„POLITEHNICA" UNIVERSITY, BUCUREŞTI

DOCTORAL SCHOOL ETTI-B

PhD Thesis Summary

OPTIMIZATION OF HYBRID POWER SOURCES BAZED ON RENEWABLE ENERGIES

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Thanks,

Now, at the end of my doctoral thesis, I would like to express my feelings of professional and personal satisfaction with the completion of this paper.

On this occasion, I would like to thank all those who guided and suported me in completing my doctoral thesis.

First of all, I would like to thank in particular my scientific coordinator, Mr. University Professor, Doctor of Engineering **Nicu Bizon**, for the permanent support, guidance and encouragement throughout the period of preparation and elaboration of this paper.

At the same time, I would like to express my gratitude to the members of the evaluation commission of the paper, as well as to the members of the evaluation commissions throughout the doctoral internship, for the observations and suggestions provided.

Finally, I would like to thank my family for their encouragement and support, expressed throughout the doctoral internship.

Thank you!

Phd student: Eng. Hoarcă Ioan Cristian

Chapter 1
Introduction

1.1 Presentation of the field of the doctoral thesis

The paper refers to the optimization of hybrid power sources based on renewable energies.

Renewable energy sources now occupy an important place in the production of electricity, due to the special advantages over conventional energy sources: they are inexhaustible, non-polluting, cost-competitive.

The paper is structured in nine chapters as follows: introduction, renewable energy sources and their potential, modeling of power sources based on renewable energies, comparative analysis of maximum power point tracking techniques (MPPT), global MPPT techniques, technique control with load tracking for a hybrid power source (HPS), optimization of hybrid power systems, case study for a photovoltaic park and conclusions.

1.2 The purpose of the thesis

The main objective of this paper is to present and analyze renewable energy sources, especially solar, in terms of optimizing operation.

The theoretical part of the paper (the first three chapters) presents the photovoltaic effect, the photovoltaic cell and its mathematical modeling: the single-diode model and the double-diode model. Also, different connection configurations of PV panels , maximum power point tracking (MPP) techniques, modeling of hybrid power source (HPS) based on renewable energies are presented in these three chapters with a theoretical touch.

The results obtained from the applied research are presented in the following chapters and refer to the comparative analysis in terms of performance for conventional MPP algorithms, optimized energy management of a hybrid power source (HPS) using renewable energy sources (RES) and a hydrogen fuel cell (FC) and Load Following control (LF) strategies applied for an FC / RES HPS architecture.

A separate chapter is intended for sizing and optimizing a hybrid power system based on renewable energies using HOMER and iHOGA applications.

In the final chapter, an experimental case study for a photovoltaic plant using the SCADA system is presented. The functional parameters of the photovoltaic park are purchased to obtain information about the efficiency of the applied energy management.

1.3 The content of the thesis

The doctoral thesis is structured in 9 chapters, presented below briefly.

Chapter 1 were presented the field of doctoral research, the purpose of the thesis and the content of the thesis.

Chapter 2 motivates the need to use renewable energy sources and then presents the main theoretical aspects for the analysis of PV panels: the photovoltaic effect, the characteristics of photovoltaic cells and their mathematical modeling. PV panel connection configurations are described, as well as commonly used PV area architectures. The techniques for tracking the maximum power point, conventional and intelligent, were presented and a comparative analysis of the MPPT techniques in terms of performance indicators is made.

Chapter 3 continues with the modeling of hybrid power sources (HPS) based on renewable energies and describes the architectures for connecting these sources to DC or AC buses, as well as modules for PV array and energy storage devices.

In Chapter 4, a comparative analysis of maximum power point tracking (MPPT) techniques was made using two algorithms: the classic Perturbe and Observe (P&O) algorithm and the adaptive algorithm based on Extreme Seeking Control (ESC). The algorithms are tested for a PV panel at various solar irradiation profiles [W / m2].

