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PhD Thesis

SUMMARY

SOFTWARE DEVELOPMENT FOR DESIGN AND CONTROL OF MICROGRIDS WITH RENEWABLE ENERGIES

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Keywords:

Intelligent Microgrids, Renewable Energies, Control, Energy Management, SCADA

1. Introduction and thesis motivation

The evolution of power generation and electricity transmission systems reduces the dominance of the macrogrids and helps in spreading of the microgrids that can effectively integrate various sources of distributed generation (DG), especially Renewable Energy Sources. **Smart microgrids** are the optimal way to add customers to the electricity market and to introduce **renewable resources** to community areas.

This thesis falls to the field of renewable energy sources, integrated into hybrid power systems. A hybrid power generation system encompasses several sources of energy and can feed consumers without interruption, even if one of the sources does not work. A wide range of resources can be integrated into smart microgrids: photovoltaic systems, geothermal and biomass generators, small wind turbines, etc. A part of the energy generated is usually stored in batteries (i.e. lead-acid batteries, lithium-ion batteries, etc.). The advantage of such a system is that it can work both day and night.

This thesis discusses aspects related to the design, control, and optimization of intelligent microgrids with renewable energies.

2. Objectives of the thesis

The main purpose of this thesis is the integration of renewable energies into cogeneration of electricity in an islanded microgrid. In order to obtain electricity at a cost-effective level, intelligent energy management is needed. The secondary aim of this thesis is to provide an innovative and complete energy management solution for the microgrid that monitors the loads, generates the required amount of energy and charges/discharges batteries in the proposed system. Another crucial problem in these power systems is to keep a reliable power balance between the consumption and the generation units.

The most important intention of this work is to contribute the implementation of various applications that will be used in smart microgrids. The problem itself can be divided into three major parts:

1. Sizing algorithms of the microgrid
2. Control methods
3. Energy Management Techniques

In the first part of the thesis the modeling, sizing and designing methods were studied, in order to implement the necessary algorithms of microgrids. The energy flow control and the real-time communications were implemented based on the communication protocols. In the second part of the thesis, optimization methods and energy management techniques are dominant.

The thesis contributes to the development of modeling and control algorithms of microgrids and tries to improve energy management algorithms. The new/ improved methods are effective, they have lower operating costs and are simple to implement. The research is in step with the innovations in the field, both at the technological development level and at the level of mathematical models and software.

Based on the problems listed above, the objectives of the PhD thesis are the following:

- Developing a modeling and sizing graphical user interface (GUI) that helps in the sizing of microgrids;
 - Studying communication protocols which are suitable to use in microgrids;
 - Studying two-level control structures in microgrids;
 - Achieving a user-friendly control interface;
 - Studying different optimization methods in order to use them as basis of implementation of the energy management of the proposed system;
 - Implementing the energy management interfaces of the proposed microgrid.
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3. Thesis methodology

The main topic of the thesis was defined after consulting the relevant published literature. The general purpose and objectives of the research were formulated, as outlined in the previous chapter.

These objectives have been approached starting from the analysis of modeling, sizing and designing applications of the microgrids, using the following applications: Homer, PV@SOL, and PVSys. A Sizing Photovoltaic-Geothermal-Biomass Smart Microgrid with Battery Storage Interface has been implemented using Microsoft Visual Studio, and its features, libraries, and extensions.

A control GUI was also implemented in Visual Studio for testing the experimental model installed in the laboratory which was sized based on the sizing GUI.

Three energy management algorithms have been studied: mixed linear integer programming (MILP), genetic algorithm and Harmony Search Algorithm. Based on them three GUIs were implemented. The MILP model was solved by the Microsoft Solver Foundation. This extension helps to reach better economic decisions.

The results are validated by simulations using the above-mentioned programs, and experimentally using the emulator system built in the laboratory.

