NATO SfP 983805

Emergent Phenomena Testbed Simulator for Improving SCADA Performance in Power System Security Management

FINAL REPORT

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Zagreb, Croatia, February 2013

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List of Abbreviations

FER Faculty of Electrical engineering and computing, University of Zagreb

HEP Croatian power company

HERA Croatian Energy Regulatory Agency

HROTE Croatian energy market operator

IEEE PES The Institute of Electrical and Electronics Engineers Power Energy Society

IP Internet Protocol

ISGT Innovative Smart Grid Technologies

NPD NATO county Project Director

PLC Programmable Logic Controller

PCS Process Control System

PoliMi Politecnico di Milano, University of Milano

PPD Partner county Project Director

PSAM Probabilistic Safety Assessment and Management

RE1 Renewable Energy solar system connected to the grid

RE2 Renewable Energy hybrid system

RE3 Renewable Energy system for solar characterization

R&D Research and Development

SG1 Smart grid measurements at FER

SCADA Supervisory Control And Data Acquisition

SOAP Simple Object Access Protocol (XML protocol)

UCTE Union for the Co-ordination of Transmission of Electricity

Project SfP 983805 – SCADA Testbed Simulator Final Report Summary

The power system is the most critical infrastructure for functioning of our society because other critical infrastructures (web, communication, hospitals, etc.) depend on it. Existing complexity has been proved to be a challenge in order of keeping high reliability and safety of the power system. With changes related to deregulated energy markets, high utilization of distributed energy sources and introduction of smart grids, the complexity becomes extremely high.

Project SfP 983805 'Designing Intelligent, Resilient, Scalable and Secure Next Generation SCADA Infrastructure' was granted to Dr. Stefano Zanero (Politecnico di Milano, Italy) and Dr. Zdenko Šimić (University of Zagreb, Faculty of Electrical Engineering and Computing, Croatia). Project implementation was carried out with support of ten additional internal and external researchers, three PhD students and nine undergraduate students.

Research focus of this project was on establishment of a simulation platform where different threats to the future power system could be investigated. The major goal is to simplify the process of finding better solutions for the optimal system design and sufficient control. This research is based on utilization of novel concepts and tools, using real systems operating conditions as inputs, as well as planned developments of the grid in the light of global policy changes regarding sustainable development. Considering the scope of the problem hybrid approach was selected as a best way to investigate different dimensions of the reliability and safety and to later integrate them in possible whole system solution.

During three years the project has succeeded to utilize different software platforms and realize several systems. Software platforms were used to model and simulate different aspects of problem: physical (PowerWorld), functional (AnyLogic) and structural (Algor and Ansys). Realized systems were used to generate data about real operation and to connect with software platforms. Four systems a built at the campus: smart grid (measurement & control), hybrid renewable system (wind and PV), PV system and Solar characterization system (also installed outside the campus). Created SCADA could be used to interact with simulations and also real systems. This altogether represents complete platform to investigate realistic and simulated complex behavior of emergent phenomena in the power system.

This implementation has resulted in publication of several journal and dozen conference papers. It is clear that this tremendous software and physical implementation presents very solid potential for years of continuous research.

1 Introduction

This is the final report for the three years of the scientific research project funded by the NATO Public Diplomacy Division in the framework of "Science for Peace". Project SfP 983805 'Designing Intelligent, Resilient, Scalable and Secure Next Generation SCADA Infrastructure' was granted to Dr. Stefano Zanero (Politecnico di Milano, Italy) and Dr. Zdenko Šimić (University of Zagreb Faculty of Electrical Engineering and Computing, Croatia). The report is organized into six chapters and three annexes.

Introduction provides information about motivation for the Project, achieved strengthening of national scientific infrastructure and expected economic benefits. Second chapter gives summary of the achieved scientific objectives (i.e., training, cooperation and infrastructure). Third chapter describes Project management structure and participating organizations. Fourth chapter explains in details Project scientific and technical results with special attention to the need for further R&D activities coming after conclusion of the Project. Fifth chapter provides information about status of the Project results implementation and expectations for the immediate and long term future economic benefits. Concluding chapter contains description of SfP experience and tangible consequences of NATO's funding for the research team and participating institutions. Annexes provide full list of internal and external collaborators, publications written as a result of the work on the Project and complete list of inventory records.

1.1 Project background and motivation

The power system (its physical grid, information infrastructure and energy trading systems) is one of the most critical infrastructures (i.e., it is necessary for most of the other critical infrastructures) and therefore its security is essential for modern society. Numerous challenges for keeping reliability and security of the power system are caused by number of recent increasingly significant changes: the consumption of electricity is rising; more and more intermittent renewable energy sources are in use; and energy market is liberalized.

Broad spectrum of approaches for improving power system reliability and safety is presented by so called smart grid concept/paradigm. This is a concept of power system fully enhanced with capabilities of ICT. One major part of such system is SCADA because it represents central point where supervision and control of the systems is carried out. Because of the mission-critical role of SCADA systems, interruptions in the power system (i.e., major accidents caused by faults, natural events, market flaws or attacks) could cause massive damage, financial losses and even physical destruction or loss of life, either directly or indirectly.

This project was motivated with this challenge of new SCADA which would improve reliability and safety by developing hybrid (software-hardware) simulation platform which could integrated all emerging phenomena and analyze power system behavior under different conditions, configurations, scenarios and control solutions. This enormous challenge has required application and integration of several software and hardware solutions.

The goal of this project is primarily related to the new SCADA testbed development which will enable better power system reliability and safety problem understanding and testing of different solutions.

1.2 Expected economic and industrial benefits

Importance and expected benefit from this project is based on the fact that research related to the emergent reliability and safety phenomena in the power system is current topic and increasingly relevant. This research involves number of players and it is important to properly connect all of them.

The expected economic and industrial benefits are outlined according to the criteria for success from the project proposal as follows.

1. ***Feedback from end-users on deliverables*** **-** Use of results from this project (contingency plans, experiences and insight gathered while modeling the testbed) was discussed with positive feedback by the following end-users in Croatia: Croatian power company (HEP), Ministry of economy, labor and entrepreneurship (MINGORP), Croatian energy regulatory agency (HERA) and Croatian electricity market regulator (HROTE). This project results complement activities in all these organizations. To HEP, as national power systems utility, this is valuable for every aspect of their operation (i.e., technical and economic). MINGORP is mainly interested in the policy and economic dimensions. While HERA and HROTE are interested in the market regulation related issues.
2. ***Installation of a working laboratory for testbed R&D*** - Completely new SCADA testbed laboratory is established at FER, gathering B.Sc., M.Sc. PhD students and researchers in topics related to reliability and security of power system. The laboratory consist of physical and virtual components and allows measurements, modeling and simulations for emergent power systems phenomena. This includes computers, server, distributed generation, and number of advanced software solutions connected as network.
3. ***Testbed components developed and functionally integrated*** – The laboratory integration and functional testing is still in progress. This is reasonable considering the scale and complexity of physical and virtual laboratory subsystems. However, usability is already high considering the value at individual subsystem level and at different levels of connectivity and integration.
4. ***Dissemination of the project results to the international scientific community*** – Total of 17 papers published in journals and conferences from activities related to this Project. With two more papers submitted for publishing and more expected in the future. Number of PhDs (1 finished and 3 are in progress) and graduation degrees (9 finished and 4 in progress) obtained through co-operation with the Project.
5. ***More than 3 end-users use one or more deliverables of the project in their operations*** – Practical implementation and use of project deliverables at the end-user is in progress at the HEP, MINGORP, HROTE and ADNET. This is challenged by both still in progress testing of project deliverables and high level of transitional activities at the end-users (related to the economic crisis, EU accession and energy market restructuring).

Achieved and expected benefits from this project are significant and direct for the research teams and host institutions, and indirect for their countries economy. Quantified benefit is expected to be direct (funding learning capabilities in relevant multidisciplinary field) and longer term (increased scientific capacity, education, research network, and economy).

2 Summary of the Achieved Project Objectives

This chapter provides summary of the achieved Project objectives related to the scientific goals, national institutions and industry participation, training, infrastructure enhancement and international cooperation.

2.1 Scientific goals

The list of Project goals which are successfully achieved are as follows:

- Study and assessment of the current status of SCADA issues related to the emergent phenomena in power systems (emphases on Italy and Croatia);
- Assessment of priorities in future needs for new SCADA testbed architectures;
- Analyzing a novel architecture for SCADA interactions modeled for increased reliability and security, based on cooperative agent negotiation and physical integration;
- Procurement and installation of working laboratory for testbed research and development;
- Testbed subsystems development and functional integration;
- Dissemination of project results to the students, researches, industry and international scientific community.

There are also goals to be completed in the near and longer term future:

- Analyzing and proposing a novel architecture for SCADA interaction modeling based on cooperative agent negotiation with formal and empirical proof of the improvements in reliability and security;
- Developing a common understanding of industrial needs and requirements regarding the reliability and security of new power systems, accompanied by a raising awareness program reaching all end-users;
- Identifying and disseminating best practice, possibly in a joint endeavor between manufacturers and end users, resulting in a joint capability and technology taxonomy for reliability and security;
- Development and deployment of a SCADA testbed platform as a complete platform for simulation and analysis of emergent phenomena in power systems.

2.2 Participation by other national institutions/industries

Many institutions were contacted and involved in the project at various stages, through direct contributions in know-how, providing feedback on questions or data for exploratory purposes.

Participation is more developed with the following institutions: United Nations Development Program, Croatia office; Faculty of Electrical Engineering University of Zagreb, J.J. Strossmayer University of Osijek (ETFOS); Croatian power company (HEP); Croatian Ministry of economy, labor and entrepreneurship (MINGORP); Adnet Ltd.; Solvis Ltd.;.

The following institutions are going to participate more in the future: Končar KET Ltd.; Croatian Energy Regulatory Agency (HERA); Institute for research and development of defense systems;

2.3 Training and international co-operation

Training goals were achieved with selected focused trainings and combined programs available at scientific conferences of interest.

- CRM Asia (LL), 2-10, May 2010
- PSAM10 (ZS), Seattle, WA, USA, 6-12, Jun 2010
- IEEE PES GM (LL), MN, USA, 24-29, Jun 2010
- Global Clean Energy Forum (LL), Sep 30- Oct 01 2010
- IEEE PES ISGT (ZS), Gothenburg, Sweden, 10 - 13, Oct 2010
- Logica Comp. Center for Smart Technology (LL), London, UK, 2-7, Nov 2010.
- AnyLogic Training (ZS, BM, IS), Paris, FR, 1-3, Nov 2010.
- MIT Energy Conference (LL), Boston, MA, USA, Feb 25- Mar 07, 2011
- IEEE PSCE 2011 (ZS), Phoenix, AZ, USA, 20-23, March 2011.
- IAEA workshop on NPP risk monitors (ZS), 11-16, April 2011, Prague, Czech Rep.
- Eurelectric Conference on sustainable city electricity (LL), 12, May 2011
- IEEE PES CC Meeting, Trondheim (ZS), 2011, 18-19, May 2011
- Managing SCADA Security Risks (LL), 25-26, May 2011.
- IEEE NPEC Meeting (ZS), Dana Point, CA, USA, 25-27, July 2011
- IEEE SGC (ZS), Brussels, Belgium, 17-20, October 2011
- Smart City Expo & World Congress (ZS), Nov. 28 – Dec. 2, 2011, Barcelona, Spain
- IEEE NPEC Meeting & DistribuTECH Conf. (ZS), 21 – 29, Jan. 2011, San Antonio, TX, USA
- 'Ensuring IT Security for Energy Infrastructure' (LL), May 24 – 25, 2012, Berlin, DE
- ANS Annual Meeting (ZS), June 22 – 28, 2012, Chicago, IL, USA
- 'Black Hat USA 2012' and 'Defcon 2012' (LL), 21 – 29, July 2012, Las Vegas, UA
- EC JRC-IET, Petten, NL (BM, NH) 16-22, January 2013.

International cooperation is established with following organizations: European Commission Joint Research Center Institute for Energy and Transport, IEEE PES and IEEE NPEC.

2.4 Enhancement of scientific infrastructure

The list of major software tools is as follows: PowerWorld 15 with educ. license, AnyLogic 6 (international educ. and research license), Algor Simulation pro. 2011 edu. license, ANSYS GAMBIT/Tgrid Research license for 2012 and 2013, GOTHIC Numerical Applications 2013, Server data acquisition & proc. (TB), and PLC Solar application (RE3).

Computers funded from the Project are as follows: server IBM X3550M3, 4 desktop PCs, 6 laptops and one tablet.

Equipment is used to create measurements and distributed generation systems as follows: SG1, measurement & control (PQube and other components), RE1, Solar system connected to the grid (1.2 kW), RE2, hybrid distributed generation connected to grid with energy storage (400 W solar & 600 W wind), RE3, solar characterization system (five stations with complete measurements for six panels).

3 Project Management Structure and Participating Organizations

This chapter describes Project management structure and lists participating organizations. Main researchers on the Project are also listed here.

3.1 Project management and organization

The overview of the managerial organization of the project is presented in Figure 1.

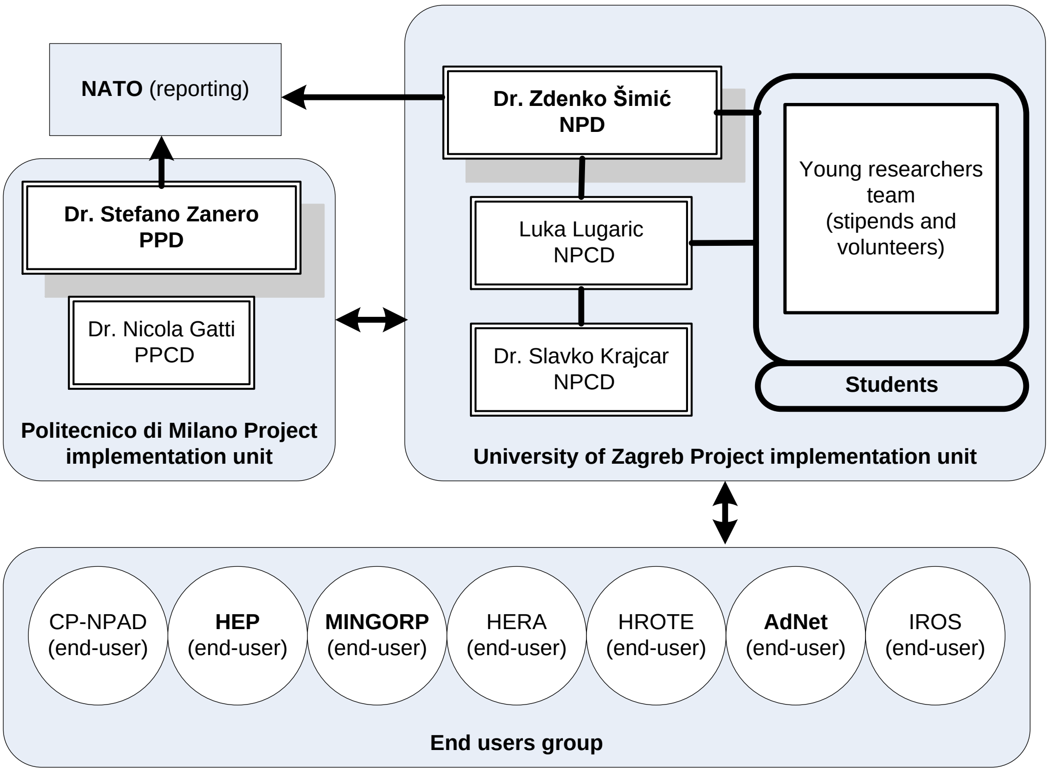

Figure 1 - General managerial organization of the Project

Project was managed by two academic institutions with respected teams as follows.

Dr. Stefano Zanero[1] has lead team with major role from Dr. Nicola Gatti and Dr. Francesco Amignoni at the Politecnico di Milano, Dipartimento Elettronica Information.

Dr. Zdenko Šimić[2] has lead team with Luka Lugarić and Dr. Slavko Krajcar at the University of Zagreb Faculty of Electrical Engineering and Computing, Power and Energy Systems Department. In addition four other researchers also co-operated with Project. Three PhD students also cooperated with Project and one has just obtained his degree. Total of eight student researchers were one or more years Projects stipendists: Boran Morvaj, Ninoslav Holjevac, Bruno Jurišić, Goran Jurišić, Roberto Rosandić, Katarina Knezović, Ivo Sluganović, and Jurica Brekalo Štrbić. Nine students have graduated (five years program) with assignments related to the Project.

[1] Politecnico di Milano - Dip. Elettronica e Informazione Via Ponzio, 34/5 I-20133 Milano – ITALY, zanero@elet.polimi.it, http://home.dei.polimi.it/zanero/

[2] University of Zagreb Faculty of Electrical Engineering and Computing, Unska 3, 10000 Zagreb, CROATIA, zdenko.simic@fer.hr, http://www.fer.unizg.hr/zdenko.simic

The core of Project activities was performed at the respected academic institutions. Communication and meetings were organized in order to connect with end users institutions and industry. The list of participating organization is presented in the next subchapter.

3.2 Participating Institutions and Industry

This subchapter lists all end users organizations (i.e., intuitions and industry). These organizations represent all dimensions related to the emergent power systems phenomena (i.e., utility, policy, regulation, and industry).