In Chapter 5, we addressed the issue of global MPP search techniques (GMPPT) that can increase by up to 40% the efficiency of energy extraction from partially shaded PV array. Several algorithms have been proposed that use in addition to the MPPT search loop from Perturbed Extremum Seeking Control (PESC) another GMPP location loop. After the theoretical presentation of the GMPPT technique and the two adaptive control loops, a simulative analysis of two GMPPT schemes based on PESC is made: G1PESC based on one BPF filter and G2PESC based on two BPF filters. The results of the comparative analysis are interpreted using performance indicators specific to MPPT techniques, respectively GMPPT, being used two specific performance indicators (searching resolution and success rate in locating GMPP on multimodal PV characteristics), which were defined by the undersigned. A detailed comparison using real solar irradiation profiles is made between the Perturbe &Observe algorithm and the G1PESC scheme, highlighting the advantages and disadvantages.

In the 6th chapter, a case study was performed for an FC/RES HPS architecture with a detailed presentation of the components and simulation results (tabular and graphical) at constant load and variable load. In the case study, two topologies were studied: the Air-LF topology and the Fuel-LF topology, which uses a control strategy of air and hydrogen flows (which supplies the fuel cell) based on Load Following (LF) mode control.

Chapter 7 addresses the optimization of hybrid power systems based on renewable energies using two programs of simulation and optimization of hybrid power systems: HOMER and iHOGA. A case study is presented for a hybrid power system located near Rm. Vâlcea locality in order to be optimized from a technical-economic point of view.

Chapter 8 details a case study for a photovoltaic park using the SCADA system with the help of which the energy management of the photovoltaic power plant can be achieved for a shorter or longer period of time.

The last chapter, the 9th, presents and analyzes the conclusions that resulting from the elaboration of the paper.

At the end of the thesis are presented the bibliographic references used.

Chapter 2

The need to use renewable energy source. The potential of renewable energy sources

In this chapter are presented detailed:

- renewable energy sources, photovoltaic effect, photovoltaic cell, their mathematical modeling and operating characteristics (I-U and P-U);
- creation of a simulation interface for a cell, module, PV array in the Matlab - Simulink simulation environment to study different PV modules used in photovoltaic installations and which allow to draw characteristic curves for different

values of solar radiation and temperature, both for uniform lighting and in partial shading conditions.

- efficiency analysis for different PV panel connection configurations and the main PV area architectures were described.
- description of techniques for tracking the maximum power point, their classification and a comparative analysis of the MPPT techniques from the point of view of performance indicators.

2.2 Modelling photovoltaic cells

The photovoltaic cell is electrically non-linear source, its operation can be studied considering the junction p-n in parallel with a constant current source [11].

2.2.1 Single diode model of a PV cell

The constant current source, in parallel with a semiconductor diode shapes the ideal cell to which is added a series resistance, and a parallel resistance, which models voltage and current losses. (Fig. 2.3) [12].

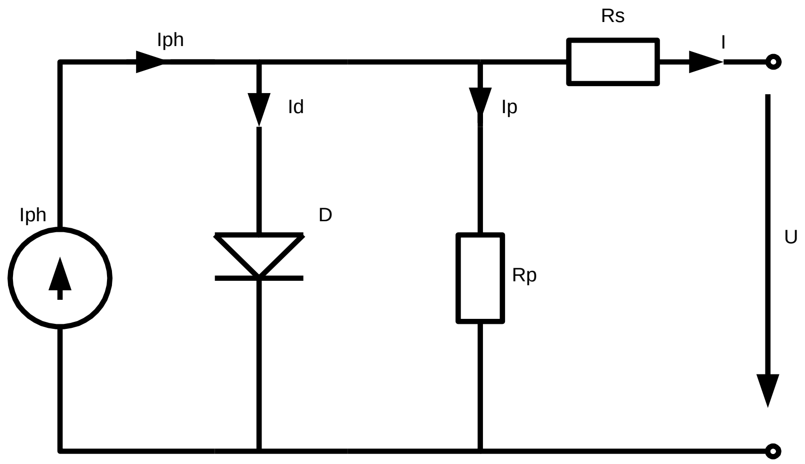

Fig. 2.3 *The one-diode model of a PV cell*

2.2.2 Double diode model of a PV cell

The double diode model of a PV cell takes into account the recombination phenomenon of load carries in the junction area and the variation of the ideality coefficient A with voltage [14-17].