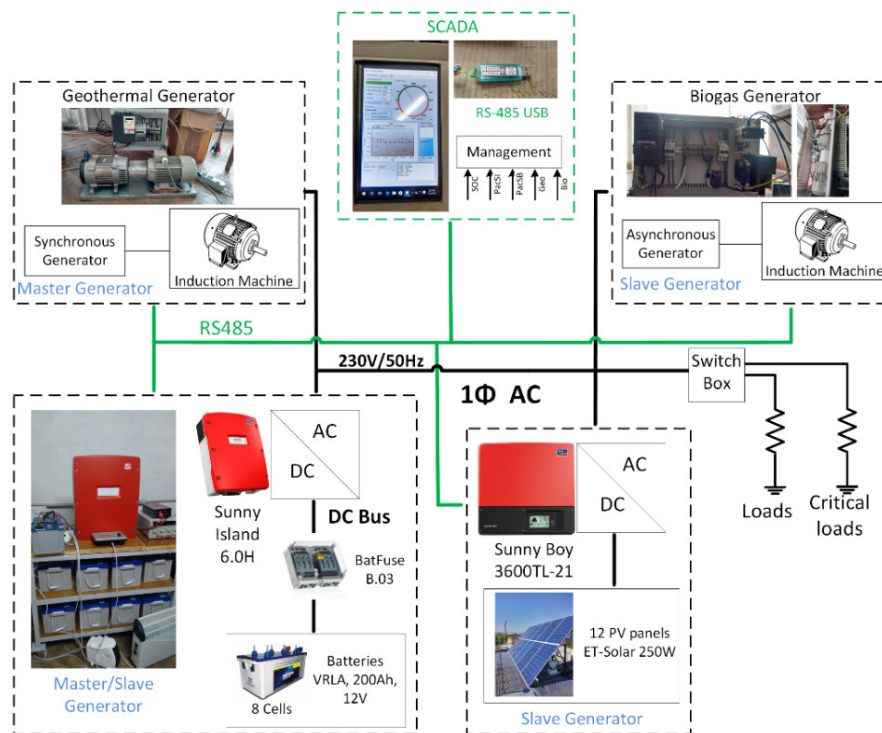


Fig. 1 Microgrid under consideration

The characteristics of the batteries, generators and PV system are:

- Number of panels: 12
- Number of batteries: 8
- Solar inverter and battery inverter
- Geothermal and Biomass Emulators
- A communication system based on MODBUS protocol
- MODBUS-Analog Converters
- Intelligent Powermeter

The results have been published in 11 scientific papers sent to international and national conferences and in scientific journals CNCSIS indexed:

- 1 ISIS WOS scientific journal
- 12 ISIS WOS scientific papers
- 1 B+ journal
- member in the contract "Parteneriate in domenii prioritare – PN II, MEN – UEFISCDI, nr. 53/01.07.2014"

After publishing the papers, the contributions have been summarized and the thesis has been edited.

4. Thesis organization

Chapter 1 presents the current state of research in the field of smart microgrids with renewable energies, the aim and objectives of the thesis and also the research methodology.

Chapter 2 presents the sizing and the optimization methods of an intelligent microgrid from a financial viewpoint. The main consumers, the used energy resources, the models of components, a preliminary sizing algorithm and a sizing optimization algorithm based on loss of power supply probability are presented. **Based on these algorithms a Sizing Interface was developed, which can facilitate the sizing processes of the islanded microgrids.**

The two studied algorithms were the Most unfavorable month method and the Loss of power supply probability method. The first method helps to find the optimal number of the photovoltaic panels and the batteries according to the power generated by the generators and

the annual consumptions. In this method the optimal number of the photovoltaic panels are calculated in the most unfavorable month from the solar irradiation point of view.

The second method uses mathematical models to characterize the operating modes of the different generators from hour to hour. It takes in account the consumptions profile, the reserved energy in the batteries and the capacity of the generators. The optimization criteria are the loss of power supply probability and the cost of energy.

Furthermore, the LPSP algorithm uses a solar radiation prediction subroutine. This can calculate the hourly solar irradiancies from the monthly meteorological data. The need for this subroutine stems from the fact that most sites provide the meteorological data only in the monthly average form.