- ***NATO Parliamentary Assembly Delegation (CP-NPAD)***, Dr. Kresimir Čosić, Zagreb, Croatia, Head manager, Consultations on the usability of the end product for purposes of national security;
- ***Croatian Power Company (HEP)***, Dr. Željko Tomšić, Zagreb, Croatia, Management Board member, Overall feedback on deliverables, consultations on usability of the end product on implementing the Croatian transmission and distribution system SCADA implementation;
- ***Energy Directorate, Ministry of economy, labor and entrepreneurship (MINGORP)***, Branimir Horaček, Zagreb, Croatia, Director, Consultations on usability of the end product in testing effects of energy policy shifts;
- ***Croatian Energy Regulatory Agency (HERA)***, Tomo Galić, Zagreb, Croatia, President, Consultations on implementation of energy market principles in the region within the testbed model, input for case studies;
- ***Croatian energy market operator (HROTE)***, Leo Prelec, Zagreb, Croatia, General manager, Consultations on usability of the end product and its alignment with legal framework in Croatia and surrounding countries;
- ***Adnet Ltd.***, Vlatko Debeljuh, Zagreb, Croatia, Software engineer, Overall feedback on deliverables, consultant on creating the SCADA model, input on case studies;
- ***Institute for research and development of defense systems (IROS)***, Ministry of defense, Dr. Dario Matika, Zagreb, Croatia, Head manager, Consultations on usability of the end product in current research within his institution.

4 Scientific Results

This chapter presents in details Project scientific and technical results with special attention to the need for further R&D activities coming after conclusion of the Project.

Scientific and technical results of the Project are described in three separate subchapters. Figure 2 shows the physical layout of Project results. The first subchapter describes the testbed as a central part of the Project ('Server' in Figure 2). This is followed by the description of the measurements for the FER electrical network ('Smart measurements' in Figure 2). The Project description is concluded with the information about built distributed systems ('Hybrid system', 'PV system' and 'Solar characterization' on Figure 2)

Presented description is limited by the report format and for more details it is best to further consult Project publications in the Annex 2.

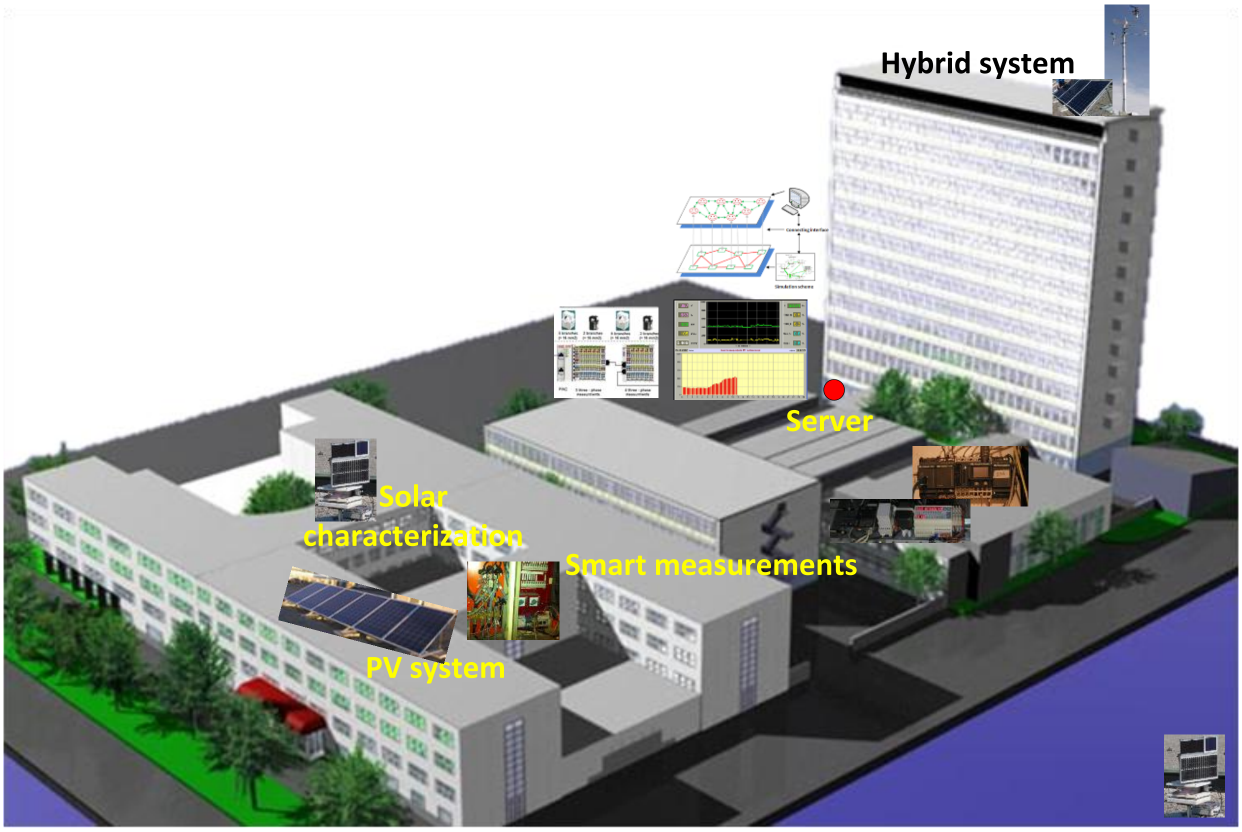

Figure 2 Physical disposition of the Project components at the FER

4.1 Integrated simulation system - Testbed

This part of the project represents central and the most important part. It is a software model for the simulation of the many different scenarios related to the power system operation. Main focus is on testing optimal SCADA implementation regarding reliability and security of power system with integrated smart grid features, distributed generation and deregulated market environment.

In order to make modeling and simulation more realistic this implementation has connections with the real systems measurements. These are the systems installed at the FER (Figure 2) and in certain level they represent realistic elements of power system.

The project consists of many parts that are all supposed to be fit together to make an integral testbed platform which will be capable of analyzing various grid configurations. The goal is to have a data acquisition system which will be constantly gathering data from all hardware components installed. This system has a task to organize all the input data into frames and then forward the organized and converted data to the various simulation programs described previously. Various calculations are done there. Risk based analysis, physical constraints analysis, optimal power flow and agent based and dynamical modelling are also included.

The value of the measured solar and wind resource and the corresponding production from PV and wind turbine is that they will enable the simulation of real scenarios. Furthermore, some trends and statistics can be obtained. This will not be the only task of the testbed since it will be also used to determine system response to unpredictable circumstances. In addition, the best possible configuration will be searched for as well as the possible problematic cases through agent based modelling in AnyLogic.

The database on server is in charge of data storage and is proposed to be developed in Microsoft SQL and the connection between the data acquisition and data management and storage will be created using LabVIEW.

LabVIEW has the possibility to collect the data from the hardware and instruments installed. In the same time through predefined set of its VIs (Virtual Instruments) in the DCT kit (Database Connectivity Toolkit) it can communicate with the database. This part of the server will be gathering the data from variables that represent the measured values. After that it will store the data in created database where it will be accessible for further data mining and revision.

The advantage of this approach is the possibility to monitor all the processes over the distance whether using local intranet on which all the components will be connected or global internet. The combination can enable the inclusion of remote alarming and command via the smart mobile phones or personal computers.

It is planned to design a web service which will be used to easily read the status of all the components of the system.

With the help of LabVIEW Web server, VI-s can be deployed as individual web services which can be called upon using HTTP protocol. These protocols do not require installation of standalone run-time mechanisms which means they can be run using just HTML or JavaScript.

The interface can be most simply designed using the LabVIEW Web UI Builder. It uses the similar graphical programming approach as LabVIEW and can be used to develop a front panel of the system which will be accessible through internet using HTTP protocol. Finally on the web page the applications developed in LabVIEW UI Builder can be found.

The system has all the components (PV system, HybridC system, PW simulation, AnyLogic simulation, ANSYS models) included and modeled separately. In the final concept, all the components will be working together as a whole and provide valuable information about system performance under various conditions. Valuable asset, as it was mentioned, is dynamic and agent-based modeling which can efficiently implement stochastic behavior. This part is done under the AnyLogic simulation.

The extended use of this proposed testbed for microgrid is for educational purposes. Since the testbed will include the real data gathering from the sun and wind resource, measure the production from wind aggregate and PV array, measure the power quality and demand, it can be used to educate and demonstrate the nature and impact of distributed renewable sources. Furthermore all the analysis which the testbed will be able to conduct can provide even more detailed information to students and even have the weight to center a certain laboratory project around it.

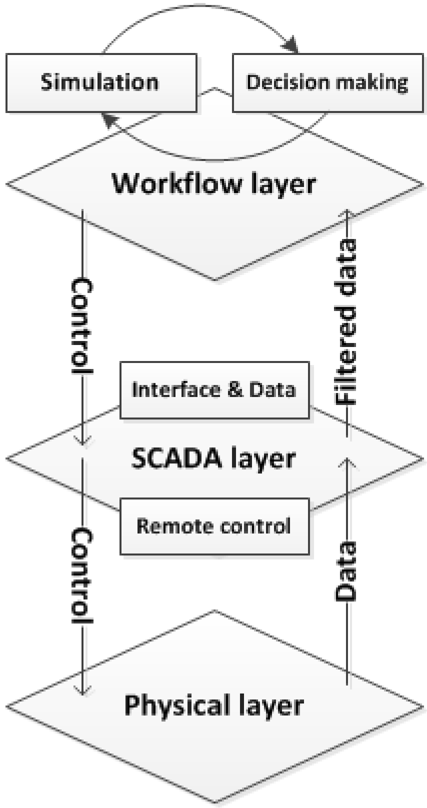

Figure 3 Conceptual layering of the testbed

4.1.1 Testbed construction

The testbed platform consists of many different components. To simplify the development the proposed concept is divided into 3 layers. As it can be seen in Figure 3, under layers are Physical, SCADA and Workflow.

4.1.1.1 Physical layer

All the physical components installed come under the physical layer which is directly connected with the server and database. The operating status of all the components will be visible in LabVIEW developed interface and in web. From there depending of the simulation results and user requirements remote control can also be established.

4.1.1.2 SCADA layer

The SCADA layer can be represented by the LabVIEW interface. On the server the proposed LabVIEW interface can be developed which will gather all the data and store it into the database. From there the information about the status of all the components can be sent to personal notebooks or phones via email notification or through access to the web-service of the LabVIEW interface. Furthermore the data collected could be sent to various developed models and there used to generate different scenarios and results. The calculations would be done in the background in the workflow layer, but the statuses and reports would also be visible in LabVIEW interface.

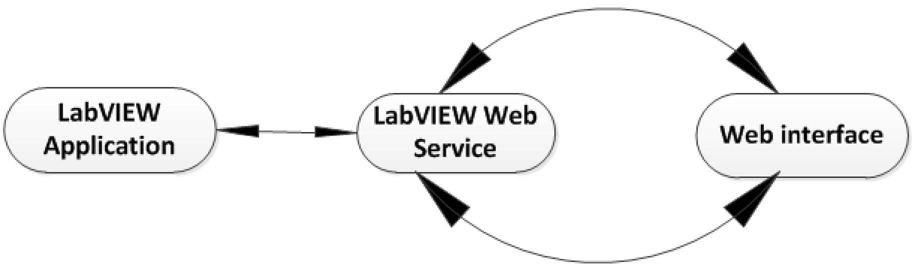

Figure 4 Web Service can communicate with the Application through

4.1.1.3 Workflow layer

In the workflow layer the most important parts are simulation software PowerWorld, AnyLogic and ANYSIS.

The data gathered by the server is used as input for the simulations in PW. PW can use the provided data to conduct more precise calculation since the real data is used. Of course certain assumptions are to be made since the developed simulation is more complex and includes more elements than are physically installed and included in data gathering process. The simulation has all the relevant elements modeled. As already mentioned, for some of them the real data from the real-time measurements is used. The rest are taken as characteristic values of certain grid elements. The similarity between the hardware system and the developed simulation is high and this is the base case. But this is not the only task the PW has to fulfill. PW will also be used to conduct calculations on a wider scale. The built LV grid on FER that includes renewables and smart metering will become one part of the grid. Using AnyLogic this part can be changed stochastically and multiplied and through different developed algorithms similarly like it has been done with the model of the house in the present AnyLogic model.

The great advantage PW has is the inbuilt script language which enables a uniform and simple change of components. This can be used to, for example, determine a new grid configuration under some specific conditions and add new parts or change already present ones. The whole graphical scheme is translated into script language. Therefore with the change of some of the rows and with help of the specific commands new elements can be added or the state of present ones can be changed. This is to be done using the Java based AnyLogic and EZ Jcom software interface as mentioned before. With simple cross software communication certain code fragments can be changed and by that the simulation configuration also. Certainly AnyLogic results would have to be interpreted in a certain way so that they can be efficiently used in PW. But the basic idea is feasible and can be done with the proposed tools.

There are several examples of connecting JADE (Java Agent Development Framework) with PW through EZJcom interface. Instead of using the JADE interface AnyLogic can be used. This approach is a little less standardized but offers more ease of access and is simpler to work with. AnyLogic is also simulation tool based on Java programming language that supports system dynamics, process-centric and agent based modeling. Mentioned features allow building some very complex models of the grid with decentralized decision making and interactions. As it is shown before, simulation of the smart city has been developed using the AnyLogic simulation tool. Important thing is that in AnyLogic an energy storage can be modeled. That has a great meaning for the PW simulation which can be managed from the AnyLogic using the EZJCOM software. Accordingly, connecting the AnyLogic and PW will enable creating the battery model in PW by adding some additional physical constraints.

```
SCRIPT Edit
{

          EnterMode(Edit);
          }
...
          DATA AddGen(GEN, [busnum, GenID, GENAGCAble, GenParFac, GenFixedCost, GenFuelCost,
                         GenMWMin, GenMWMax, GenEnforceMWLimits...])
          {
…
```

Figure 5 An example of the script command inside edit mode in PW

The workflow layer can be also used to expand the measured results and observed part of the electrical grid. Implemented solar and hybrid system on the Faculty of Electrical Engineering and Computing represent future LV grid alongside with the installed smart measurement. Mentioned implemented systems together with the corresponding load represent the paradigm of prosumer, a proactive consumer that has the ability to control part of the grid. Main point of many smartgrid researches is to envision how the grid containing many prosumers would work. The solution is to use simulations and expand the collected data for a small part of the grid to the whole grid.

Another link to have even more detailed insight into the grid is to be established between the PW and ANSYS. PW is used to determine physical constraints and limitations, optimal power flows and voltage distribution across the network. If any of the modeled elements comes to a critical point, power line overload or wind aggregate emergency shutdown due to strong wind, the more detailed simulation and calculation in ANSYS can be conducted. ANSYS model takes into consideration heat transfers and dimensional constraints regarding the element position. At present time models for the different types of lines and model of the air flow for the wind turbine are available. The set of these ANSYS models can be expanded.

To sum up, the loop of PW and ANSYS would be able to together measure the importance of certain elements and could calculate the consequences of certain actions. The PW would be getting data from the server application for some of its elements. AnyLogic would feed this loop of physical simulation tool with possible and suggested grid configurations. Also the data from measurements would be used.

4.1.2 Detailed scheme of the server network connections

Complete scheme of the project is shown on the figure below (Figure 6). On the figure (Figure 6) the detailed connections between physical, SCADA and workflow layer can be seen.

The physical layer contains PV system on the top of the D building and the hybrid system situated on the top of the C building. Parts of the physical layer are also the resource, both sun and wind, the consumption and the power quality measurement achieved with installed smart meters. All mentioned produces information which is collected and processed on the server. Physical disposition of the mentioned components at the Faculty of Electrical Engineering and Computing is shown on the figure below (Figure 2).

Server can be both placed in physical and the SCADA layer. What makes the server belong to the SCADA layer is LabVIEW being installed on it. Through the intranet or global internet users will be able to control their production and consumption, see system status, alarms etc. from a mobile phone or a personal computer.

Furthermore, the workflow layer has been represented by the AnyLogic, PowerWorld and ANYSIS. Communication between different software tools can be established using the EZJCOM environment as mentioned before.