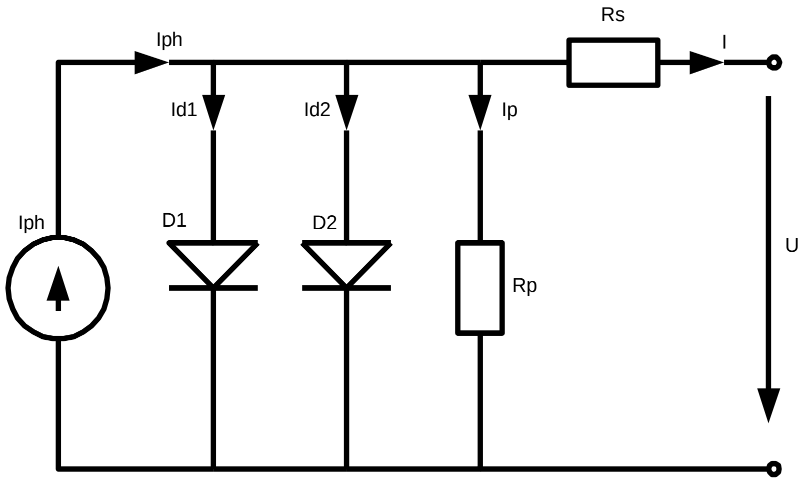

Fig. 2.4 *The double diode model of a PV cell [14]*

2.3 Characteristics of a PV cell

The characteristic current - voltage and power - voltage depend mainly on two parameters: the intensity of the solar radiation G and the temperature of the solar cell T (Fig. 2.5) [27].

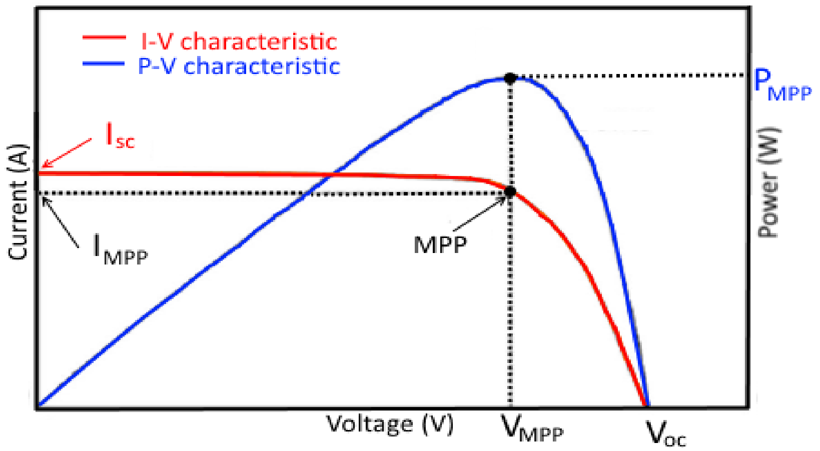

Fig. 2.5 *Characteristics I-U and P-U of a PV cell (under standard test conditions G=1000W/ m² and T=25^{0}C)[27]*

2.3.6 Application: simulation interface for a cell, module, PV array

The interface is made in the Matlab - Simulink simulation environment. With the help of this interface we can analyse and study different types of cells, modules or PV array used in photovoltaic installations, namely you can draw the characteristics I - U and P-U for different values of solar radiation and temperature. The model allows to raise the characteristics even in partial shading conditions. The implementation of the model is shown in Fig.2.17, and in Fig. 2.18 is presented the interface for the resulting model.

