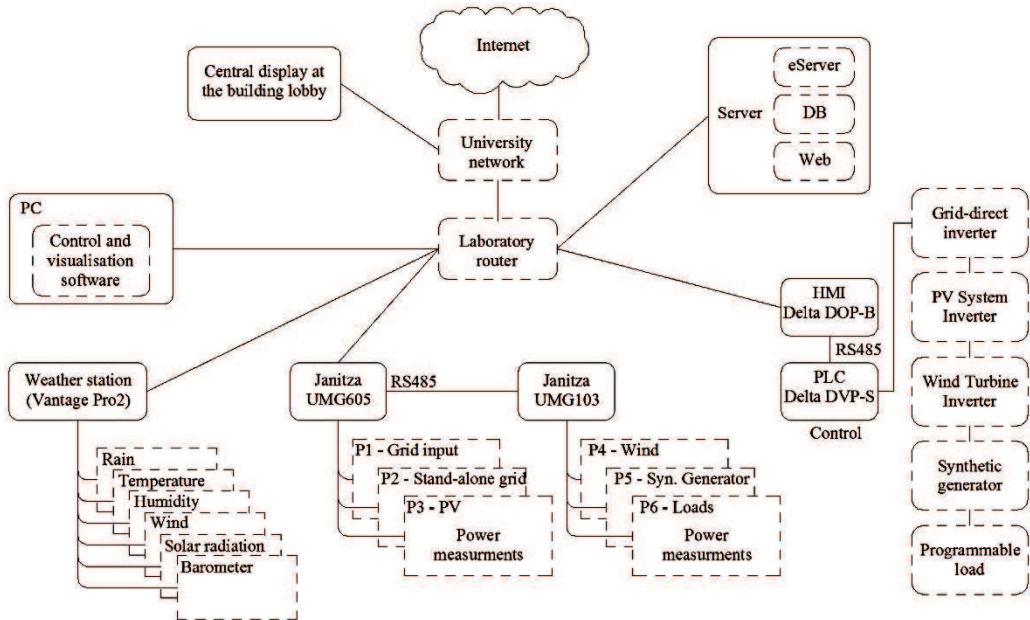
Figure 6. Data connection of measuring and control devices.

A Vantage Pro2 weather station is used for real-time data collecting from rain collector, barometer, temperature, humidity and solar radiation sensors and anemometer. Power flow and quality parameters are measured with power quality analysers (Janitza UMG605 and UMG103). Programmable logic controller (PLC) is used to interact with inverters, synthetic generator and programmable load. Also the safety rules of switching devices are defined in the PLC program logic. All the information is stored in the server computer database.

Reports, data tables and charts are composed based on that database and displayed in three different locations:
1. Laboratory PC enables full online overview of system parameters, control of system devices and export of historical data.
2. Central display at building lobby displays system parameters in real-time on one summarised page.
3. On the laboratory web page an online overview of full system and individually of components are present.

In order to control the synthetic energy generator and the programmable load online accordingly to site-based measure result the laboratory control system has to be linked to an on-site metering device with network connectivity. In a site-based control mode the power output of the SEG and the load of the PLB are determined by a programmable

logic controller (PLC). A LabVIEW based software platform needs to be customized to define the interface that automatically updates the PLC with the current tag value given by the metering device. The variable tag can be processed in the software to make scaling or modifications in the system.

Similar existing laboratories

The nearest similar laboratories with hybrid wind- and PV microgeneration can be found at the Tallinn University of Technology (Rosin, 2012) and the Faculty of Engineerging of the Latvia University of Agriculture in Jelgava (Osadcuks et al., 2013).

The laboratories mentioned above and the laboratory that is in the focus of the present article have similar installed capacities of energy generation devices, which makes their data comparable and is a good prerequisite for future cooperation (Table 2).