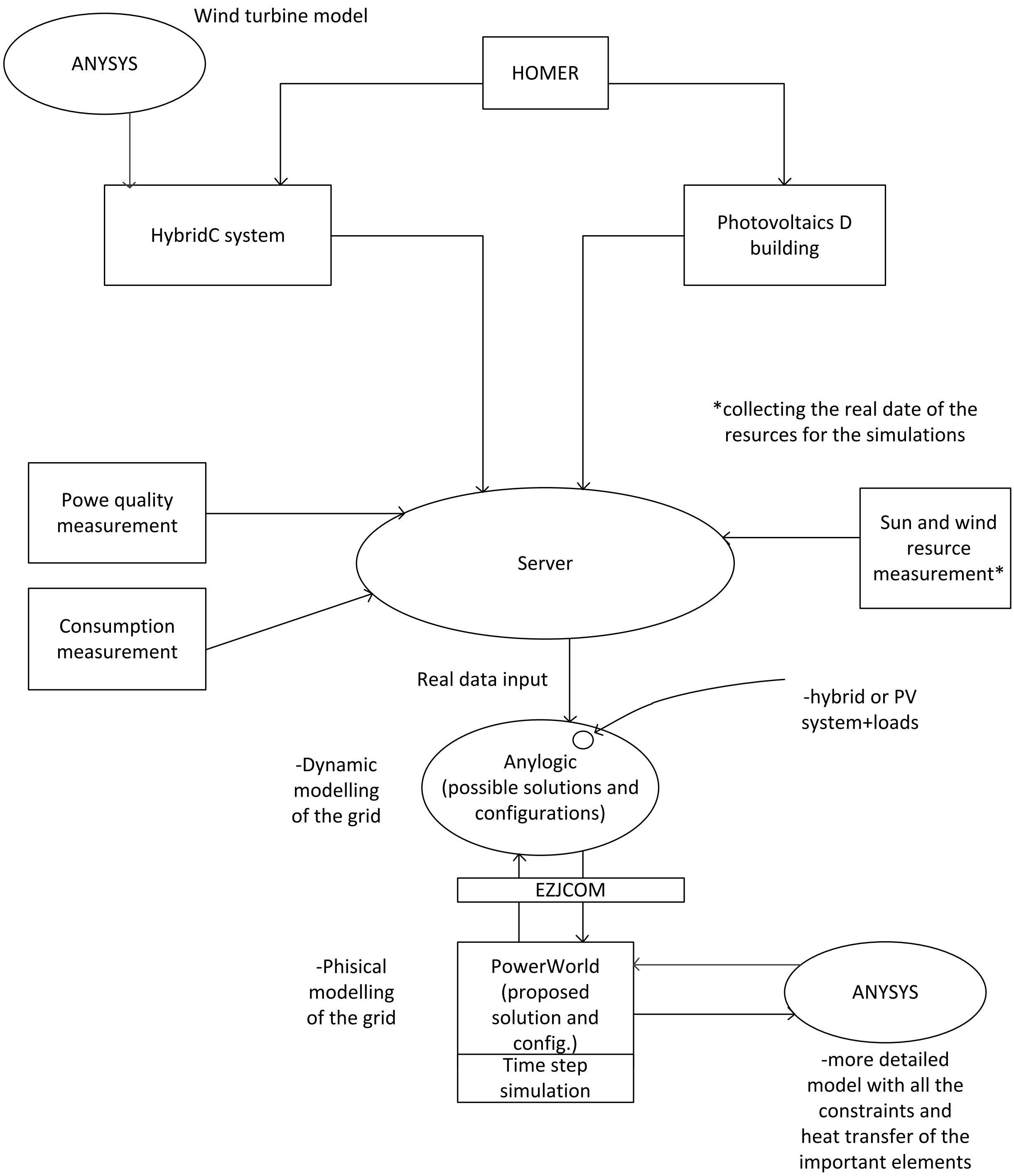

Figure 6 Detailed scheme of the server

4.1.3 Example case of use

Model for evaluation and analysis of the certainty process control system (PCS) can be defined as a recorded current situation of the system to the risk model. To be able to perceive risks of the process ordinary risk model must be expanded by the business model as it is shown on the figureFigure 7. Business model gives opportunities to monitor the current state of the grid, safety of the operation and, enable the work of auxiliary services coordination with the grids.

In this situation there are several issues:

- is the data transferred correctly
- how is synchronization of changes in IT system done
- does the model provide enough information

The PCS system of the new generation has the extension which provides other functions:

- initial export of the architecture of the system in the risk model (arrow 2)
- modification of the risk model in response to some change in the IT system
- sending the status of the IT system components in the risk model to allow dynamic risk monitoring and risk assessment
- notification of the changes in the IT system
- possibility to change the functionality in the critical situations in order to limit the consequences of an assault on the system

As it is shown on the figure Figure 7the system extension for the risk monitoring and assessment is also part of the new system.

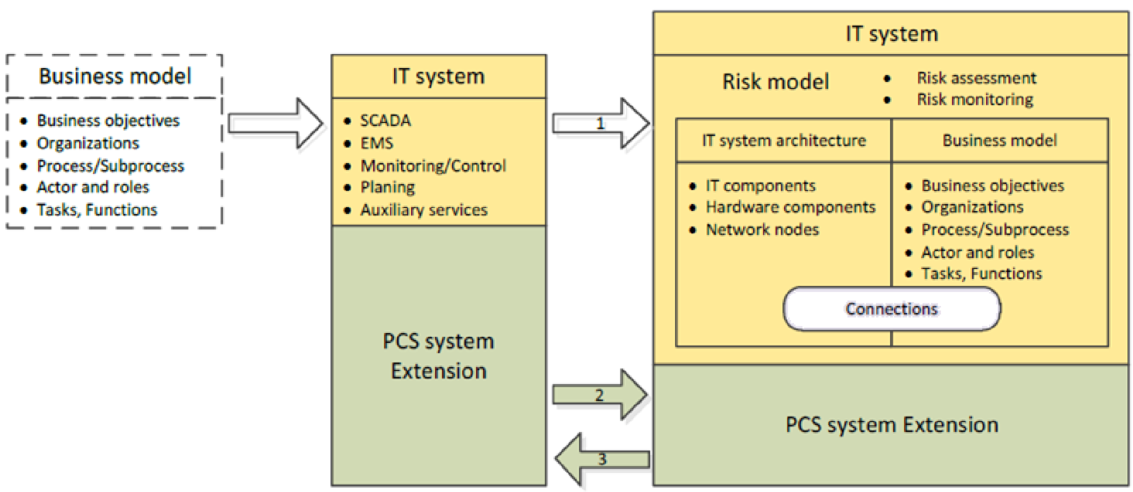

Figure 7 Model for evaluation and analysis of the certainty process control system

PCS system contains both physical and logical structure. The physical structure defines a physical position of the computers and the LAN connections between them. PCS system Extension allows dynamic reading of the physical structure and real time comparing with the logical structure. The logical structure defines program modules and communication between them. The program modules are connected by client-server connector independent from their physical position. Both structures are shown on theFigure 8.

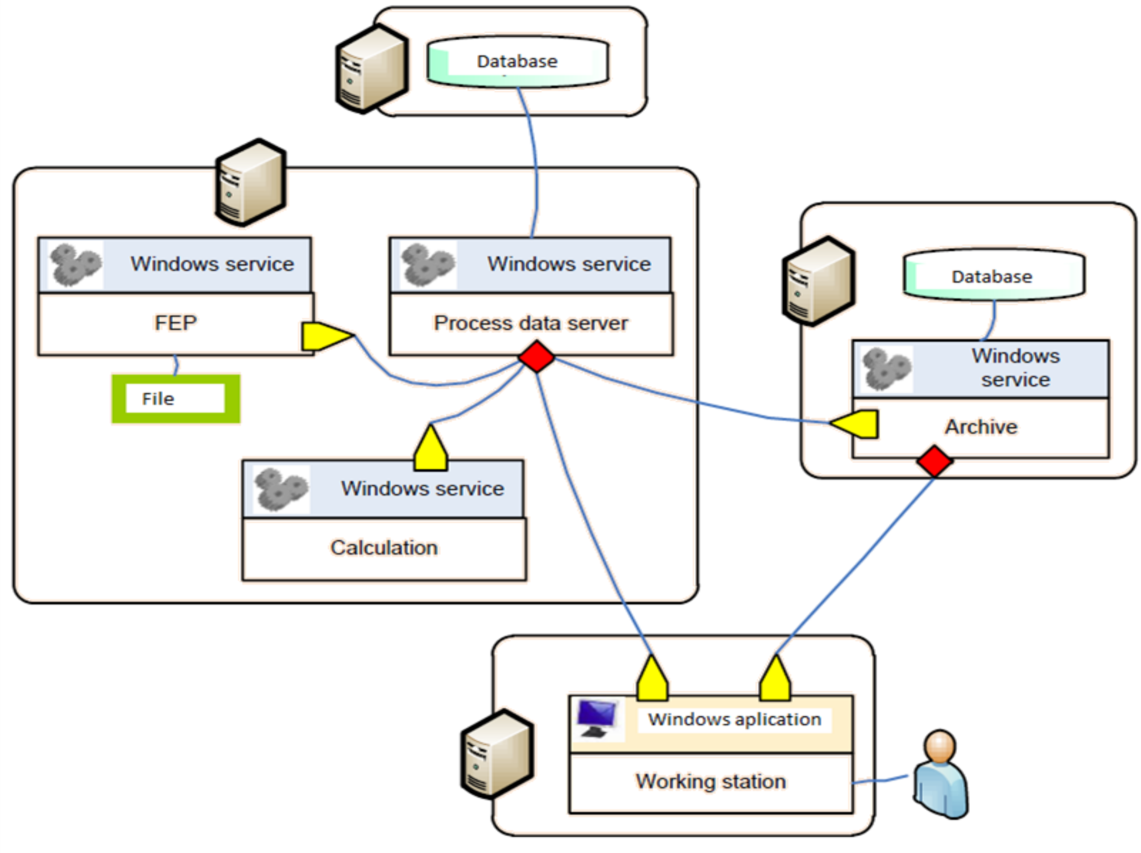

Figure 8 Physical and logical structure of PCS system

4.1.4 Implementation of PowerWorld for microgrid simulation

PowerWorld Simulator is a power system simulation package designed from the ground up to be user-friendly and highly interactive. Simulator has the power for serious engineering analysis, but it is also so interactive and graphical that it can be used to explain power system operations to non-technical audiences.

Simulator consists of a number of integrated parts. At its core is a comprehensive, robust Power Flow Solution engine capable of efficiently solving systems of up to 100,000 buses. This makes Simulator quite useful as a stand-alone power flow analysis package. Unlike other commercially available power flow packages, Simulator allows the user to visualize the system through the use of full-color animated one-line diagrams enhanced with zooming and panning capability. System models can be either modified on the fly or built from scratch using Simulator's full-featured graphical case editor. Transmission lines can be switched in (or out) of service, new transmission or generation can be added, and new transactions can be established, all with a few mouse clicks. Simulator's extensive use of graphics and animation greatly increases the user's understanding of system characteristics, problems, and constraints, as well as how to remedy them.

The base package also contains all the tools necessary to perform integrated economic dispatch, area transaction economic analysis, power transfer distribution factor (PTDF) computation, short circuit analysis and contingency analysis.

In addition to listed features of the base Simulator package, various add-on tools are available, including transient stability feature, optimal power flow (OPF), time step simulator, graphic information system and many others.

4.1.4.1 Microgrid modeling

Configuration of the microgrid was chosen with help of the program called HOMER. Main factor in choosing configuration was not economy, but it was the ability that the microgrid can work both in the island operation as well as when it is connected to the grid.

The chosen microgrid is composed of:

- 500 kW of PV (2000 PV modules with power of 0,25 kW per unit)
- 4 wind turbines with power of 2 MW per unit
- 1000 diesel aggregates with power of 4,5 kW per unit
- 250 batteries with capacity of 7,6 kWh per unit and cumulative power of 0,51 MW
- industry and households demand, scaled on 30 MWh/d and 51 MWh/d

Important thing to notice is the simple way the simulation components can be added or modified. More of this procedure which will be found as very valuable for the integration into the testbed will be described later. As it can be seen from above only the active power is observed in the simulation. The idea was to simulate the grid which consists of few micrograds and observe what happens with the current and voltages in the grid. What is called microgrid in the simulation could also represent the Smart House or Building if the power of the components is reduced. The microgrid is shown in the Figure 9.

As it is shown (Figure 9) the microgrid contains two buses named K7 (10,5 kV) and N8 (0,4 kV). Four wind turbines, photovoltaic modules and the demand are all connected to the bus K7. A generator and a load connected to the bus N8 represent diesel aggregate and a battery.

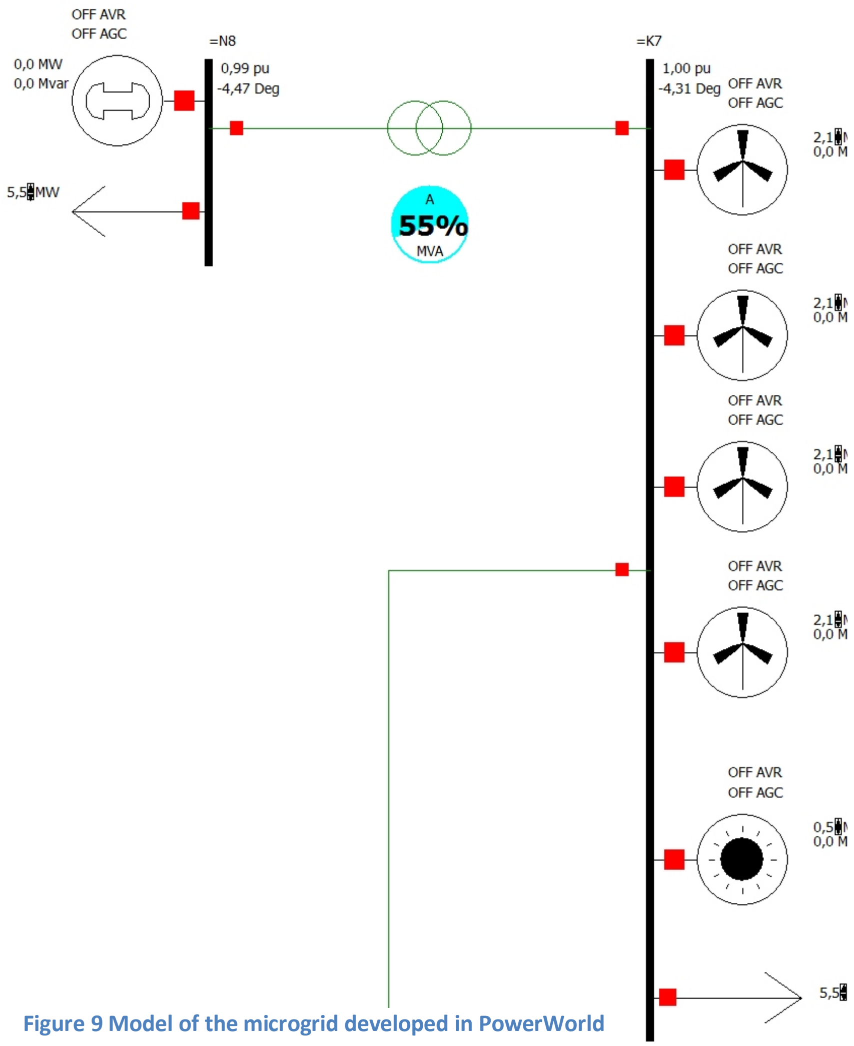

Figure 9 Model of the microgrid developed in PowerWorld

The load is needed to simulate the battery discharging, that is to say giving the power to the microgrid in the moment of a lack of energy from distributed sources. Generator on the bus N8 has a range of output power from -0,5 MW (maximum power which can be charging the battery) to 5 MW (maximum power which can both the battery and the diesel aggregate send to the grid). Parameters of the line and the transformer are typical values for distribution network. Capacity of the line and the nominal power of the transformer are both 10 MVA.

First model is built of four microgrids and the goal of the model was to show what happens on the connection between the distribution network consisting of microgrids and the transmission network. Real data for insolation, wind speed and load are used in the model. One year is shown through four characteristic days (one for each season). The result of the simulation indicated that distribution network built from the modeled microgrids can be independent part of the system for most of the year (except winter). Thing which is more important than the mentioned result is fact that PowerWorld can simulate behavior of as much as you need microgrids that work in a parallel. For this simulation was used add-on Time Step Simulator which allows usage of the time series of data as the input data.

Second model is more oriented on the connection between the microgrids. It consist of three microgrids and is shown on the figure below (Figure 10).