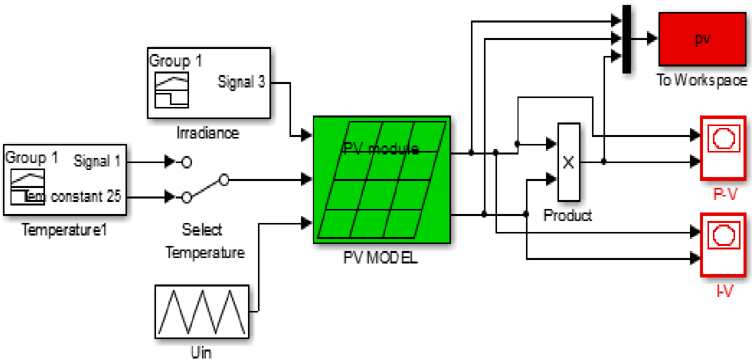

Fig. 2.17 *Simulink implementation of the model*

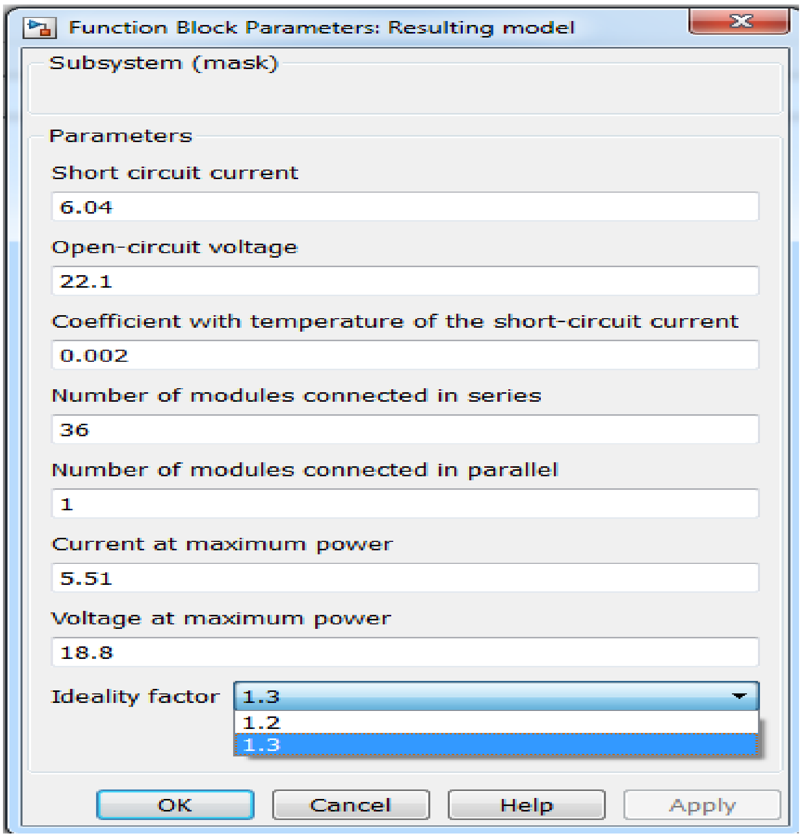

Fig. 2.18 *The interface for the resulting model*

The proposed model uses a friendly interface and can be used successfully to train technical staff operating in photovoltaic parks.

2.5 PV array architectures

The way PV panels and converters are connected determines the cost, operation and efficiency of the entire photovoltaic system. The main types of architectures for PV systems are: architecture with central inverter, string architecture , multi-string architecture, modular architecture, microinverter architecture.

In Fig. 2.33 and Fig. 2.34 are show the commonly used PV array architectures.