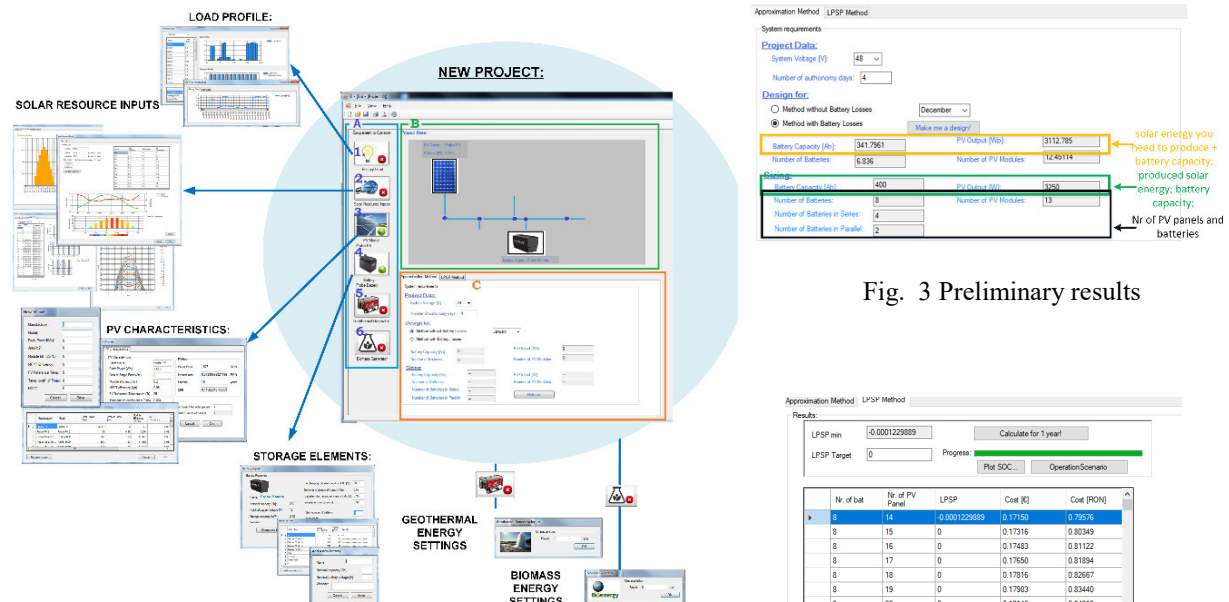


Fig. 2 Sizing Interface Structure

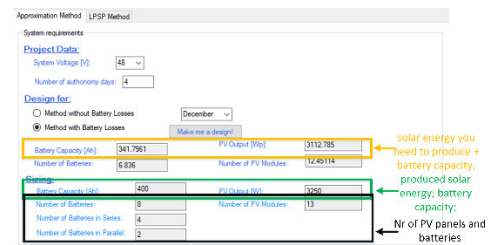


Fig. 3 Preliminary results

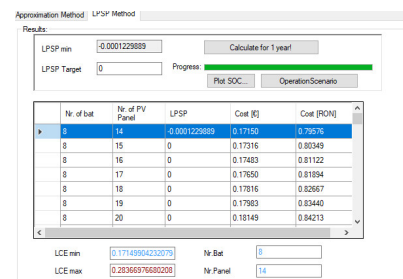


Fig. 4 Optimized Results

Chapter 3 presents the control methods of an intelligent microgrid. In this chapter, the SCADA systems, their properties, and two communication protocols are analyzed.

The control system consist of a primary level voltage-reactive power and frequency-active power and a secondary level energy management algorithm based on the balance between the power produced by the renewable energy generators, state of charge of the battery bank and the loads. The management control strategy is to cycle charge the batteries at a reference value in order to use the available resources efficiently.

The SMA inverters use a modified Modbus proprietary communication protocol. The geothermal and biomass emulators have Modbus compatible devices, control commands are transmitted via MODBUS-Analog converters and powers are read with an intelligent powermeter with MODBUS communication. Data is transferred between the devices and a central processing unit using an RS-485 network.

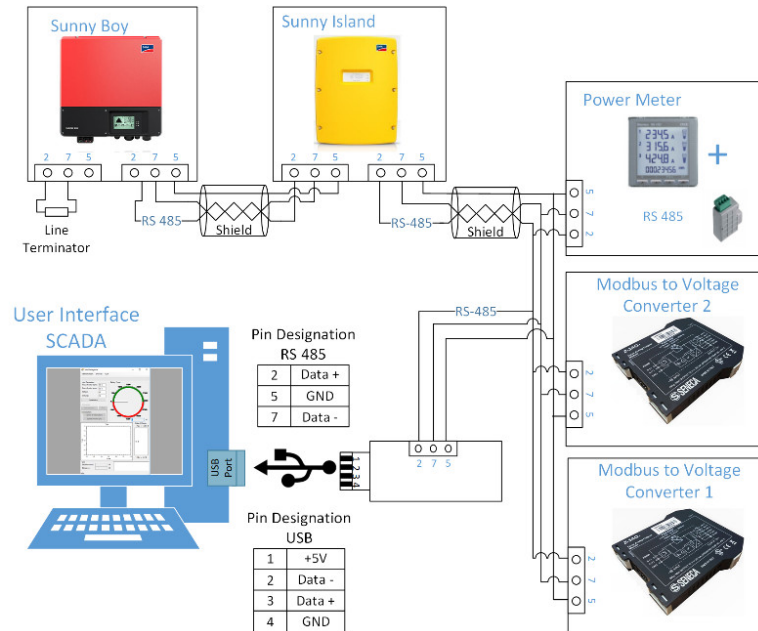


Fig. 5 The proposed RS-485 communication network

Furthermore, the control commands and the energy management algorithm based on SOC are tested. The proposed control method has been tested experimentally. The user-friendly control GUI is presented in Fig. 6.