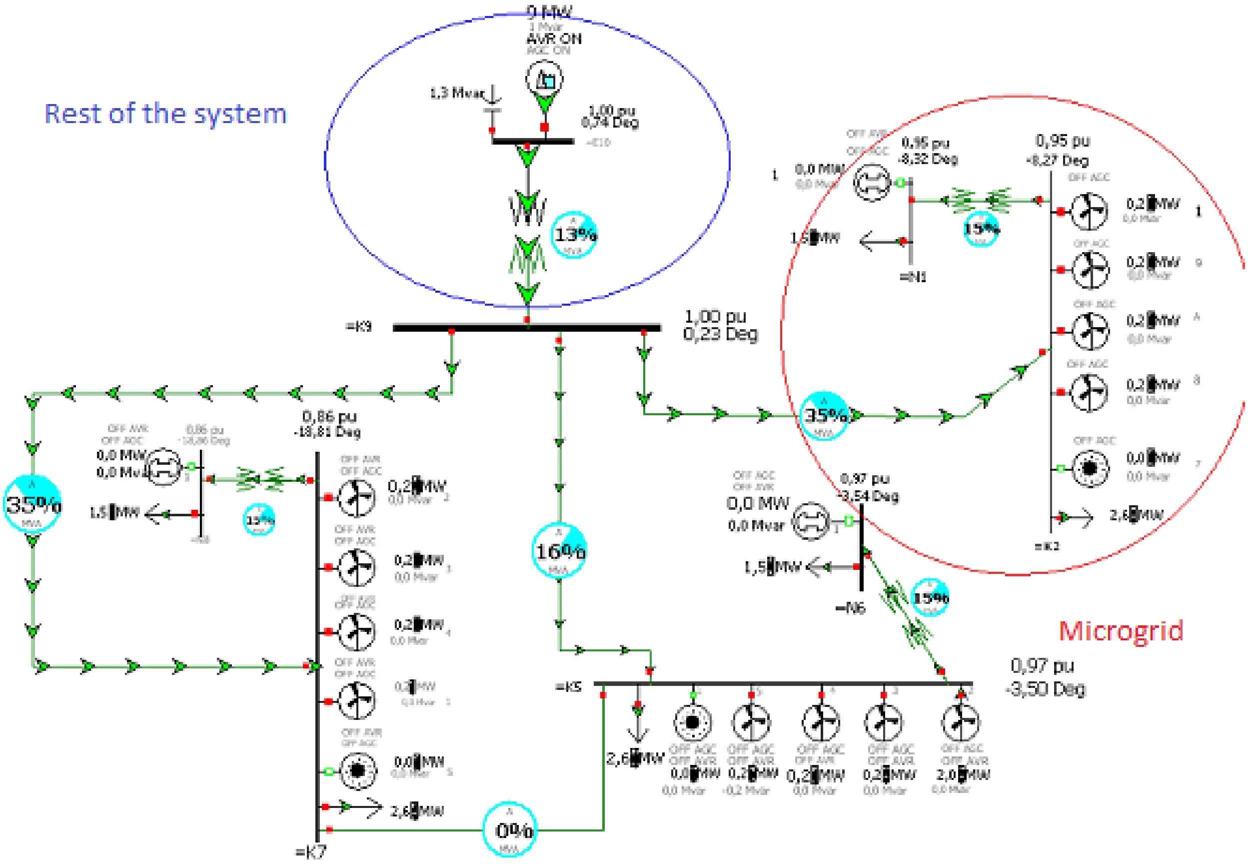

Figure 10 Grid consisted of three microgrids

To make the simulation possible one bus must be marked as a referent. Referent bus is the bus which represents the grid that is to say the rest of the transmission network. It is needed because of the nature of the power flow analysis mathematical background. A few scenarios were reviewed including the island operation, fast change of demand and stochastic nature of renewable sources. The observation was made on power flows through lines and on bus voltages. It has been discovered that the tested microgrid suffers from big voltage drops, voltage increases and line congestions in some scenarios. Mentioned problems can be avoided by choosing another component in the microgrid or with a better connection between the microgrids.

Every microgrid contains battery, which is different from conventional distribution grid which usually does not contain battery. PowerWorld does not have the battery model in it. Solution to this issue can be found for that issue in using the generator and load connected to the same bus and controlling them simultaneously. That can not completely solve the problem because battery inherently has a parameter, its capacity, which cannot be modeled with the presented solution. Only way to limit the energy of the battery is to connect PowerWorld to some other program as the suggested AnyLogic.

Another microgrid characteristic is two ways power flow. PowerWorld does not have any limitations in that field.

4.1.4.2 Results and conclusions

PowerWorld can be easily used to simulate the photovoltaic microgrid on the D building and the hybrid microgrid on the C building. Also the load can be simulated from the real measurement from the building of FER where Power System department is located. That will allow testing and observing of many different combinations of variables such as distributed generation or consumption using the real measured data.

The problem of implementation of the mentioned case is how to model the battery in the PowerWorld. The issue can be solved, as mentioned before, using the EZJCOM which is a program interface which can connect both Java and PowerWorld. AnyLogic is the program which uses the Java code and the connection can be made between PowerWorld and AnyLogic..

All the components of the simulation can be added through a integrated command line in the PowerWorld. PowerWorld uses its own script language and has its own syntax which is not so complex (Figure 5). Different macros and scripts can be coded and run from this integrated code editor. But most important thing is that this can be used to connect PW with other programs through above mentioned EZJCOM environment.

The script language allows easier connection of models. The idea is to send results of AnyLogic simulation to the PowerWorld (dynamic making of the model could be established). AnyLogic would be responsible to run the multi-agent dynamic simulation of the representative microgrid and find possible problematic scenarios. Data formed to fit the PowerWorld would be sent and the microgrid configuration would be changed to check the static stability of the given network configuration under given conditions in the certain scenario.

4.1.5 AnyLogic model

The purpose of the model is to simulate a city that has implemented smart grid and demand response paradigm. There are two scopes of this model. First one is to find out what effect does implementing demand response on city level has and does it reduce peak power values. Second one is to find out if it increases security in power supply.

The city model is modeled in software AnyLogic. AnyLogic is simulation tool based on Java programming language that supports system dynamics, process-centric and agent based modeling. For this model, both agent based and system dynamics modeling were used.

The city model consists of two levels. The lower level are buildings, and the higher level is the main level which controls the city and manages demand response by having direct control over building's level.

The buildings are modeled as an agent and they act as smart buildings which means that automation system controls all loads and also utility can control the building. There are 1030 buildings in the city model. The agent building's behavior is defined by the system dynamics modeling and a state chart. Each building agent acts independently so there are 1030 buildings behaving differently which corresponds to the real city where human behavior is irregular. Building's consumption is based on average Europe home building consumption. Each building has 7 specific loads modeled using the system dynamics modeling. The most common loads are modeled. They are water heater, dishwasher, washing machine, refrigerator, television and PC, air condition and lightning. Based on the research, carried out in USA, the average consumption and working hours per day of the loads are defined but each load's consumption is represented by a uniform distribution to implement more irregularity in the model since not all consumers will have the same kind of load that needs the same amount of electricity. Parameters of the loads are shown in Table 1. Also, each load starts at different time in each building which makes 7210 modeled loads that are independent.

Table 1 Parameters of the loads in the building – data for one day

Load	On time (min)	Off time (min)	Power (W)
Water heater	30	70	800-900
Dishwasher	60	1380	1300-1450
Washing machine	60	1380	1000-1200
Refrigerator	15	35	400-470
TV and PC	480	960	500-600
A/C	15	35	900-1100
Lightning	480	960	200-300

Each building also has a photovoltaic system and an energy storage – battery. Photovoltaic system is modeled using system dynamics. Photovoltaic generates electricity depending what time of the day it is and if there is any sun resource available. Battery storage is modeled using state chart. The overview of the agent building can be seen in Figure 11.

At the main level, the whole city is controlled by developed algorithm. The consumption, number of turned off loads, amount of generated electricity from the building, total consumption and generation can be read on the simulation screen. The city is divided into five neighborhoods and is supplied by two power plants – thermal power plant that can change its output power by 5 percent total and hydro power plant that can change its output power by 50 percent. The overview of the main level can be seen in Figure 12. The developed algorithm works in the following manner:

- If the PV system produces electricity and consumption is lower than generation then the energy surplus is stored into the energy storage to balance generation and consumption. This is done only after the thermo and hydro power plant decreased their generation by the maximum possible value;
- If the consumption is higher than generation due to a malfunction or some terrorist attack, first the thermo and hydro power plants increase their generation. If that is not enough then the extra needed energy is taken from the batteries. If in the meantime the malfunction has not been repaired and all the batteries are empty, the four controllable loads (water heater, dishwasher, washing machine and refrigerator) start to be turned off in buildings until the balance is again achieved. During this, it is taken into account that if the refrigerator is turned off, it must be turned on after 4 hours or the food inside will start to turn bad. Same is with the water heater, if it is turned off, it must be turned on after 45 minutes because tenants must not suffer from any decrease in comfort if they want to take a shower. When the fault is repaired and the generation is higher than the consumption, one by one the loads are turned on while taking into an account not to exceed the generation capacity. After particular load has been turned on, its behavior resets and starts to have original on/off time periods.

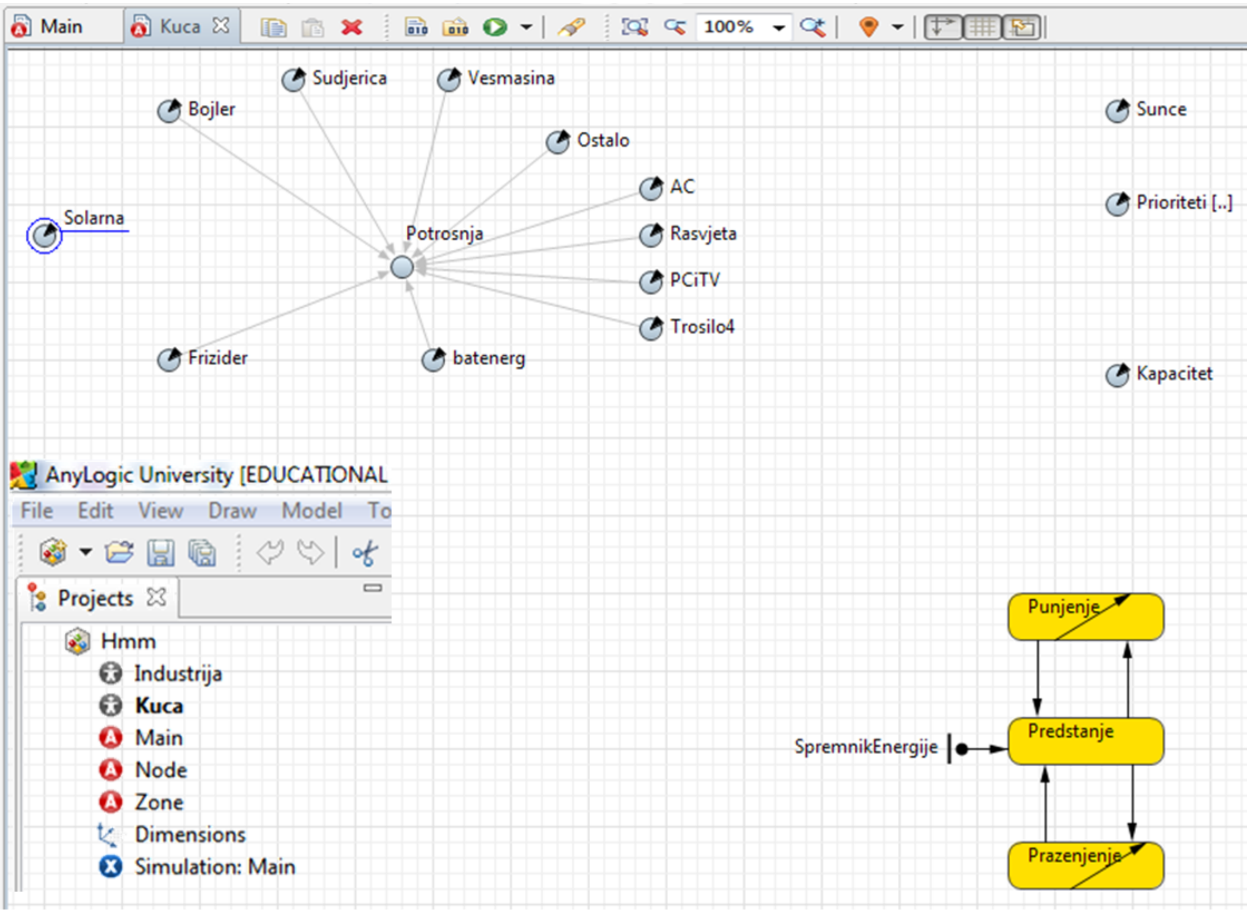

Figure 11 Overview of the building modeled as an agent in AnyLogic

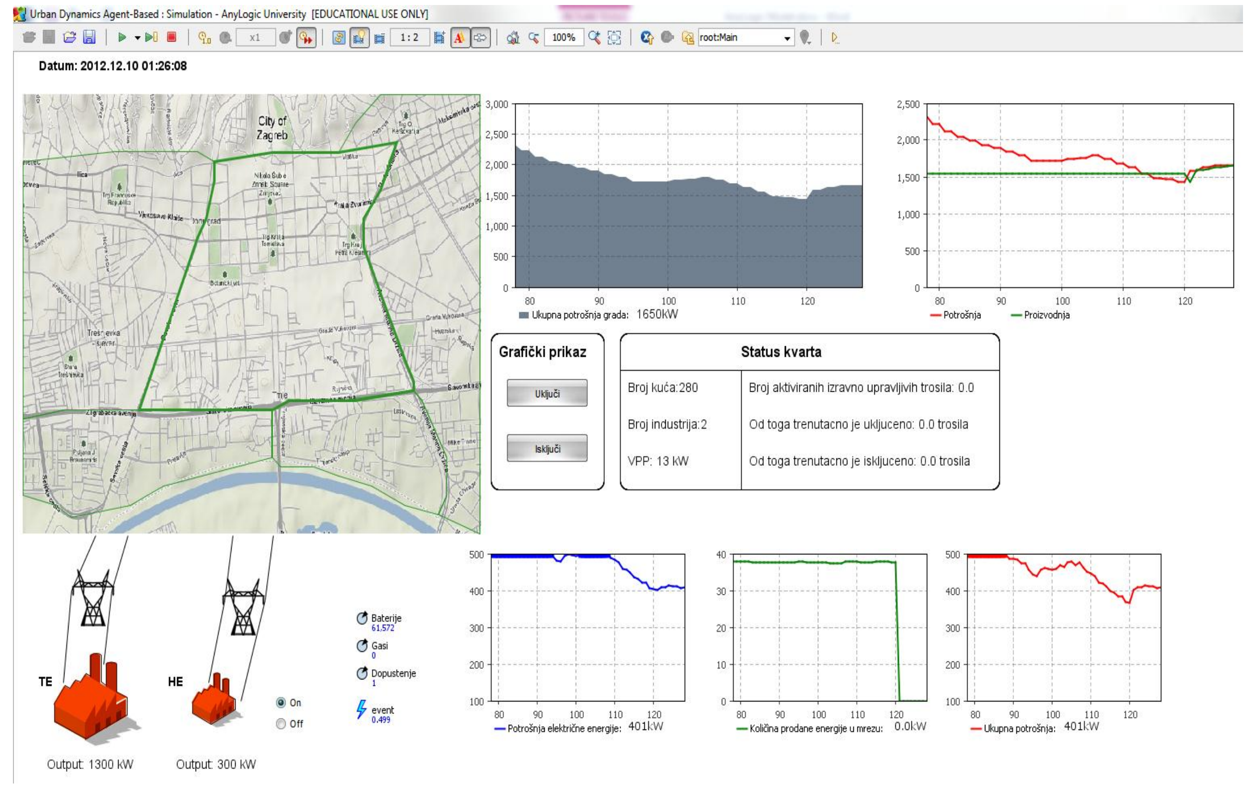

Figure 12 Overview of the main level

4.1.5.1 Simulation and Results

In the simulation, two scenarios were analyzed:

- Scenario 1: meeting the peak power using the demand response
- Scenario 2: minimizing the effect of bigger malfunction or terrorist attack also using the demand response.

Scenario 1

During some periods of the day, there is an increase in consumption and higher power generation is needed. In business as usual case, the result is that there is an imbalance between the generation and the consumption. Additional 490 kW is needed to meet the peak period and another 250 kWh of energy.

After analyzing the same event, but this time using the demand response, the generation and consumption are always balanced due to the extra energy from the battery storage.

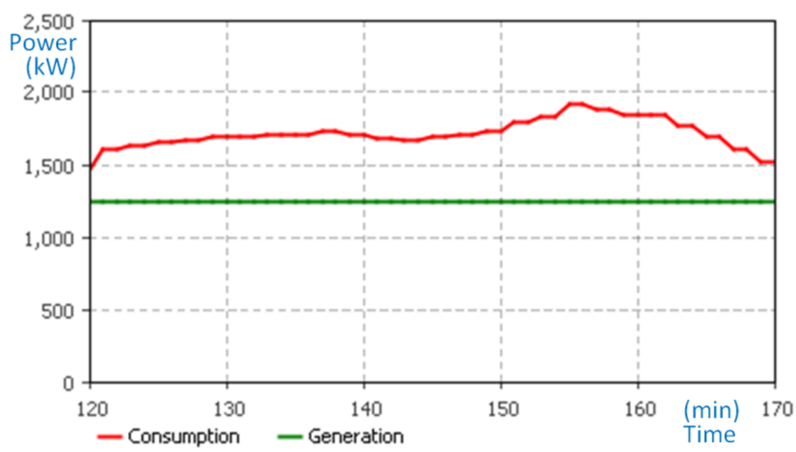

Figure 13 Generation and consumption without demand response

Scenario 2

In this scenario, the following situation was analyzed. Hydro power plant has stopped working due to a huge

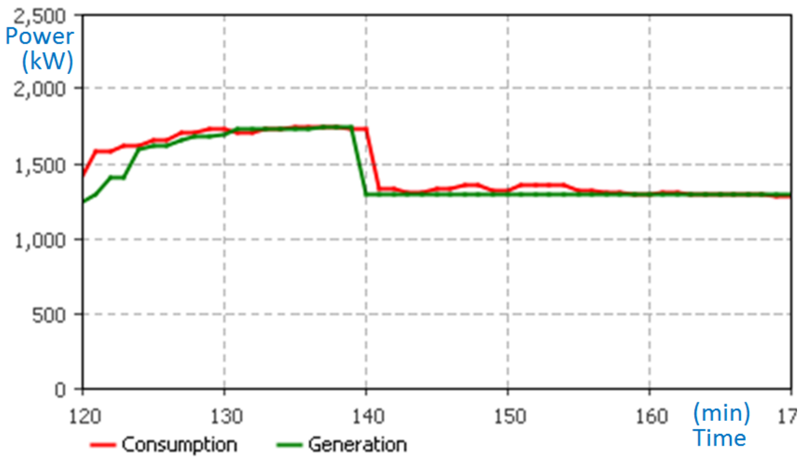

Figure 14 Generation and consumption with demand response

malfunction or a terrorist attack. It is not possible to import energy from anywhere else and all that is available is the demand response. The situation without the demand response is shown in Figure 13. The hydro power plant is turned off at time simulation 120 and as it can be seen, there is big difference between the generation and the consumption. This imbalance is not sustainable and protection measurements would probably react and start disconnecting consumers.