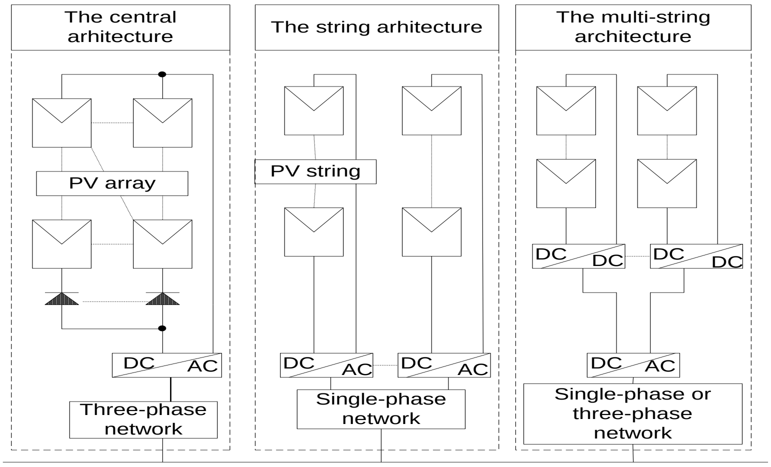

Fig. 2.33 *PV system architectures with central inverter, string, multi-string*

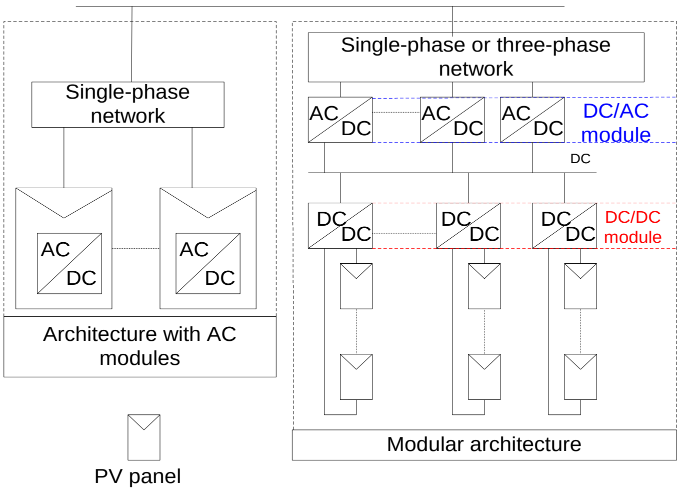

Fig. 2.34 *Modular architectures and with AC module*

2.6 Maximum power point tracking techniques (MPP)

In order to achieve the maximum power transfer between a PV generator and the receiver, MPPT systems have been designed with the tracking of the maximum power point (MPPT).

MPPT techniques are broadly classified into three groups [48], [58-62]: indirect techniques (off-line) that usually use the technical data of PV panels to estimate MPP, direct techniques (on-line) that use measured parameters (U, I) in real time, other methods comprise a combination of these methods or on the basis of indirect calculations.

Depending on the solar radiation, MPPT techniques are divided into two large groups [70--80]: MPPT at uniform radiation, MPPT under partial shading conditions.

Table 2.8 provides a comparative analysis of MPPT techniques based on specific performance indicators:

Tab. 2.8 *Comparative analysis of MPPT tehniques [46], [62], [83-85]*

MPPT Techniques	**PV power measurement**	**Dependence on PV are parametres**	**Sensors**	**Complexity**	**Tracking speed**	**Energy efficiency**	**Partial shading efficiency**	**Application**
OCV	Indirect	Yes	U	Simple	Slow	Low	No	Isolated
SCC	Indirect	Yes	I	Simple	Slow	Low	No	Isolated
CF	Indirect	Yes	U	Simple	Slow	Low	No	Isolated
P&O	Direct	No	U,I	Simple	Medium	Good	No	Isolate, System
HC	Direct	No	U,I	Simple	Medium	Good	No	Isolate, System
IC	Direct	No	U,I	Medium	Fast	Good	Yes	Isolate, System
FLC	Indirect	No	U,I	Complex	Fast	Very good	Yes	Isolate, System
ANN	Indirect	No	U,I	Complex	Fast	Good	Yes	System
PSO	Indirect	No	U,I	Medium	Fast	Good	Yes	Isolated

Conclusions

The theoretical study of the component elements of photovoltaic installations resulted in the creation of an interface for the study and analysis of cells, modules or PV array. It can be used successfully to train technical staff operating in photovoltaic parks.