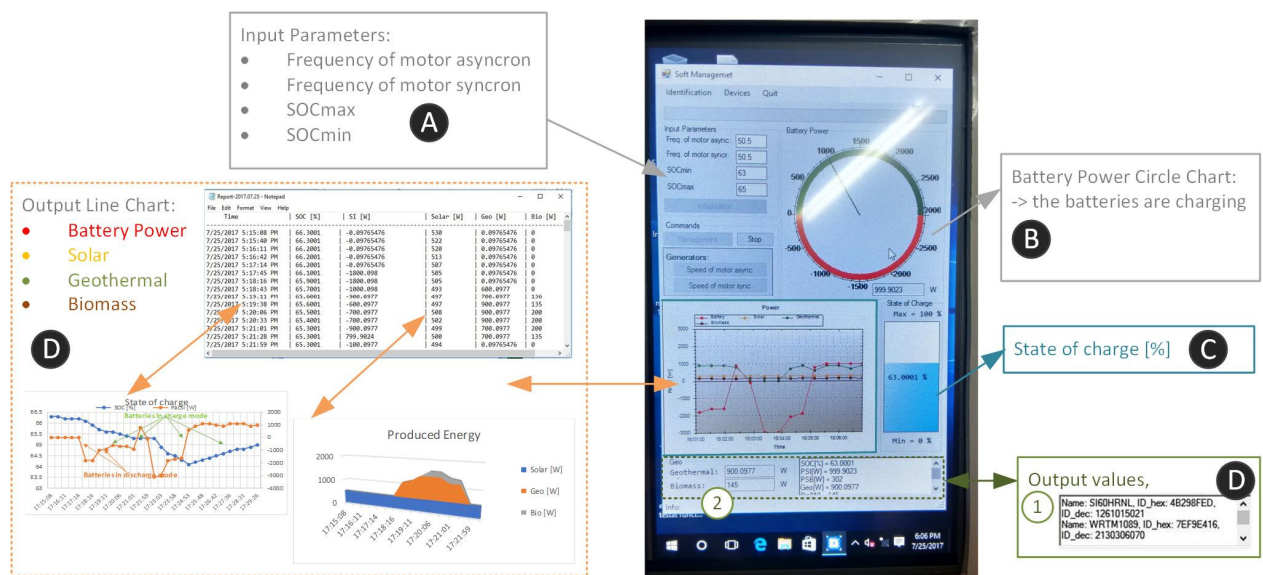


Fig. 6 Control GUI

Chapter 4 proposes an algorithm based on mathematical models to solve the energy management problem. Different mathematical algorithms are studied to find optimal solutions, the mathematical model of the proposed system is built and a mixed integer linear programming (MILP) algorithm is developed to determine the amount of generated energy and its distribution among the generators, given the minimum operating cost of the system.

Using the Matlab program, the mathematical model of the proposed system was built and tested. The optimal solution is represented graphically. Then, another GUI was developed using Microsoft Visual Studio C# 2015 and its special extension, Microsoft Solver Foundation (MFS).