After analyzing the same event but this time using the demand response, the results are shown in Figure 14. After the hydro plant stopped working, the extra energy which was needed had been taken from the batteries. Batteries had enough capacity to balance out the consumption until time 139. After that only thermal power plant is generating electricity so the generation falls down to 1300 kW. Because there is no additional energy source available, controllable loads start to be turned off. It can be seen that due to that fact, the balance between generation and consumption has been successfully maintained and no consumer had to be disconnected.

4.1.5.2 Results

The developed simulation and exemplary scenarios show that Anylogic software can be used and fit in into the wider perspective of the emergency phenomena simulator.

Its main value lies in the possibility to easily model and generate different disturbances. Condition for that is the addition of a smart agent which will have the task to dynamically create and alter minor or major disturbances.

Once all the prerequisites are satisfied model developed in Anylogic can be in the center of the whole testbed simulator chain. Its main goal will be to provide the variety of possible problems and possible solution while not taking into account physical characteristics of a certain grid configuration but only considering the ideally modeled actions and responses.

As it can be seen, demand response can decrease the need for building new power plants for the peak power periods and increase the security and availability of the supply. New SCADA system that would oversee the future grid and make it resilient to any disruption and/or attack would need three modules. The purpose of the first one is to collect the current state of the grid after the disruption and to pass it to the second module which analyzes available current state and possible options, and then calculate optimal usage of the renewable energy sources, battery storages and controllable loads. The third one, based on the calculated results of the second module, will check if the solution is possible in the context of physical power flow. For the second module, it is proposed that the developed model, which is made in software

Anylogic, is used in order to propose optimal usage results to the third module. Third module would be made using PowerWorld and ANSYS software and it would check if the solution is possible in terms of physical power flows. More of this will be explained later in text.

If the proposed optimal usage is not possible, second module would propose another usage distribution and third module would analyze the possibility of the new solution. This would be carried out until the best possible solution is found. Naturally, on the basis of the developed module and acquired knowledge current simulation would be modified to fit into the whole scheme.

4.2 Exploratory testing and use of grid monitoring equipment

Power quality has become a very important feature for consumers in the market. European Directive calls for it to be considered a product of electricity like any other, and that electricity producers are responsible for the quality of its products. The resulting changes in the electricity sector increased attention given to the power quality in terms of continuity of supply and voltage quality, and cost of connecting customers to the network. Since there is a significant proportion of devices based on power electronics in the distribution systems, whose nonlinear current causes voltage distortion and propagation of faults in the system, the need for understanding of that phenomena is becoming increasingly important because consequences of poor power quality (higher harmonics, voltage dips etc.) can no longer be neglected. With the development of technology, devices are not only becoming more and more sensitive to the quality of electric energy, but there are also becoming the main causes of voltage and current distortion in the grid.

Many reports have shown that most of the problems related to the quality of the electricity come from the consumers. It is clear that the measurement and monitoring of power quality is necessary to ensure optimal performance of the power system and the effective controlling of the distribution network. Furthermore, monitoring of the power quality, information about the power flow and demand are helping to identify the causes of the problems in the grid. [9]

The introduction of different standards that deal with issues of power quality (the European standard EN 50160, International Standard IEC 61000-4-30) has led to simple qualitative analysis of results. The power quality parameters defined with EN 50 160 can be classified into three groups. In the first group are power quality parameters with defined limit values (frequency, voltage variations, asymmetry, higher harmonics of the signal voltage, flickers). In the second group are the parameters with indicative values (rapid voltage changes, voltage dips, short and long interruptions) and in the third group are parameters without a defined value (temporary and transient over-voltages, inter-harmonics). The collected data can be used to determine power quality in distribution, for determining the cause of possible interference and for planning.

The controllable power semiconductors are significantly used in equipment for connection of renewable energy sources to the power system. Such systems have a significant impact on the normal operation of a distribution network, causing voltage distortion. With the development of distributed production, such as wind turbines, fuel cells and small hydro, electricity produced is not so „clean“ when speaking in terms of power quality as it is usual for systems without large penetration of such sources. The increasing penetration of renewable energy sources, which means a larger share of distributed, time-dependent and electronically controlled electricity generation and a growing proportion of consumers who contain power electronic devices, will lead to growing problems with power quality.

During the development of renewable energy sources several studies on the behavior of renewable energy sources and their impact on power system were done. It was found that proper control of renewable energy sources can have positive impacts. The power quality, the voltage safety and efficiency of supply can be improved.

4.2.1 PQube- Energy and power quality monitor/analyzer

The central point of currently installed system for Power Quality monitoring and analyzing on the "Department of Energy and Power Systems", FER is the PQube device. PQube is an instrument for monitoring electric power systems. It is conceived as a power disturbance monitor, a power meter, a power recorder, and a digital camera in one-unit device and combining the best features of all. On the market exist several types of these devices for power quality and energy monitoring (the PowerSight PS4500, the NI Power Quality Analyzer) with many features. PQube Monitor is selected in „*Emergent phenomena testbed simulator for improving SCADA performance in power system security management*" project for power quality measurements because of the extra features and various ways of communication. It can monitor single-phase or three phase circuits, at up to 690 VAC phase to phase (400 VAC phase-to-earth), at 50 Hz, 60 Hz, and 400 Hz. General-purpose digital input is also included, which is controllable with switch contacts or a logic signal, and a relay contact input, which opens for at least 3 seconds whenever PQube detects an event.

It is compatible with several optional modules that provide additional options. The selection of optional modules is dependent on the measurements that are needed, on the power mode type, on the way of communication with PQube and exigency of measuring the temperature and humidity. The location of connections to the distribution grid can be seen on the figure below (Figure 15).

Currently installed configuration on „Department of energy and power systems" consists of:

- PQube- base module
- PS1- power supply module, necessary for 230 Vac power supply
- XCT4- current module for current transformers with 1 Amp current secondary
- ETH1- Ethernet module

ETH1 optional module is providing communication of PQube Monitor with external devices (personal or portable computers). The ability for real time communication with PQube can be realized in four ways:

- e-mail
- FTP Server
- Web Server
- Modbus TCP/IP

The communication with PQube in project *„Emergent phenomena testbed simulator for improving SCADA performance in power system security management”* is established over Web Server, access to the measured data is done through the website with a fixed IP address http://161.53.66.233.

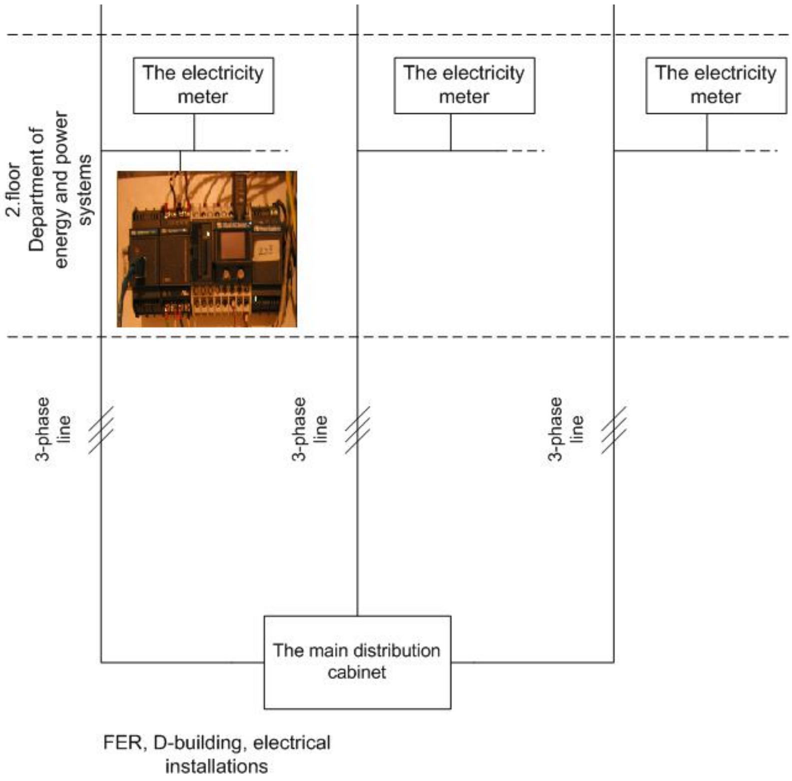

Figure 15 FER, D-building, location of PQube connection to the grid

The home webpage consists of the following tabs for reading the results and controlling the PQube:

- Status tab – basics information about PQube device are shown, such as IP address, power configuration, nominal voltage and frequency.
- Meters tab – in this section can be seen all measured data in real time, in the end are shown internal multimeter readings, PQube records measurements one time per second.
- Events tab – this section is important for analyzing the power quality and will be explained below.
- Trends/Statistics tab – all changes and voltage movements for each day are shown.
- Commands – settings of PQube device (the energy counters reset, editing of Setup.ini file, the peak measurements reset, PQube reset) are included.
- Network tab – providing Network information and Network Statistics, TCP Connections information.

Tab “Events“ provides an overview of all the events by months. For each event date, time, type, amount, duration and list of files where the information is stored about the event, are recorded in a variety of formats (.csv, .gif, .xml, .pqd). The stored data of each event contains specific information for the particular event. For example, a voltage drop includes the exact start of the event, duration of event and size of event. Most recorded events include waveform start and end, as well as RMS values for the start and the end of the event. If more events appear very shortly one after another (at intervals around 30 seconds), PQube will record all events, but will store the waveform and RMS values for only the first event. It is important to note that while PQube works an important event almost cannot be missed (can be missed only if there are more than 4 events of any kind at intervals shorter than 4 seconds). For the duration of event, PQube always takes 256 samples per cycle.

The following channels are available for connection and data acquisition:

- L – N Voltage (Line to Neutral)
- L – L Voltage (Line to Line)
- N – E Voltage (Neutral to Earthing)
- Current
- Earth Current
- Analog Channels
- Frequency (RMS graphs only)
- Digital Input

Communication and transferring of the measurements collected with PQube is also possible with FTP Server. This simple FTP is used for transferring files between computers (in our case portable computers bought from the project budget) that are connected in a network. FTP Server is currently active and running and any FTP client can be used.

The Modbus TCP/IP is an industry-standard protocol which can be used to transfer meter readings to a Modbus client program. The Modbus OPC Server is used for reading the PQube Modbus registers which contain PQube measurements. The Modbus registers in the PQube are offsets from a base address (the base address is set in Setup.ini file). For example, L1 to earth RMS Voltage is represented by 0-1 offset.

4.2.2 "Smart" monitoring of consumption

The "smart" monitoring of consumption is currently being developed on the Faculty of Electrical Engineering and Computing (Figure 16). For consumption measurement of FER are currently used two SENTRON 3200 multimeters that are embedded in the main low voltage distribution, conductive fields R03 and R05. The multimeters are represented in figure with MT P1 symbols. The control of two multimeters is achieved with PLC (Programmable Logic Controller) and current data is displayed on the 12" TOUCHscreen.

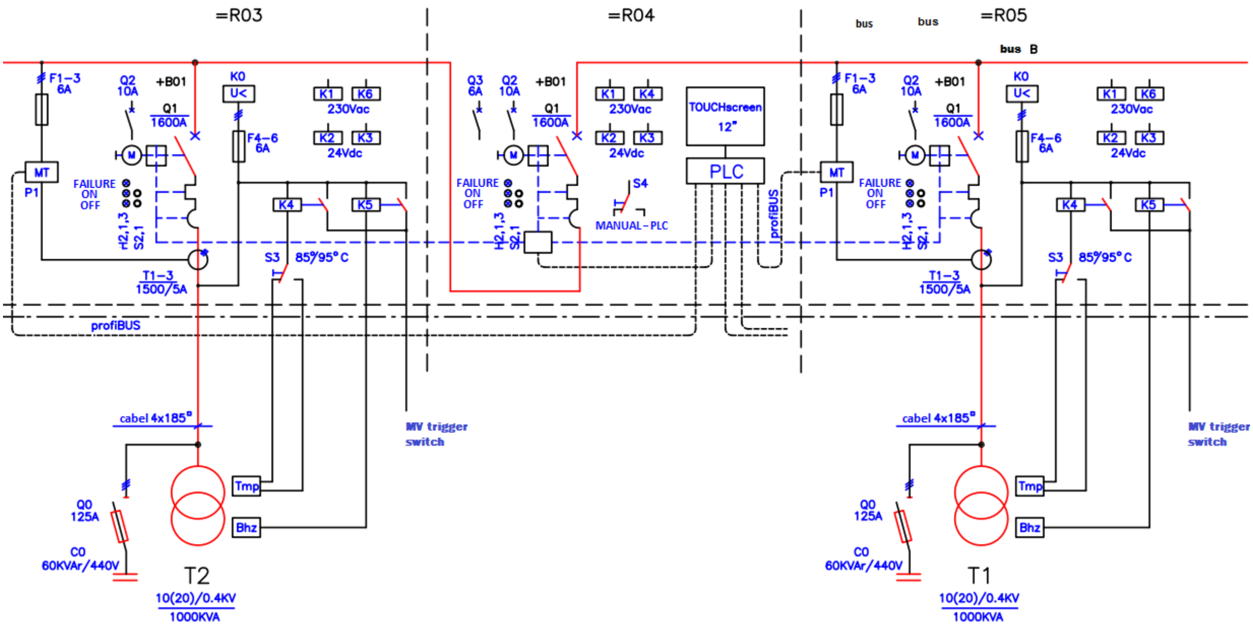

Figure 16 The 'smart' consumption measurement at FER

The TOUCHscreen display is shown on figure below (Figure 17). The multimeters are equipped with an Ethernet module and multimeter data for active and reactive power are read with the Modbus OPC Server. Currently configuration is set to store data about active and reactive power in 15 minute intervals.

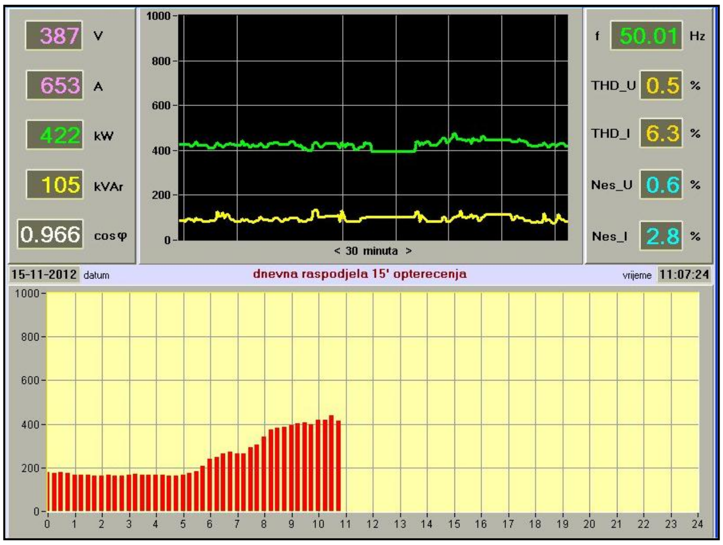

Figure 17 The display of FER – power meter

Information about voltage and current, about THD (Total Harmonic Distortion) of voltage and current, asymmetry of voltage and current and power factor are currently not stored in order to save the memory on the server. In case of need, which will come with developing of the system, the data about mentioned parameters will be also stored.

The lack of current configuration is in the fact that information about consumption on each line is unknown, only information about total consumption is available. The smart grid of the future should include detailed information about consumption on each line for better information about failures in the grid and for better response to them. For intelligent monitoring of consumption the following equipment is installed:

- CX8090-1011 – Embedded PC for Ethernet with K-bus interface,
- KL3043-0333 – 3-phase power measurement terminal, max. 500V AC 3 transformers with 333 mV AC,
- KL9020 – Terminal bus extension, end terminal at KL9050,
- KL9050 – Terminal bus extension, coupler terminal from KL9020 or KL9050,
- KL9010 – Bus end terminal ,
- ADAPTER AC CLAMP ON FOR DMM.

The following split – core current transformers are also installed:

- CTSA010-5A/1.67mA ,
- CTSA010-50A/16.67mA,
- CTSA016-100A/33.33mA,
- CTSA024-200A/66.67mA,
- CTSA035-300A/100mA.

The future smart monitoring of consumption is included of the split-core current transformers that will be installed on all active cable drains of the LV grid and will be connected to the power – measurement KL3043 terminals that are an integral part of the PAC configuration. The proposed system is shown in the Figure 17.