The chapter contributes to the deepening knowledge of PV array architectures, MPPT methods and MPPT algorithms developed extensively in it.

Chapter 3

Modelling of a hybrid power source (HPS) based on renewable energy sources (RES) and energy storage devices (ESD)

Hybrid power systems for the production of electricity consist of two or more renewable sources, being provided with energy storage devices (batteries or ultra capacitors).

Objective

The main target is the modeling of hybrid power sources based on renewable energies, the one-diode model of an PV array with the estimation of the model parameters, as well as the modeling of electricity storage devices: accumulator battery and ultracapacitors.

3.1 RES/ESD HPS architectures

Three types of architectures are used in the design and realization of hybrid systems: architecture with common direct current bus (DC), architecture with common alternating current bus (AC), hybrid architecture (with common bus of DC and AC).

In Figs. 3.3 presents the architecture of a hybrid system with two DC and AC buses.

In this type of hybrid system, the AC power sources, namely the wind unit and the diesel unit, are connected to an AC bus system, and the DC power sources: PV panels and energy storage units are connected to a DC bus system. The two bus systems are interconnected with a bidirectional power converter.

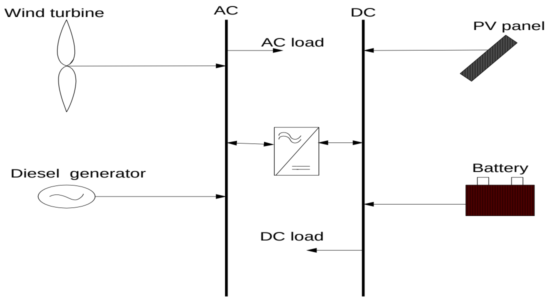

Fig. 3.3 *Hybrid system architecture with two bus systems: alternating current (AC) and direct current (DC)*

3.3 Models for energy and power storage devices

Hybrid power systems based on renewable energy sources consist of storage devices that allow to accumulate energy in the load gap and release it at the peak load.

3.3.2 Battery modeling

It is necessary to know the battery parameters to model the battery pack. A detailed model of a battery is presented in Fig.3.11 where are associated the following parameters: internal resistance with the three components: charging resistance R_c, variable discharge resistance R_d during charging - discharge and resistance R_b, polarization capacity C, V_p and V_b are open circuit voltage, capacitor voltage C_p and terminal voltage C_p, charging-discharging current [103].

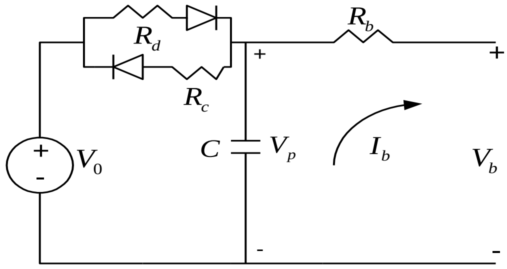

Fig. 3.11 *The Thevenin equivalent battery model[103]*

Conclusions

This chapter classifies the architectures for hybrid power sources and presents the simplified model of a PV array.

There are analyzed electricity storage devices: batteries and ultracapacitors.

Chapter 4

Comparative analysis of maximum power point tracking techniques(MPPT)

MPPT techniques and algorithms allow tracking the maximum power point MPP to transfer the maximum power from the photovoltaic generator to the receiver in order to streamline the photovoltaic installation.

Objective

This chapter aims to perform a comparative analysis, from the point of view of the performance indicators, of three algorithms: the Perturbe and Observe (P&O) algorithm and two algorithms based on the ES control: aESC and mESC, the testing being done for a PV panel at different irradiation profiles using the Matlab - Simulink environment.