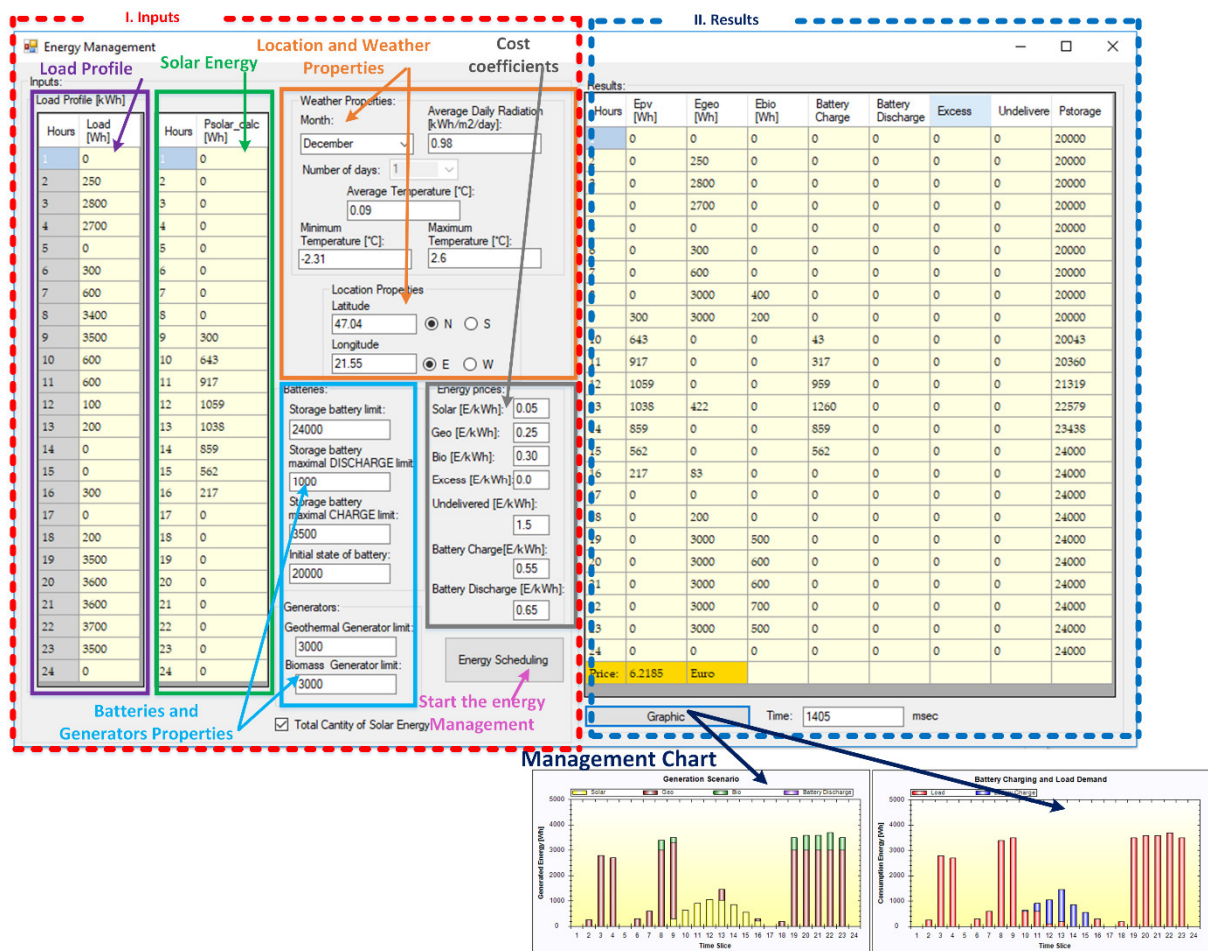


Fig. 7 Energy management interface - MILP

The user can introduce the load demand, geographical and meteorological data, the limits of batteries and generators and the cost coefficients. The scheduling problem is predetermined for a 24h time interval and represented in the Result table. It is possible to check the created energy distribution using the management charts.

Chapter 5 presents the energy management with stochastic search methods. Metaheuristic optimization deals with optimization problems using metaheuristic algorithms. These are inspired by nature and mimic processes such as the biological evolutionary process and animal behavior. In this chapter two metaheuristic algorithms based on random numbers were studied: Genetic Algorithm (GA) and Harmony Search Algorithm (HSA). Both algorithms have a graphical user interface:

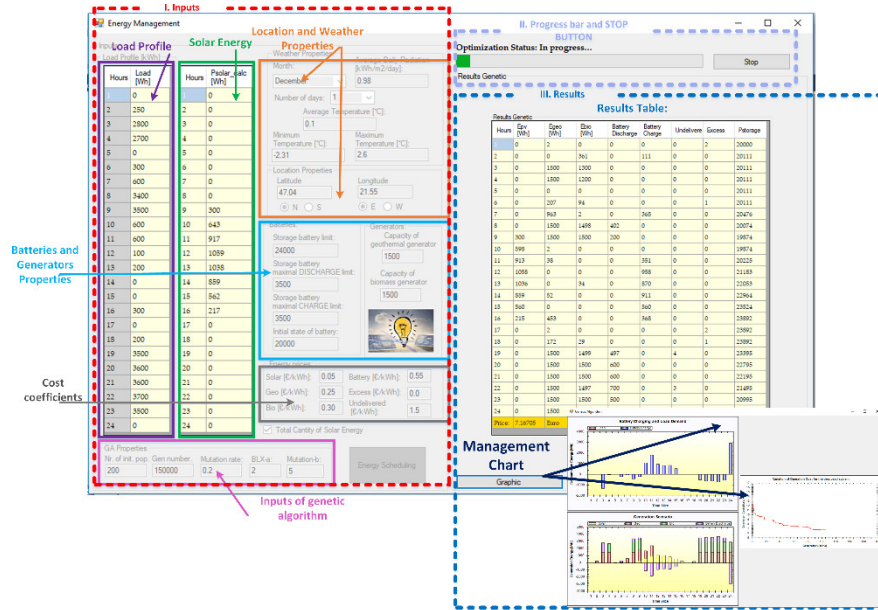


Fig. 8 Energy management interface – GA

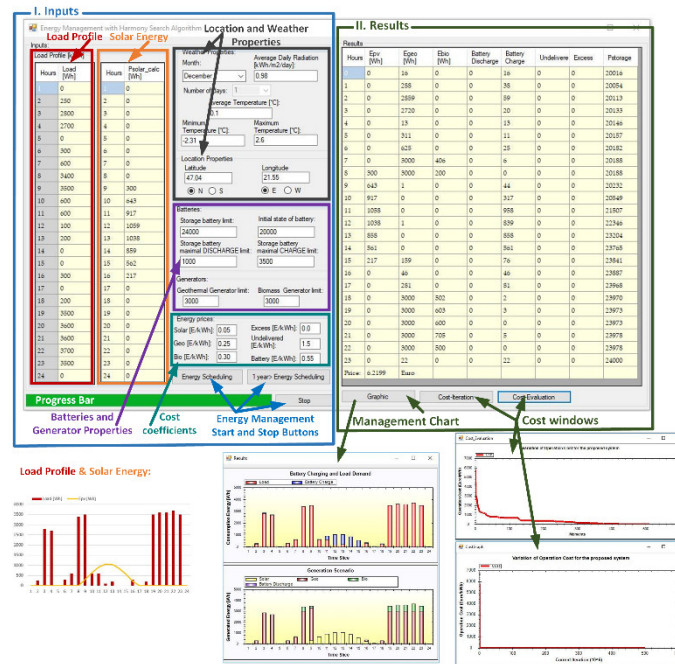


Fig. 9 Energy management interface – HSA

The implemented energy management interfaces are very similar to the MILP GUI. The following elements have been added:

- The interfaces are improved with a progress bar that allows the user to check the progress.
- A Stop button has been added to allow the process to be interrupted.
- A section with algorithm characteristics that allows changes in input parameters (GA) is also implemented.

The CPU and memory usage, respectively the running time are illustrated in the following table:

Tab. 1 Summary of the results

	MILP	GA	HSA
Running time	2-10 sec	14 sec	8454 sec
Memory usage	~ 25% of all processors	~ 38% of all processors	~ 54% of all processors
CPU usage	~ 22 MB	~ 32 MB	~ 40 MB

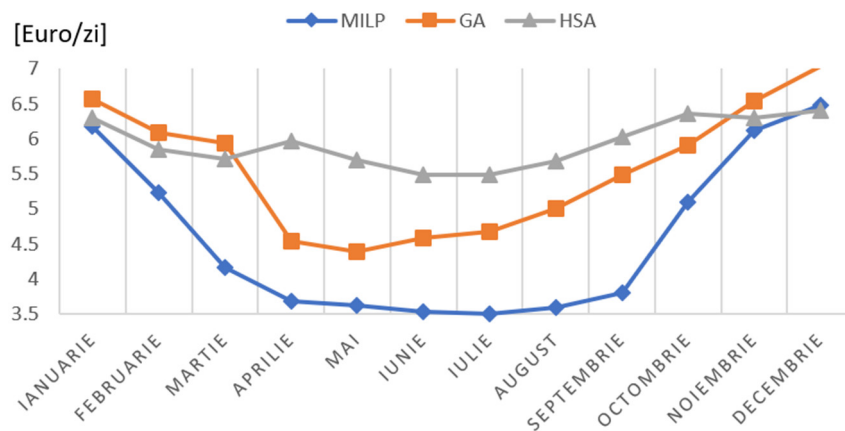


Fig. 10 Cost of functioning MILP, GA, HSA

It can be concluded that the MILP algorithm, which is an algorithm based on mathematical models and looking for the optimal solution around a starting point, gives the best results from all examined points of view: operating cost of the proposed microgrid, running time, memory and processor usage.

The tests were done under the following conditions:

- Geothermal generator and biomass generator capacity: 1.5 kW

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- Characteristics of the microgrid's location: Oradea - 47°02'N latitude și 21°58'E longitude
 - Weather data is taken from NASA's database
 - The main consumer is a vegetable greenhouse
 - Solar inverter capacity: 3.5 kW
 - Cost coefficients: 0.05 €/kWh, 0.25 €/kWh, 0.30 €/kWh, 0.55 €/kWh, 0.00 €/kWh și 1.5 €/kWh.

Chapter 6 highlights the main contributions and the most important aspects of the thesis.