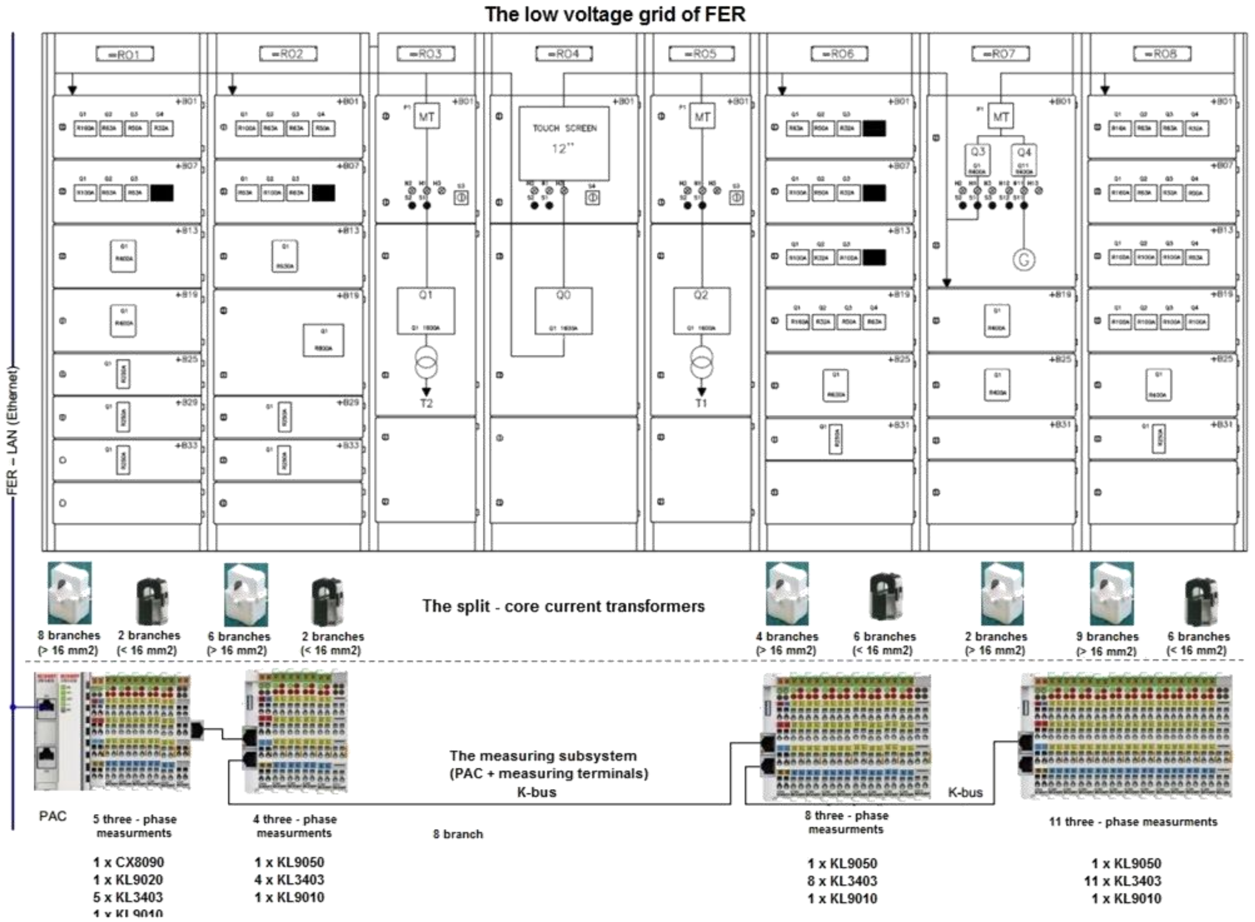

Figure 18 The proposed consumption management system

4.2.3 Testing results

The first part of this chapter was dedicated to the power quality. Smart grids, electrical grids of the future without advanced power quality monitoring, are incomplete and future research of them definitely has to include power quality domain. Taking into account this fact it is understandable why the team gathered around the „*Emergent phenomena testbed simulator for improving SCADA performance in power system security management*" project devotes attention to the power quality issue.

Accepting the unpredictability of production of renewable energy sources power quality monitoring is imposed as a something necessary, as a real need. Regarding the fact that the power quality monitoring system is being developed in the "Department of energy and power systems", FER. PQube Monitor/Analyzer is currently installed and is measuring three-phase consumption and power quality parameters. Photovoltaic plant, which has recently been installed on the roof of D-building of Faculty of Electrical Engineering and Computing will definitely have impact on the power quality. One role of the mentioned photovoltaic plant in the future will be studying of the impact of renewable energy sources on the power quality.

In the introduction of this chapter is has been mentioned that loads containing power electronic devices have a significant impact on the power quality. "Department of energy and power systems" is suitable for the monitoring of those impacts because of the large share of the devices with such characteristics. For the analysis of the impact of individual devices it is required to have additional equipment than the currently installed PQube monitoring system.

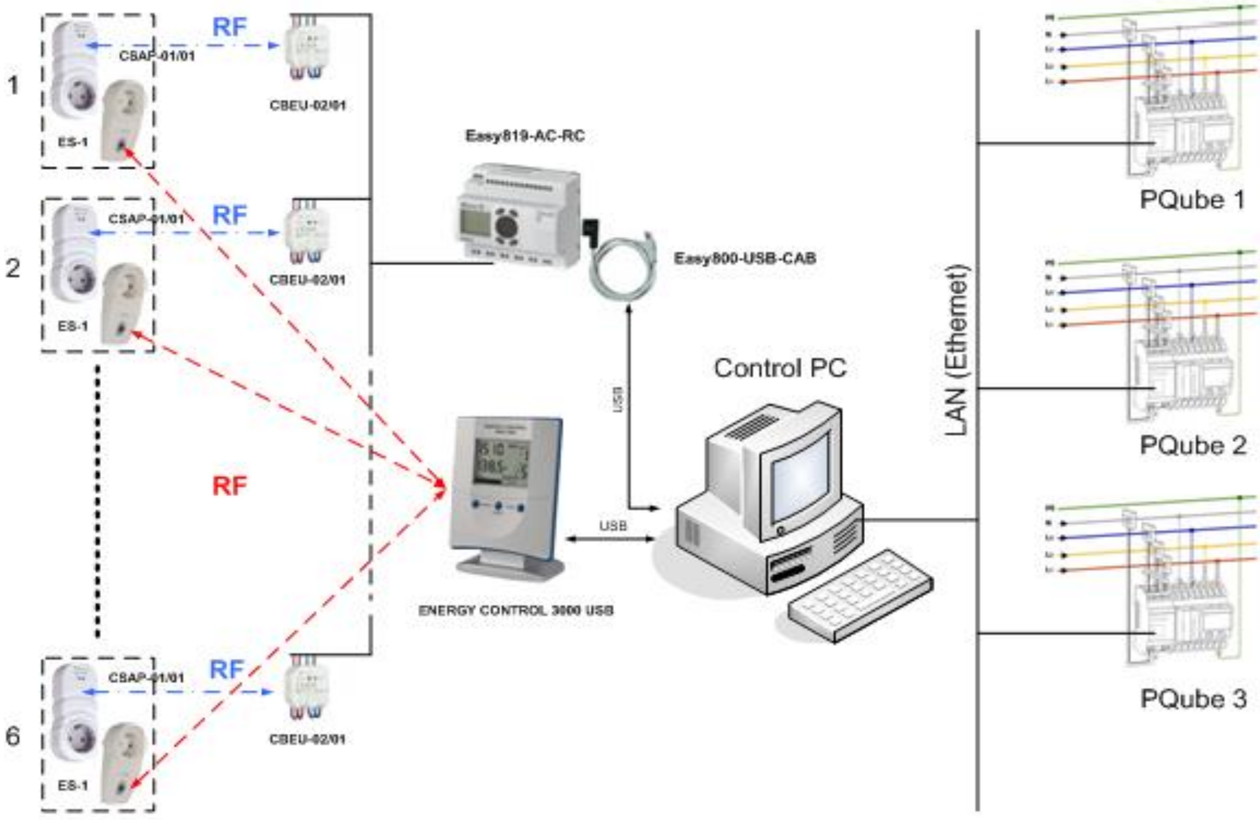

Figure 19 Proposed scheme of future system responsible for the monitoring of power quality [10]

Considering mentioned facts in the paragraphs above the proposed scheme of future system responsible for the monitoring of power quality is shown in Figure 19.

The future system for monitoring the power quality will consist of three fixed and six moveable measurement points. The fixed measurement points include installation of another two PQubes in a control cabinet at the main supply installations in the „Department of energy and power systems“ and will serve for three-phase measuring of consumption and the power quality. The moveable measurement points are planned for connecting specific single phase loads to a standard earthed socket.

Furthermore additional data about energy quality with distributed renewable energy sources will be gathered from the hybrid system located on the top of the FER building C. All the data will be relayed to one central data gathering point. The server will manage the communication between all the measurement equipment and energy sources. The data gathered will be used as an input for the design of other modules in the testbed platform.

The second part of this chapter was dedicated to the smart monitoring of consumption. The “smart” grid, electrical grid of the future, will be incomplete without progress in area of the monitoring of electricity consumption.

The more sophisticated monitoring of consumption is important part in that area of interest. The conventional electricity meter, which is measuring the amount of electric energy consumed, is not enough for the future “smart grid”, the necessity for sophisticated monitoring of consumption is created and the concept of smart meter devices is introduced. The “smart” monitoring of consumption on FER is transitional stage between electricity meter and smart meter concept.

With the enhanced monitoring of consumption additional information of the grid will be provided, earlier responses to the failure will be enabled and the system will be more safe and reliable.

4.3 Integration of distributed power generation in power system simulations

One of the increasingly significant challenging part of the power system are distributed power sources. They are characterized with intermittent relatively hard to predict power availability. This is even more important because a huge number of distributed generation power sources is expected in the future (this is already happening in some power systems like in Germany).

In order to acquire realistic data and to have distributed sources connected in the laboratory network three systems were designed and built. First is the system for solar characterization with purpose of better measurement of solar radiation and different photovoltaic technology in operation. Then complete photovoltaic system was built in order to measure grid connected operation in real conditions. Finally, hybrid system was built in order to measure conditions when wind power, solar power and energy storage are working together.

Description for these three systems follows with some initial results.

4.3.1 Solar power characterization (RE3)

Photovoltaic panels produce electricity, depending on their characteristics and solar radiation. Variability of solar radiation intensity (and spectrum) and variations in current-voltage characteristics of photovoltaic panels (temperature and technologies) affect the large uncertainty of predictions for expected production of electricity. For more realistic assessment of electricity generation from photovoltaic panels, it is necessary to make better assessment of the behavior of photovoltaic panels in different conditions and predict the intensity of solar radiation better.

Typically, photovoltaic panels are installed at a fixed tilt for maximum annual electricity production or continuously positioned for maximum utilization of solar radiation (one-axis and two-axis tracking the sun). In some special applications, such as on the top of buildings, photovoltaic panels are positioned according to specified criteria. For empirical monitoring of the behavior of different photovoltaic panels in all common types of installations it is necessary to make the same number of test installations. Taking into account that there are at least five photovoltaic panels technology and many more variations, now widely available, the number of necessary installation becomes unfeasible for an empirical test. Therefore, this project is designed so that with selected photovoltaic panels of different technologies (poly, mono and amorphous silicon, and two types of thin film without silicon) placed in the two positions with the measurements system that covers critical set of possible positions (with necessary analytical processing).

Already designed and installed pilot unit with three technologies (Figure 20) and project ready for installation are aimed to establish empirically the behavior of different photovoltaic panels at FER (Zagreb) and four additional locations in Croatia (i.e., Osijek, Karlovac, Rijeka and Split).

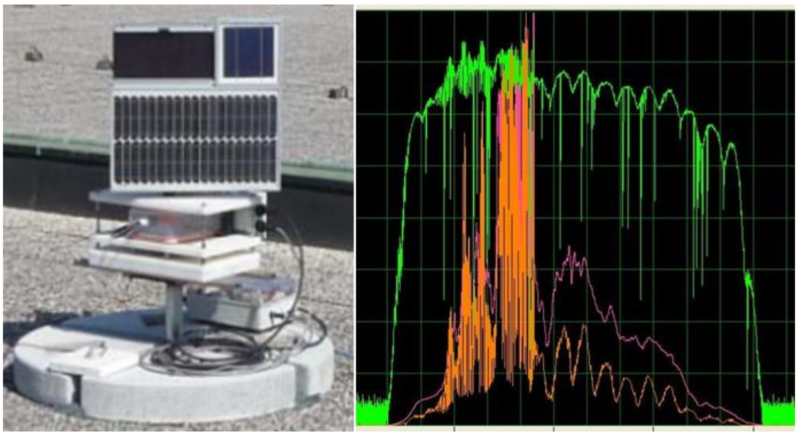

Figure 20 Solar power characterization system (RE3, pilot unit)

For both positions current-voltage characteristics of the panel, temperature and solar irradiation on horizontal surfaces are measured. In this way very detailed results of the behavior of photovoltaic panels in two most important positions at different actual solar irradiation and different weather conditions (temperature) are obtained. Depending on the specific settings for each position the measured values range at intervals of 5 to 15 minutes. The benefit of these measurements can be seen from the fact that common basis for these calculations of the solar irradiation is from the measurements for a broad region at a daily resolution, expressed as an average day for each month of the year. These figures are relatively coarse and relate only to the horizontal surface. The production forecast of photovoltaic panels installed at each position is done analytically, by applying correlation terms where horizontal values are converted to values of solar radiation reaching the surface of the panel position. Correlation models assume an average share of direct and diffuse components in a certain area and can more or less correspond to a specific location.

Expected outcomes of annual measurements from this system could be used for different purposes. First, the results obtained would help improving the correlation and verification procedures. Then, the results obtained would demonstrate the actual performance of certain photovoltaic technology depending on the actual conditions (solar irradiation, temperature, etc.).

Finally, this would empirically show the advantage or lack of it for the application of advanced solutions that specifically position photovoltaic panels toward the sun direction. It would also improve prediction of best fixed position of photovoltaic panels for maximizing the annual or seasonal electricity production.

4.3.2 Integration of solar power in power system (RE1)

RE1 or PV1kW_D stands for the solar system located on the top of the D building at Faculty of Electrical Engineering and Computing.

In the past few years, price of solar systems has been constantly decreasing. Besides the decrease in price, government of almost every country stimulates building solar systems of different sizes. As an effect, on many house roofs all over the globe small scale solar systems are built. Consumers who produce electricity by themselves are called prosumers. Installing the photovoltaic system on the top of the D building will provide a real measurement which can be used for the simulation of the prosumers' behavior. Furthermore, to have such a system installed is useful for better understanding of the system behavior.

First the software predictions and calculations were made using the HOMER software. After the simulation of the PV system in HOMER all necessary hardware was bought (PV modules, inverter, communication and monitoring system, protection). Momentarily PV system is installed and ready to use.

This system has important place in the studding of the smart grid and also takes an important role in the scheme of the proposed testbed in this work.

4.3.2.1 System components

PV module SV-60

Using the meteorological data for city of Zagreb as an input for the HOMER software helped reaching the decision of choosing the output power of the PV system. For the installation 5 SV-60 PV modules with 200 W peak power per unit were chosen. SV-60 PV modules were constructed in Solvis d.o.o. in Croatia. Electrical data for SV-60 module are displayed in Table 4, mechanical in Table 3 and thermal in

Table 4 Electrical data for SV-60 module

Peak power	P_{MPP}[W]	200
Short circuit current	I_{SC}[A]	7.55
Open circuit voltage	U_{OC} [V]	36.2
Rated current	I_{MPP}[A]	7.03
Rated voltage	U_{MPP}[V]	28.4
Current and voltage tolerance	+-3%	

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The data from in tables were measured in the standard test conditions (1000 W/m, 25°C, AM 1.5). SV-60 module satisfies IEC 61215 and IEC 61730 standards. PV modules were installed following the producer's recommendations. Producer suggests also to check corrosion protection and mechanical and electrical interconnection once per year.

Table 2 Thermal characteristic and work conditions for SV-60

Nominal operating cell temperature	[°C]	48,2±2
Temperature coefficient of peak power	[%K]	-0,41
Temp. coefficient of short circuit current	[%K]	0,05
Temp. coefficient of open circuit voltage	[%K]	-0,29
Temperature range [°C]	From -40 to 85	
Maximum system voltage [V]	1000	
Maximum surface load capacity	Tested up to 5400 Pa (Snow load test)	
Resistance against hail	Max. diameter of 25 mm with impact speed of 23 m/s	

Table 3 Mechanical data for SV-60 module

Dimension (H x W x D)	1663 x 998 x 35-+2 [mm]
Weight [kg]	21,5

Solar cells	60 cells, polycrystalline Si, 156 x 156 mm
Cell encapsulation	Ethylene vinyl acetate (EVA)
Front	Tempered solar glass, 4 mm
Back	Composite polyester film
Frame	Anodized aluminum frame with twin-wall profile and drainage holes
Junction box	Tyco SOLARLOK with 3 bypass diodes, IP65
Cable and connectors	Solar cable 4 mm2, length 1000 mm, Tyco SOLARLOK compatible

Table 4 Electrical data for SV-60 module

Peak power	P_{MPP}[W]	200
Short circuit current	I_{SC}[A]	7.55
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Rated current	I_{MPP}[A]	7.03
Rated voltage	U_{MPP}[V]	28.4
Current and voltage tolerance	+-3%	

The SMA Sunny Boy 1200 inverter

Modern inverters are characterized by the high efficiency and by the various additional features. Since the PV modules have summed peak output power of 1000 W, inverter's rated power must be above 1000 W. That was the main condition which had to be fulfilled. SMA Sunny Boy 1200 inverter with around 1200 W rated input power was chosen.

Input data (DC side) for SMA Sunny Boy 1200 are displayed in the Table 5 and output data (AC side) is in Table 6.