4.4 Results

Fig. 4.6 presents comparing diagram of performances of the three algorithms:

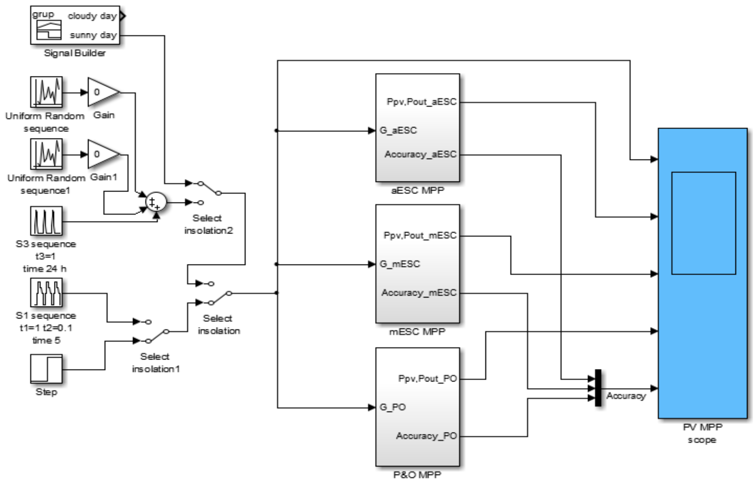

Fig. 4.6 *The performance comparison diagram of the three algorithms: aESC, mESC and P&O*

4.4.1 Step irradiation

The simulation results for the irradiation level ($G=500W/m^2$) and step ($A = \Delta I = 0.1$ A) are presented in Fig. 4.7:

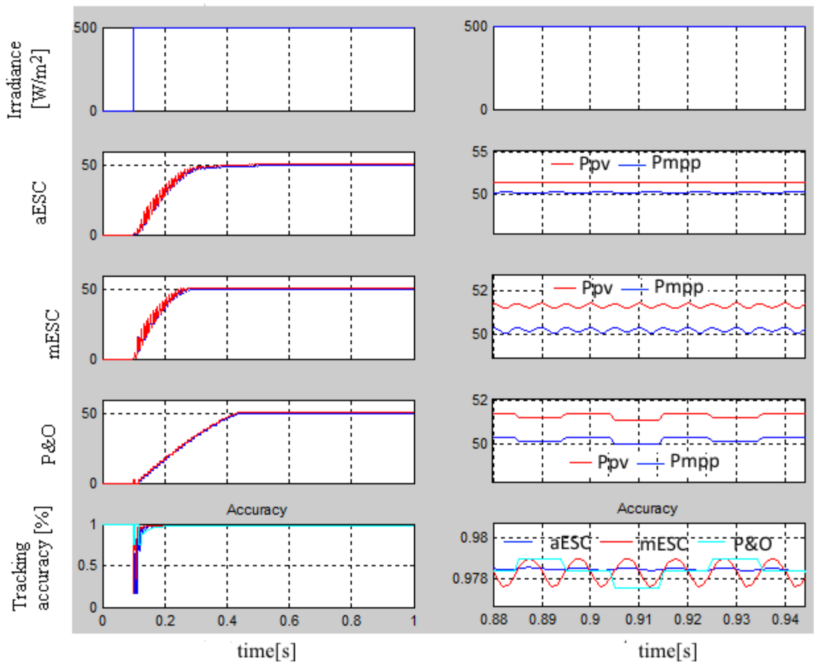

Fig. 4.7 *Simulation results for irradiation level ($G=500W/m^2$) and step $A = \Delta I = 0.1$ A(with magnification on the right side)[120, 122]*

4.4.2 Variable irradiation profile

The performances were also tested for a variable irradiation profile, the obtained results being presented in Fig. 4.9, Fig. 4.10 and Fig. 4.11. at different time sequences.