5. The PhD thesis' main contributions

1. Implementation of sizing algorithms for a microgrid

Two sizing methods were studied. The first algorithm calculates the capacity of the generators using both the annual average energy consumption and the annual average amount of generated energy by the generators. The second, based on the results of the first one, optimizes the capacity of the generators taking into account the evolution of meteorological data and loads at an hourly interval, estimated over a 1 year period.

2. Implementation of the sizing interface for a microgrid.

This GUI allows the user to select solar panels and batteries in a database. The database can be also completed with new items. Introducing the meteorological and geographical features of the microgrid's location is another important step. After the initial settings, the PC application calculates the minimum price of one kilowatt of energy together with the optimal number of batteries and photovoltaic panels for the proposed microgrid.

3. Developing prediction algorithms for solar irradiation

Most sites only provide data about monthly solar irradiation and monthly temperatures at a selected geographic location. The LPSP algorithm works with hourly data, so it was necessary to develop an algorithm that converts monthly data into hourly data.

4. Elaboration of the text-based communication algorithm

The communication between the first C# interface and the communication program in C is based on text files. The C# interface writes into a file the command that should be executed, the program in C reads from there and executes the command, then saves the results of the command into another text file. The output file contains the powers, capacities, frequencies, and voltages queried. The C# graphical interface must interpret the read data correctly according to the transmitted commands.

5. Elaboration of the communication algorithm with its own functions

The implemented C# GUI provides the direct communication between the units of the microgrid, no need of intermediate text files. The SMA-Net protocol, the types of commands and the importance of bytes for each type of message were studied. The PC application contains functions to communicate with the SMA devices using the SMA-Net protocol (a MODBUS-derived data transfer protocol) and also provides standard MODBUS functions to communicate with other equipment.

Three classes are achieved: *MODBUS class* - communicates with standard MODBUS equipment (intelligent powermeter, MODBUS-Analog converters), *SMAbus class* - communication with SMA inverters and *Device class* which store the information about identified SMA channels.

The PC application was also tested in the laboratory using the experimental model. An energy management algorithm based on SOC of the batteries was implemented.

6. Implementation of energy management algorithms based on predictive algorithms

These algorithms are based on meteorological phenomena and statistical data of the microgrids. Three types of algorithms were studied (Mixed Integer Linear Programming, Genetic Algorithm, and Harmony Search Algorithm) and three interfaces were implemented. The three methods attempt to minimize the operating cost of the microgrid, taking into account the cost coefficients of each generator.

Each interface has a part for the input parameters (consumption profile, weather and geographic data, battery and generator capacity, cost coefficients). The program can calculate

the hourly solar power using the developed algorithm: Prediction of hourly solar irradiation. The second part of the interfaces contains the results table and a button called "Graphic". Pressing the button shows a new window, the results are shown on graphs.

6. Future work

The theoretical and practical results obtained from the thesis elaborated are facilitating the understanding of sizing, modeling and control of off-grid microgrids. The following research directions can be identified:

- Implementing and studying the possibilities to connect in sizing application other types of energy sources (wind turbines, diesel generator, fuel cell etc.) are also particularly important.
 - The implemented application focuses only on isolated systems, studying the connection of the microgrid to the national network is another direction of research.
 - The PC control application implementation is designed to run under the Microsoft Windows operating system. An application for Unix operating systems is possible and can be further developed.
 - The control GUI resolves the energy management problem based on maintaining the state of charge of the batteries between two limits. Modifying the program to achieve energy management using mathematical models or intelligent methods based on meteorological phenomena and statistical data of the microgrid can be also considered as further development opportunity.
 - Three "intelligent" methods have been developed for energy management. There is a risk that they will remain in the local optimum depending on the initial conditions. It is proposed to use hybrid methods that integrate traditional methods and intelligent methods or two different intelligent methods to solve the local optimal problem.
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JOURNALS

List of papers published as the first author

ISI Journals:

- E1. **E. Lazar**, D. Petreus, R. Etz, T. Patarau, "*Software Solution for a Renewable Energy Microgrid Emulator*", Advances in Electrical and Computer Engineering, vol.18, no.1, pp.89-94, 2018, doi:10.4316/AECE.2018.01011 [**Impact Factor: 0.699**]

Conferences - ISI proceedings:

- E2. **E. Lázár**, D. Petreuş, R. Etz, T. Pătăraş, "Minimization of operational cost for an Islanded Microgrid using a real coded Genetic Algorithm and a Mixed Integer linear Programming method", 2017 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics (ACEMP), Brasov, Romania, 25-27 MAY, 2017, pp. 693-698, doi: 10.1109/OPTIM.2017.7975049
- E3. **E. Lázár**, D. Petreuş, R. Etz, T. Pătăraş, "Optimal Scheduling of an Islanded Microgrid Based on Minimum Cost", 39th International Spring Seminar on Electronics Technology - ISSE2016, Pilsen, Czech Republic, MAY 18-22, 2016, pp. 290 – 295, doi: 10.1109/ISSE.2016.7563207
- E4. **E. Lazar**, R. Etz, D. Petreus, T. Patarau, I. Ciocan, „SCADA Development for an Islanded Microgrid”, IEEE 21st International Symposium for Design and Technology in Electronic Packaging (SIITME) Brasov, Romania, 22-25 October 2015, pp. 147 - 150 (DOI: 10.1109/SIITME.2015.7342314)
- E5. **E. Lazar**, T. Patarau, R. Etz, D. Petreus, "Sizing Photovoltaic-Geothermal Smart Microgrid with Battery Storage Interface", 38th International Spring Seminar on Electronics Technology, Eger, Hungary, 6-10 May 2015, pp. 364 – 369, DOI: 10.1109/ISSE.2015.7248023.
- E6. **E. Lazar**, A. Ignat, D. Petreus, and R. Etz, "Energy Management for an Islanded Microgrid Based on Harmony Search Algorithm", 41th International Spring Seminar on Electronics Technology ISSE, Zlatibor, Serbia, May 16–20, 2018, pp. 1-6.

ISI proceedings:

- E7. I. Ciocan, C. Farcas, D. Petreus and N. Palaghita, **E. Lazar**, „Comparison between Fixed and Solar Oriented PV Modules' Energy Production using a Simplified PSIM
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- Model*”, IEEE 21st International Symposium for Design and Technology in Electronic Packaging (SIITME) Brasov, Romania, 22-25 October 2015, pp. 221 – 225, DOI: 10.1109/SIITME.2015.7342328
- E8.** A. Grama, M. Dan, **E. Lazar**, “*Photovoltaic Panel Model Using Matlab*”, 39th International Spring Seminar on Electronics Technology - ISSE2016, Pilsen, Czech Republic, MAY 18-22, 2016, pp. 322 – 327, DOI: 10.1109/ISSE.2016.7563213
- E9.** T. Patarau, D. Petreuş, R. Etz, **E. Lazar**, “*Small Signal Induction Generator Model Connected in a Frequency-Droop Controlled Renewable Energy Microgrid*”, 39th International Spring Seminar on Electronics Technology - ISSE2016, Pilsen, Czech Republic, MAY 18-22, 2016, pp. 296 – 300, DOI: 10.1109/ISSE.2016.7563208
- E10.** D. Petreuş, T. Păţărău, R. Etz, **E. Lázár**, “*Supplying a Renewable Energy Single Phase Microgrid from a Biomass Generator Using a Three Phase Induction Machine*”, IEEE CPE-POWEREN16, Bydgoszcz, Poland, 29.06 – 01.07, 2016, pp. 208 – 213, DOI: 10.1109/CPE.2016.7544186
- E11.** R. Etz, D. Petreus, T. Patarau, **E. Lazar**, “*An islanded renewable energy microgrid emulator for geothermal, biogas, photovoltaic and lead acid battery storage*”, 2017 IEEE 26th International Symposium on Industrial Electronics (ISIE), Edinburgh, UK, 19-21 June 2017, pp. 2109 – 2114, DOI: 10.1109/ISIE.2017.8001583
- E12.** T. Patarau, D. Petreus, R. Etz, E. Lazar, “*Techno-economic feasibility study on an off-grid renewable energy microgrid for an isolated greenhouse in Romania*”, 18TH INTERNATIONAL CONFERENCE ON POWER ELECTRONICS AND MOTION CONTROL, Budapest, Hungary, 2018 [acceptate spre publicare].
- E13.** A. Ignat, D. Petreus, E. Lazar, “*Energy Management for an Islanded Microgrid Based on Particle Swarm Optimization*”, IEEE 24th International Symposium for Design and Technology in Electronic Packaging (SIITME) Iasi, Romania, October 2018 [acceptate spre publicare]

Journal B+

- E14.** A. Grama, T. Patarau, **E. Lazar**, D. Petreus, „*Estimating the Size of the Renewable Energy Generators in an Isolated Solar-Biodiesel Microgrid with Lead-Acid Battery Storage*”, Journal of Electrical and Electronics Engineering, vol. 8, no. 2, October 2015, pp. 15-18.
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