Table 5 Input data (DC side) for SMA Sunny Boy 1200

Maximum DC power	1320 W
Maximum DC voltage	400 V
MPP voltage range	100 V – 320 V / 120 V
Rated input voltage	120 V
Min. input voltage	100 V
Initial input voltage	120 V
Max. input current	12.6 A
Internal consumption	< 4 W

Table 6 Output data (AC side) for SMA Sunny Boy 1200

Rated AC power for 230 V, 50 Hz	1200 W
Max. apparent AC power	1200 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V – 265 V
AC power frequency / range	50 Hz, 60 Hz / -4.5 Hz ... +4.5 Hz
Rated power frequency / rated power voltage	50 Hz / 230 V
Max. output current	6.1 A
Power factor at rated power	1
Feed-in phases / connection phases	1/1
Max. efficiency / European efficiency	92.1 % / 90.9 %

Figure 21 is showing dependency between efficiency and output power.

Inverter is connected in the PV system between PV modules and distribution network as it is shown on the figure below. The inverter was installed following the producers recommendations.

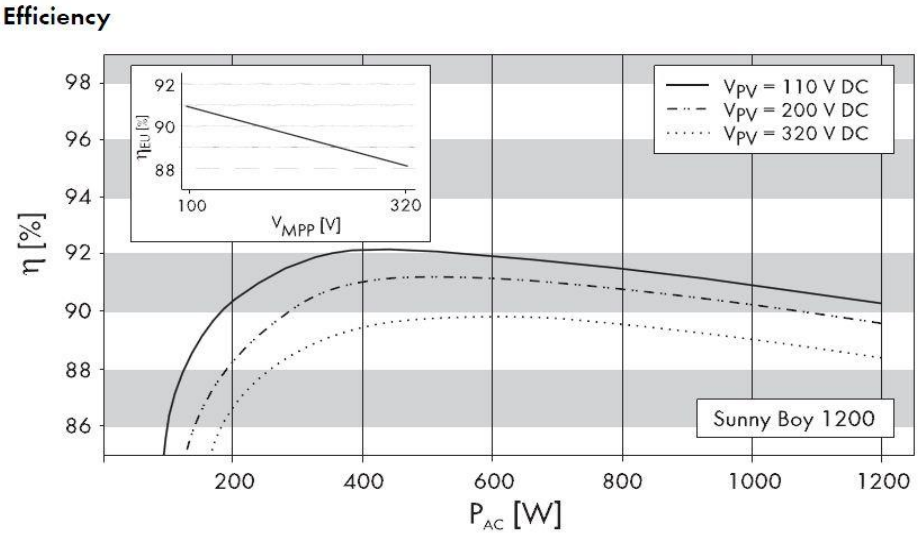


Figure 21 Dependence between efficiency and output power

Sunny WebBOX

As a high-performance communication hub, Sunny WebBOX represent central interface for communication of the PV system. Sunny WebBOX collects all the data from PV modules and also allows controlling system monitoring, remote diagnosis and visualization of the data. Connection between Sunny WebBOX and personal computer or portable device can be provided through global internet or GSM or locally by 10/100 Mbit Ethernet. RS485 communication bus is used for connection between Sunny Boy inverter and Sunny WebBOX. A constraint for communication range of RS485 is 1200 m and for Ethernet is 100 m. .

Data measured by the Sunny WebBOX can be treated by Flashview software or by Sunny Web Portal. Sunny WebBOX is placed and connected to the Sunny Boy 1200 inverter by the RS485 and is also connected to the server by the Ethernet.

Connection electricity boxes

Two types of boxes are needed: protective and measuring. Protective equipment has function to protect PV modules and inverter from short circuit current, overvoltage or from overload etc. Measuring equipment is connected to the LV grid to measure power which is produced from PV system.

4.3.2.2 Integrated system overview

All the mentioned components are installed and ready to use. PV system will be started when the server component of the project will be physically established. Test runs of the PV system could be done before implementation of the server component. This system can be used to study PV effects on the grid or to study PV power production but on the small scale. PV system which will be an important component in the smart grid testbed is shown on the figure below (Figure 22).

Figure 22 Photovoltaic system PV1kW_D connected to the grid (RE1)

4.3.3 Hybrid distributed generation system (RE2)

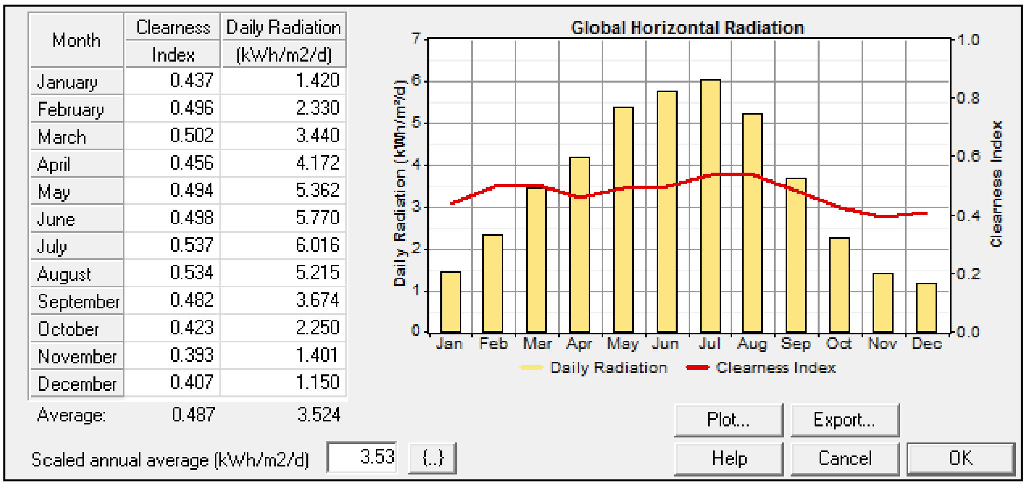
The hybrid system uses both solar and wind energy to make electricity. This is not necessary but these two (i.e., wind and photovoltaic) complement each other well, especially if it is planned to build an independent system. In future it is expected that many of these small scale low voltage hybrid systems will be connected to the grid. This is naturally changing the way the grid works and transits it further towards the idea of the “smart grid”.

Therefore it is useful to have such a system installed to monitor its work in order to understand it better. As an important component of the whole project design, a installation of a small hybrid system on the top of the FER building C was initialized. In order to have a complete figure of all the components that are to be included in the testbed simulator real data from this hybrid system (along with power quality measurement, different software simulations) is very valuable.

First the software predictions and calculations were made using the HOMER software. After establishing certain scenarios which are most likely to happen the search for all the necessary hardware had begun. A couple of different offers were analyzed and a decision was made to buy certain hardware (PV, WT, inverter, controller, data communicator, battery bank) which will be listed later.

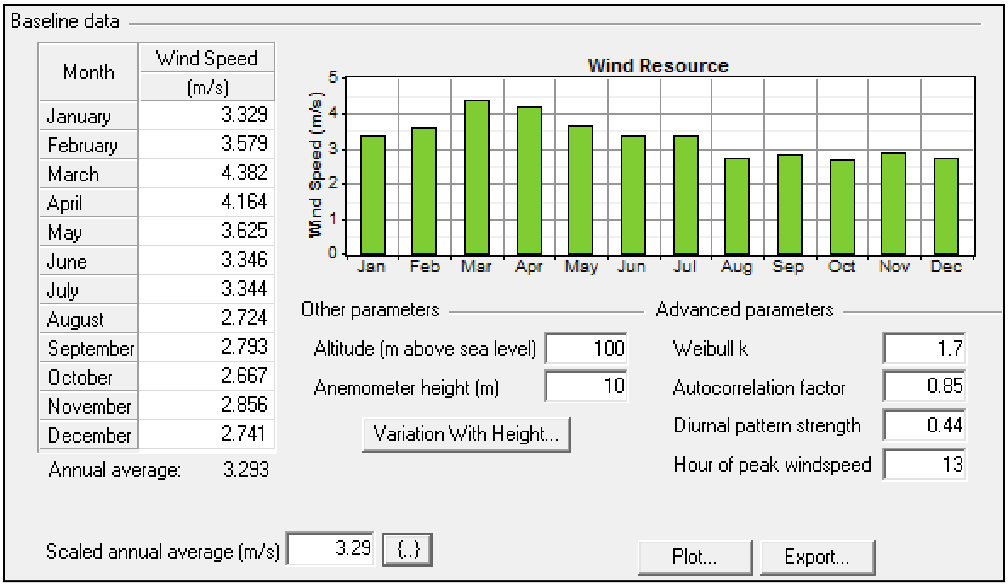
Momentarily due to some specific design problems of the wind aggregate pole and lack of space on the site that was predicted to be used for this hybrid system, the system has still not been installed.

The software simulation using HOMER was conducted with local wind and sun resources as depicted in figures below:



Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.437	1.420
February	0.496	2.330
March	0.502	3.440
April	0.456	4.172
May	0.494	5.362
June	0.498	5.770
July	0.537	6.016
August	0.534	5.215
September	0.482	3.674
October	0.423	2.250
November	0.393	1.401
December	0.407	1.150
Average:	0.487	3.524

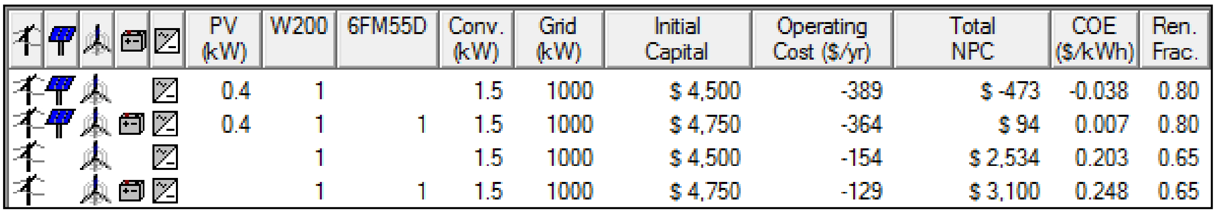
Figure 23 Solar resource



Month	Wind Speed (m/s)
January	3.329
February	3.579
March	4.382
April	4.164
May	3.625
June	3.346
July	3.344
August	2.724
September	2.793
October	2.667
November	2.856
December	2.741
Annual average:	3.293

Figure 24 Wind resource

Based on the results the optimal solution which had all the components (a battery, PV, wind) was chosen:



	PV (kW)	W200	6FM55D	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
	0.4	1		1.5	1000	$ 4,500	-389	$ -473	-0.038	0.80
	0.4	1	1	1.5	1000	$ 4,750	-364	$ 94	0.007	0.80
		1		1.5	1000	$ 4,500	-154	$ 2,534	0.203	0.65
		1	1	1.5	1000	$ 4,750	-129	$ 3,100	0.248	0.65

Figure 25 Possible solutions and system configuration

HOMER gives the predicted energy productions, battery states throughout the year etc. but that is not of great importance once the components were chosen and bought.

The software ANSYS was used to further determine the optimal position of the wind turbine depending on the available wind. ANSYS can give distributions and simulate the wind flow based on the input data of the developed model. Since the predefined place for this hybrid system is the roof of the FER building C model was used to check if there is acceptable placing available on the rooftop. The geometry of building C is simple but nevertheless the wind varies significantly.

The results are depicted in the following Figure 26.

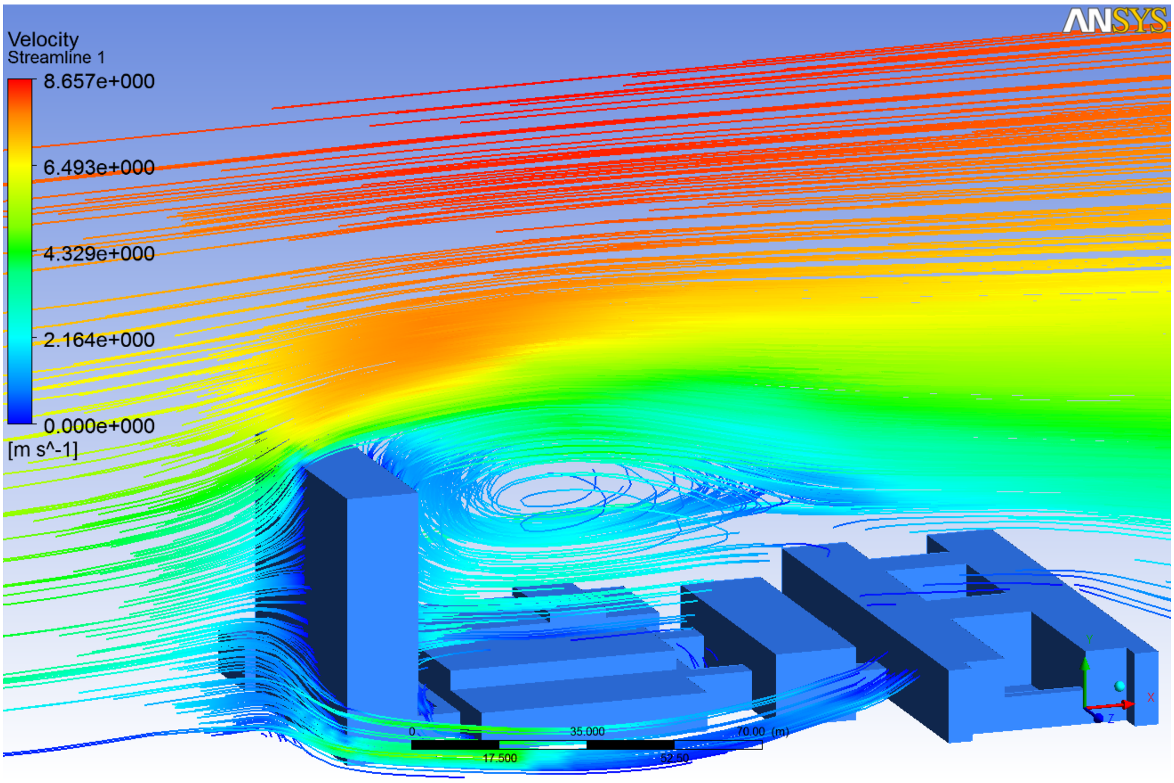


Figure 26 Wind passage over the C building (h=55m) in north-south direction

The position was chosen based on two most frequent wind directions, north-west and north.

Regarding the best position it is concluded to be in the center of the building when looking along the shorter side oriented north-south. Furthermore the position along the longer side is 33 meters from the west edge of the building and 22 meters from the east edge.

The rooftop is already used for various purposes and most of its available surface is already occupied with other ongoing measurements and projects.

Therefore the planned positioning for the RE2 system will be in the north-west angle (illustrated in Figure 2).

The system will be installed like shown in the scheme on Figure 27. In the figure it was assumed that all the connection can be made directly without the need to install some current sensor for example. Also for efficient control certain switches will be needed.

Basic idea of the control of this simple hybrid system is to charge the batteries depending of their SOC (State of Charge) and the batteries would power the DC load. Production of the wind aggregate and PV array is measured and the data is stored. Also the possibility to transfer suffice of power produced to the grid is planned. This would be the case when the batteries are fully charged and the production is high.

PV array is connected to the MPPT (Maximum Power Point Tracker) regulator. The battery is also connected to the regulator over the DC bus alongside with the MATE controller. In this case the controller decides based on the production rates and SOC level of battery whether to charge the batteries or to relay the power to the grid. The same case is with wind aggregate. Wind aggregate is connected to its own hybrid controller. This controller is also connected through the DC bus with the batteries. Finally to enable the transfer of power to the grid and from the grid in case the hybrid production is not enough to power the load inverter is connected to the DC bus and on the other side to the AC grid.

In order to efficiently manage the control more equipment is needed such as different voltage and current measurements (Hall sensors for example and switches and simple control units. As it was already stated the goal of the design of this small hybrid system is to constantly power the load from the DC bus and in the same time have the ability to transfer the power to the AC grid through the inverter. At the same time all the measurements are logged and all the production rates and desired variables are organized and stored on the central SCADA system run on the server.