Table 2. Similar laboratories in the proximity

Laboratory location	Installed capacity of PV, kW	Installed Wind turbine or turbines, kW	Storage devices	Coordinates
Estonian University of Life Sciences	2.5	3.5 kW, HAWT	8 x Deep Cycle AGM 220 Ah, 12 V	N58°23/E26°41
Tallinn University of Technology	1.8	3 kW, WAWT	4 x 220 Ah, 12V	N59°23/E24°40
Latvia University of Agriculture	2.5	0.3 kW, HAWT	2x VRLA, 100 Ah, 12 V,	N56°39/E23°43

Laboratories with similar purpose but slightly southern latitudes can also be found in Ballymena in Northern-Ireland (N54º52/W6º17) (Mondol et al., 2006) and in Pennsylvania in the U.S.A. (N40º47/W77º51) (Pennsylvania State University 2014). It has to be noted that the laboratory in Ballymena is concentrated on solar energy research and has no wind turbines.

When compared with the laboratories mentioned above, then the main difference of the laboratory in Estonian University of Life Sciences is the existence of controllable synthetic load and synthetic generator, which can import remote data. In turn, some of the other laboratories (in Jelgava and in Pennsilvania) have electric vehicle charging stations that lacks in the laboratory which is in the focus of this paper, but could be considered as future development.

DISCUSSION AND FUTURE WORK

Conventional energy networks designed for one way power flow from grid to consumers have to adapt to the growing share of distributed energy production from renewable resources. They are influencing the whole energy system complicating significantly the work of large centralized power plants. Today, conventional power plants are already supporting the management of the grid by providing reserve and balancing power to cope with the stochastic nature of renewable sources. As the share of fluctuating renewable generation is growing, a critical question is: what is the maximum capacity that can be accommodated in the existing electricity network.

Different approaches in the field of DG are researched. One way to flatten the power output of renewable energy is the use of energy storage technologies. It can be used for storing electricity at peak times and discharging it at off-peak times. One of the main research fields of energy storage technologies is developing advanced energy storage materials to increase storage capacity and power densities. The presented laboratory gives good possibilities for testing different electrical energy storage technologies and algorithms for storage control according to real-time site-based measure results.

Another option is to involve end-users in the process of balancing energy production and consumption. It can be done using real-time tariff systems. This means that the consumer price changes in real time according to the network load i.e. availability of wind or solar energy, system load, power quality in network etc. In particular, this means that the networks have to be equipped with information technology such as smart meters and communication interfaces.

Different approaches exist when modelling the use of micro renewable energy generation devices. The laboratory gives opportunities to test previously simulated computer-models. There is also a variety of applied research opportunities for this kind of equipment, especially since the public sector has interest in the field of solar and wind energy applications in urban areas (Muiste & Veskimeister 2013). The main scientific topics that are planned to be implemented in the laboratory:
- Evaluations of optimal PV, wind and storage devices mixture depending on consumers load characteristics and location;
- Research in the field of load management and production control based on real online measured consumption and production data linked to the laboratory programmable load and synthetic generator;
- Evaluation of PV and wind charts peak period cutting technologies to fit consumer consumption curves;
- Assessment of power quality impacts of distributed generation.

Solutions of this laboratory expected to common use in few years. This will be used in dwelling energy supply but in advance for energy societies. The sizes of the devices in the laboratory enable to scale the experiments and transfer the results to any energy system sizes. Most important are the relative sizes of wind and solar device´s capacities and relation to consumer's average capacity. These sizes are developed by correspondingly to characters of wind, solar and consumer's production and load graphs. The laboratory can be further expanded to cover more topics like electric vehicle charging, smart metering fuel cell stacks etc.

CONCLUSIONS

In this article, a Digital Electronics Laboratory located in Estonian University of Life Sciences Institute of Technology was described. The laboratory electrical energy producers and consumers are connected to a stand-alone AC system, which can be disconnected from the utility network. To compensate the imbalance between supply and demand, electrical energy storage equipment is used. The maximum output of power supply units are 9.6 kW (PV array 2.5 kW, wind turbine 3.5 kW and synthetic generator

3.6 kW). This laboratory is designed from typical elements that are used in traditional 230/400 V AC microgrid systems. This system may be as prototype for developed real microgrid solutions.

When compared with similar laboratories, then the main difference of the laboratory of at the Estonian University of Life Sciences is the controllable synthetic load and synthetic generator, which can import remote data. The novelty of this laboratory idea is the possibility not only register energy flow data but also control energy flows under considered algorithm.

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