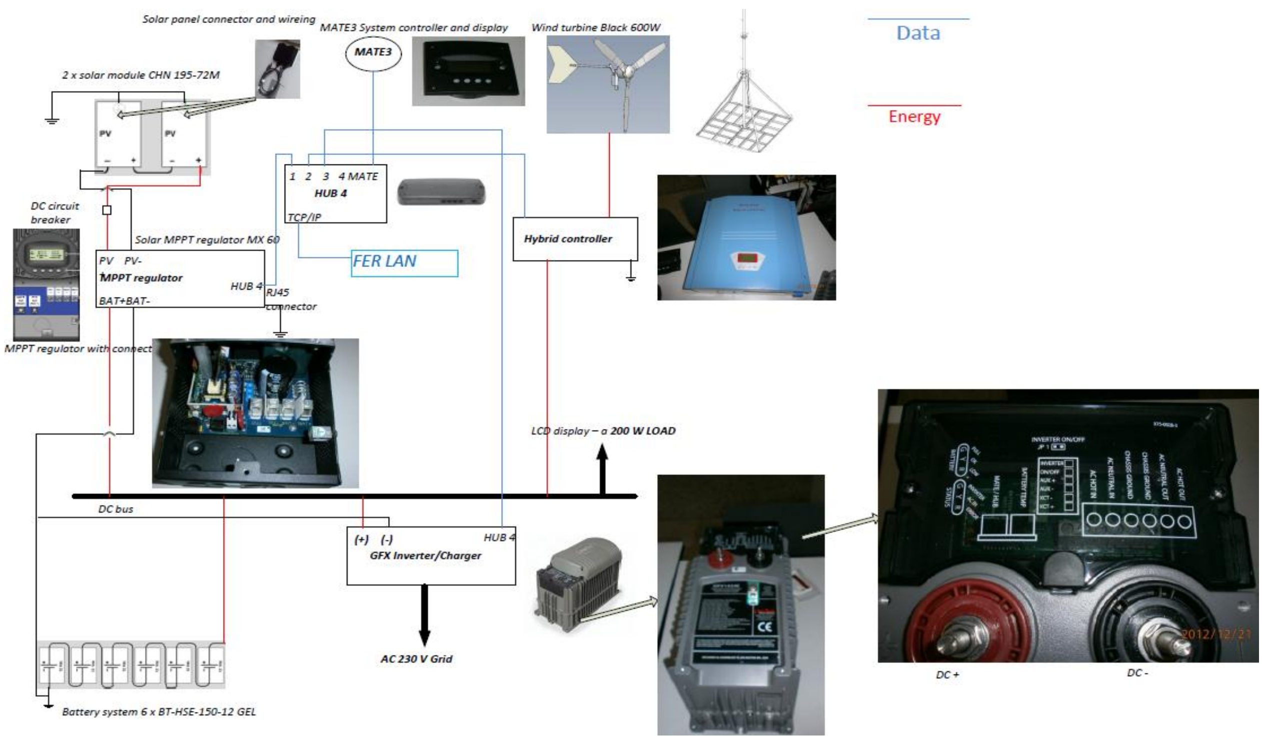


Figure 27 Basic wiring scheme of the HybridC system (RE2)

4.4 Further R&D needs

Ambition of this project is very broad and approach taken for the realization has so many elements and huge complexity that three years were certainly not enough to bring laboratory to completion(i.e., fully functional). Therefore it will be necessary to continue work in order to make the best use of this multidisciplinary platform (i.e., power system, computing and communication).

Primarly further work will be focused on the full competion (i.e., testing of designed features) and verification and validation for all planned functionality.

After functionality is assured the results from the physical systems operation and modeling will determine the use of the established platform. This will then depending on the results define some specific needs and potentials for further research and development. Need for the certain changes to the software and hardware is certainly not excluded and that will also require certain resources.

Further research and development plans are also to add new features with more details and special attention to the following:

- Security of IT systems in the framework of smart grid,
- Risk and reliability assessment with inclusion of current and expected conditions in the power systems;
- Smart energy city planning with optimization for the efficiency, reliability and security;
- Power system optimization regarding distributed (renewable) energy sources integration and sustainability;
- Scenario cases which will demonstrate usability and relevance to the real power system conditions and operation.

Further research and development needs are directly related to the necessity of validation and verification to the planned use of this platform. This means that the dynamic of the realization of these future plans will depend on the availability of resources. This is related to the manpower (i.e., support for PhD research) and external commercial support (i.e., specialized software and hardware services).

5 Implementation of Results

This chapter describes status of the Project's results, implementations and expectations for the further development and immediate and long term expected economic benefits.

The Project was implemented according to plan, with basic points as follows:

- Research laboratory was established and fully equipped with hardware and software,;
- Working testbed components were developed and documented;
- Project results were communicated to end-users and the scientific community.

Considering the complexity of this Project it is not surprising that after all necessary resources are procured and installed, complete testing of numerous functionality still presents serious challenge. It is expected that in the time frame of next six months all necessary testing and validation and verification will be fully performed.

Since the main contribution to further development in the long term is the SCADA-NG research laboratory, it is planned for the laboratory to be used for the following:

- Continued development and use of established environment.
    - Use of the software tools for modeling smart cities, smart buildings and appropriate SCADA systems;
    - Use of the installed smart meters for building-level measurement of energy consumption in real-time making them ready for connection to whole system;
    - Analysis and measurements of solar insolation and integration of photovoltaic power in building systems;
    - Use of the hybrid power system on the FER roof for further examinations of smart energy systems integration;
- Further work on the implementation of the functional specifications for a smart energy system model;
- Continued work of main researchers and young researchers on individual tasks and tools (software models development):
    - Work on the involvement of new post graduate level of young researchers – two are investigating smart cities, entailing smart grids and smart buildings and pertinent SCADA interfaces;
    - Results related to the work on the project are connected with other activities such as thesis in the field of future power systems with an accent on information technology and security related to smart metering and SCADA systems;
    - Focused study of distributed (renewable) energy sources in the smart grid paradigm and increased inclusion in the existing energy system;
- The topics covered in this project maintain their position as relevant fields of interest for related student seminars, projects, and other class activities;

During this project scientific collaboration was established with complementary projects in order to achieve further development of smart metering solutions and implementation of advanced SCADA systems. Furthermore scientists from this project will use their experience and knowledge to benefit other compatible activities. Currently there are three such projects:

- ACROSS, Research Centre for Advanced Cooperative Systems (ACROSS), 2011.-2015., FER & 18 partners (including international),
- Croatian national scientific program: "Electricity market tools development", 036-0361590-1591, Croatian Ministry of science,
- Croatian national scientific program: "Nuclear energy for sustainable electricity production ", 036-0361590-1589, Croatian Ministry of science, and
- SEEERA.NET, “Intelligent information system for monitoring and verification of energy management in cities”, Consortium of research institutions from Zagreb (Croatia), Novi Sad (Serbia), Sarajevo (Bosnia & Herzegovina) and Ljubljana (Slovenia).

It should be emphasized that additional value of this Project lies in the fact that established platform presents open and rich foundation for the research of numerous multidisciplinary issues related to the reliability and security of power systems.

5.1 Economic and industrial benefits for the country

Implementation of the Project has created synergy with some ongoing projects and activities at the University aiming to enhance the FER Energy and Power Systems department laboratory with capabilities for studying and analyzing distributed (renewable) energy sources and smart grids. The Project team procured and installed equipment at the Faculty of Electrical Engineering and Computing buildings with some dislocated installations.

Available measurements, data analyses, models and simulations from established laboratory will be available to researchers from FER, PoliMi and elsewhere. Full insight into real life behavior will be given to researchers on this project for direct use and for the generation of advanced solutions. This will also serve well the involved end-users from the industry. Especially Croatian national power system utility HEP and industry which is significantly involved in the operation, maintenance, and future planning.

Overall half of the amount of more than 200 k€ of SfP funding was used to increase knowledge and learning capabilities (i.e., as direct benefit) and the other half to increase scientific capacity, improve education, help establish research network all with attached multiplicative influences to industry and institutions to improve national economy (i.e., as longer term benefit).

Estimating total direct benefits from this Project is not simple task. using findings from Z. Griliches in ‘R&D and productivity’ (1995) it could be estimated that they are at the level of around one third of million EUR. Long term benefits for society (i.e., institutions and industry) are even harder to estimate and based on the same source it could be, because of the engineering nature of the Project, that they will be at around the half a million EUR (this is at the level exceeding the totally invested sum).

Major guarantee of expected significant benefit from this Project is coming from the fact that it was executed in the environment where research and education are well bound and where strong relations between institutions and industry exist.

6 Conclusion

Opportunity to get funded by the NATO Public Diplomacy Division in the framework of "Science for Peace" for the realization of the project SfP 983805 'Designing Intelligent, Resilient, Scalable and Secure Next Generation SCADA Infrastructure' was an incredible experience. This framework is completely well organized and allows clearly defined ways of Project realization.

Research focus of this project was establishment of a simulation platform where different threats to the future power system could be investigated. The major goal is to simplify the process of finding better solutions for the optimal system design and sufficient control. This research was based on utilization of novel concepts and tools, using real systems operating conditions as inputs, as well as planned developments of the grid in the light of changes regarding sustainable development. Hybrid approach, incorporating software-hardware interactions, was selected as best way to investigate different dimensions of the reliability and safety and then later lead to their integration in the possible whole system solution.

During three years Project has succeeded to utilize different software platforms and realize several systems. Software platforms were used to model and simulate different aspects of the problem: physical (PowerWorld), functional (AnyLogic), and structural (Algor and Ansys). Built systems were used to generate realistic data about operation and to connect with software platforms. Four systems are built at campus: smart grid (measurement & control), hybrid renewable system (wind and PV), PV system and Solar characterization system (also installed outside campus). Created SCADA could be used to interact with simulations and with real systems. This altogether represents complete platform for investigating realistic and simulated complexity of various behaviors caused by the emergent phenomena in the power system.

Granted funding in the amount of more than 200 thousands EUR has created resources for training and meeting of other researchers from all-around the world (used 34% of the budget). The next 30% of the budget was used for information technology (hardware and software) which has allowed the completion of the research laboratory (server and network) and equipment for main researchers (personal computers). Laboratory was completed with 16% of budget resources used for the measurement and distributed generation equipment. Next 17% of the budget was used for student stipends and miscellaneous expenditures in order to make project run smoothly over all three years. Finally 3% percent of the budget was used in order to follow current publications (books and journals) related to research.

With direct and full support from this Project's funding main researchers were able to travel for training and participation to over 20 different conferences. Total of 17 scientific papers was result related to this Project. Ambitious network of software tools and models connected with designed and built measurement and distributed generation systems is enabling and will allow in the future research work for PhD students and other researchers. The results of this Project are also incredible foundations for better education of undergraduate students.

It can be concluded that half of funding amount was used to increase knowledge and learning capabilities (i.e., direct benefit), and the other half to increased scientific capacity, improve education, help establish research network all relaying multiplicative influence to improve national economy (i.e., longer term benefit).

Total benefit from NATO SfP funding could be estimated to 300 k€ (based on Z. Griliches, R&D and productivity, 1995). Benefits for society are harder to estimate and based on the same reference it could be expected that, because of the engineering nature of the Project, they could be around or exceeding the level of totally invested amount(i.e., 400 k€ or more).

Annex 1: List of Significant Collaborators

This is the list of all internal and external full and part time collaborators at the Project. Note is added regarding special role or condition related to the co-operation with the project (i.e., obtained higher degree, stipends, graduation project).

Collaborator	Status	Note
Dr. Stefano Zanero	**Lead researcher, PoliMi**	**PPD**
Dr. Zdenko Šimić	**Lead researcher, FER**	**NPD**
Luka Lugarić	Lead PhD researcher, FER	NPCD
Dr. Slavko Krajcar	Researcher, FER	NPCD
Dr. Nicola Gatti	Researcher, PoliMi	PPCD
Dr. Francesco Amignioni	Researcher, PoliMi	
Dr. Sofia Ceppi	Researcher, PoliMi	
Dr. Tomislav Tomiša	Researcher, FER	Significant project co-operation
Dr. Davor Grgić	Researcher, FER	Significant project co-operation
Dr. Juraj Havelka	Researcher, FER	Partly project co-operated
Dr. Mario Kušek	Researcher, FER	Partly project co-operated
Dr. Damir Šljivac	Researcher, ETFOS	Partly project co-operated
Dino Mileta	PhD obtained, FER	Partly project co-operated
Igor Petrović	PhD student, FER	Partly project co-operated
Domagoj Talapko	PhD student, FER	Partly project co-operated
Boran Morvaj	Undergrad. student, FER	Stipends 3 years / Grad. project
Roberto Rosandić	Undergrad. student, FER	Stipends 2 years / Grad. project
Katarina Knezović	Undergrad. student, FER	Stipends 2 years / Grad. project
Goran Jurišić	Graduated, FER	Stipends 1 year / Grad. project
Jurica Brekalo Štrbić	Graduated, FER	Stipends 1 year / Grad. project
Bruno Jurišić	FER	Stipends 2 years / Grad. project
Ninoslav Holjevac	FER	Stipends 2 years / Grad. project
Ivo Sluganovic	FER	Stipends 2 years
Ivan Simunic	Graduated, FER	Graduation project
Zvonimir Meštrović	Graduated, FER	Graduation project
Ivan Toplak	Graduated, FER	Graduation project
Ivan Livić	Graduated, FER	Graduation project
Katja Nodilo	Graduated, FER	Graduation project
Luka Romac	Graduated, FER	Graduation project
Marino Bajčić	Graduated, FER	Graduation project
Pero Vukić	Graduated, FER	Graduation project

Annex 2: List of Publications

1. Šimić, Zdenko, Juraj George Havelka, and Maja Božičević Vrhovčak. "Small wind turbines–A unique segment of the wind power market." Renewable Energy 50 (2013): 1027-1036.
2. Zoran Morvaj, Luka Lugarić and Boran Morvaj, Smart Energy Cities - Transition Towards a Low Carbon Society, "Energy Efficiency - A Bridge to Low Carbon Economy", book edited by Zoran Morvaj, ISBN 978-953-51-0340-0, Published: March 16, 2012
3. Pašičko, Robert; Branković, Čedo; Šimić, Zdenko. Assessment of climate change impacts on energy generation from renewable sources in Croatia. Renewable Energy. 46 (2012) , October; 224-231
4. Davor Grgić, Zdenko Šimić, Bruno Glaser - Prediction of Local Hydrogen Concentrations in PWR Containment Using GOTHIC Code, ANS Annual Meeting, Chicago, USA, 24-28 June 2012
5. Hrvoje Grganić, Zdenko Šimić – On the Estimation and Reduction of the Frequency of the Loss of Offsite Power Event, 9th International Conference on Nuclear Option in Countries with Small and Medium Electricity Grids, Zadar, Croatia, 3-6 June 2012
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18. Igor Petrović, Zdenko Šimić, Mario Vražić - Advanced PV plant planning based on measured energy production results – Approach and measured data processing, (Submitted for publishing to journal)
19. Boran Morvaj, Ninoslav Holjevac, Bruno Jurisic - Stochastic Simulation of the Smart Grid and Demand Response Implementations on a City-wide Scale, (Submitted for publishing at conference)

Annex 3: Complete Inventory Record

Inv. Lbl.	Property Item	Manufacturer	Model Number	Date of Purchase	Cost (EUR)	Location at FER
2008	Power World	PowerWorld Corp.	V15 Educational licence	Apr. 2010	4.288	**D2-VNE/ZS**
2009	AnyLogic	AnyLogic Europe	V6 Educ. & Research licence	Apr. 2010	3.590	**D2-VNE/ZS**
2010	PQube	Power Standards Lab.	PQB100141	Jun. 2010	2.104	**D2-VNE/TT**
	FER SG1	Different	Measurement and control	Jun. 2012	3.786	
2011	Desktop PC	ATI, Intel, Asus, Dell	Asus P6T WS Pro, i7, U2711b	Sep. 2010	2.671	**D2-VNE/ZS**
2012	Algor Sim.	Autodesk	Professional 2011 Edu. lic.	Sep. 2010	3.275	**D2-VNE/DG**
2013	Desktop PC	HP, Intel, Asus, ATI	Asus 1366 AS P6T, i7, HP LP2475w	Dec. 2010	1.733	**D2-VNE/LL**
2014	Notebook	HP	Elitebook 2540p	Mar. 2011	1.939	**D2-VNE/LL**
2015	Notebook	Apple	MacBook Air 13”	Mar. 2011	1.858	**D2-VNE/SK**
2016	FER RE1	Solvis	PV 1.2 kWp	May. 2011	2.765	**D2-VNE/ZS**
2017	ANSYS	ANSYS	ANSYS GAMBIT/Tgrid 2012 Research License	May. 2011	4.850	**D2-VNE/DG**
	ANSYS	ANSYS	ANSYS, GAMBIT/Tgrid 2013 Research License	Jun. 2012	5.286	
2018	Server	IBM	X3550M3	Jun. 2011	3.610	**D2-VNE/ZS**
	FER TB	Kom-Pro	Central web server app. for data aq. & processing	Jan. 2013	3.870	
2019	Notebook	Apple	MacBook Air 13”	Oct. 2011	1.329	**D2-VNE/ZS**
2020	FER SG2	Different	Measurement and control	Jul. 2012	4.953	**D2-VNE/TT**
2021	FER RE2	Different	Wind & PV hybrid system	Sep. 2012	4.985	**D2-VNE/ZS**
2022	Desk. PC	IC, Intel	i7 3930K, EAH6670, 4GB	Oct. 2012	1.462	**D2-VNE/DG**
2023	Desk. PC	IC, Intel	i7 3770K, P8Z77, U2412	Nov. 2012	1.757	**D2-VNE/LL**
2024	FER RE3/1	Different	Embeded PCs + A&D IOs	Dec. 2012	4.754	**D2-VNE/ZS**
	FER RE3/2	Krovel	PLC application for RE3	Dec. 2012	3.605	
	FER RE3/3	NRG, Kipp&Zonen	NRG#40H, NRG#200P, NRG#110S, Pyran. SP Lite 2	Dec. 2012	4.748	
	FER RE3/4	Enconet	Electronic loads ET30V/5A	Jan. 2012	3.102	
	FER RE3/5	Sunset, Sole	Sunset SA90; Sole SL80, Sole SL100	Feb. 2012	3.244	
2025	GOTHIC	Numerical Applications	SW, maintenance and user support	Dec. 2012	5.295	**D2-VNE/DG**
2026	Notebook	Apple	Mac Book Pro 15”	Jan. 2013	2.048	**D2-VNE/DG**
2027	Notebook	Lenovo	ThinkPad X1 N3K6HSC	Jan. 2013	1.396	**D2-VNE/ZS**