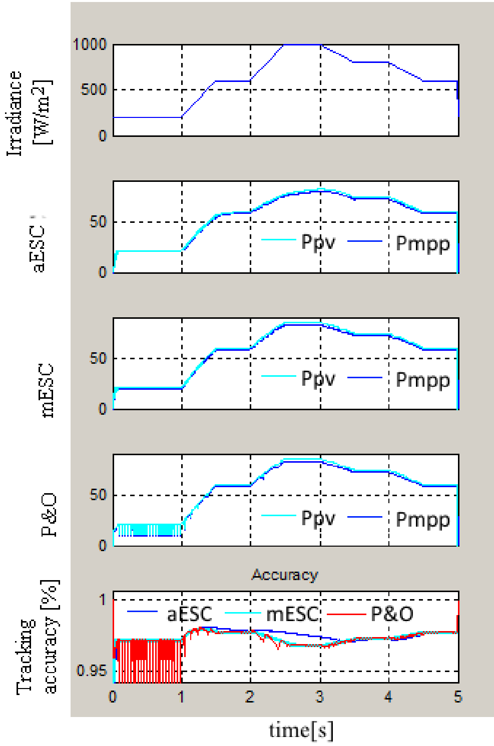

Fig. 4.9 *Simulation diagram for variable irradiation profile (t2 = 0.5) [120, 122]*

4.4.3 Irradiation profile for one day

The simulation diagram for a sunny day is shown in Figs. 4.13:

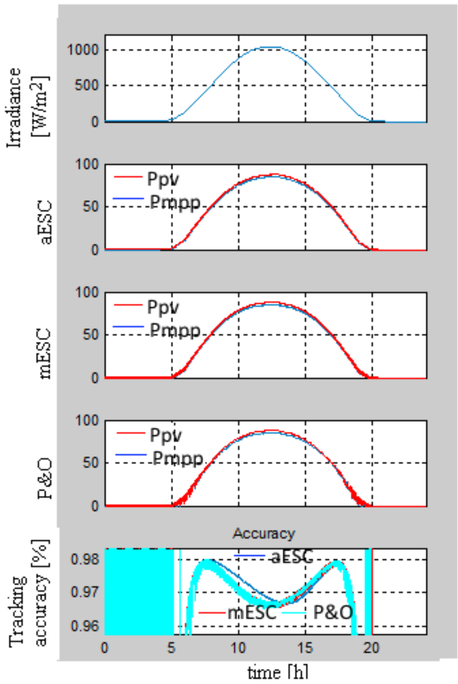

Fig. 4.13 *The simulation diagram for a sunny day [120, 122]*

Conclusions

The comparative analysis, regarding the performances of the three algorithms, shows good results for the MPPT techniques based on the ES control. The aESC control is superior to the mESC control and the P&O algorithm, obtaining a higher accuracy in finding the maximum power point. The aESC control has the following performance: a negligible oscillation of power after the maximum power point is caught and internal robustness, performances that are ideal in case of rapid weather changes. The P&O algorithm performs well at constant solar radiation, instead it loses control of tracking the maximum power point at rapid weather changes.

Chapter 5

Global MPPT Techniques(GMPPT)

Large photovoltaic systems are composed of several photovoltaic modules connected in series-parallel, some of the modules can be illuminated differently due to clouds, tree shadows, buildings and neighboring objectives. This phenomenon known as partial shading, determines either the decommissioning of the system or a P-V power characteristic with several local peaks, only one of them being the global point of maximum power. Hence the need to develop algorithms for GMPP tracking under partial shading conditions (PSC).

Objective

The chapter presents the method for GMPP search, based on a new extreme search scheme: Perturbed Extremum Seeking Control (PESC) [122].

Several PESC schemes are known depending on the included filter block: the global PESC scheme based on one BPF filter (G1PESC) and the scheme based on two BPF filters (G2PESC). A comparative analysis of the simulation results is made for the two schemes G1PESC and G2PESC and between the global PESC scheme based on a BPF filter (G1PESC) and the Perturbe & Observe (P&O) algorithm on tracking the maximum GMPP power point.

5.3.3 Comparative analysis of simulation results for G1PESC and G2PESC

The simulation results for the signals corresponding to the two schemes are displayed in Fig. 5.9 (a) și Fig. 5.9 (b):

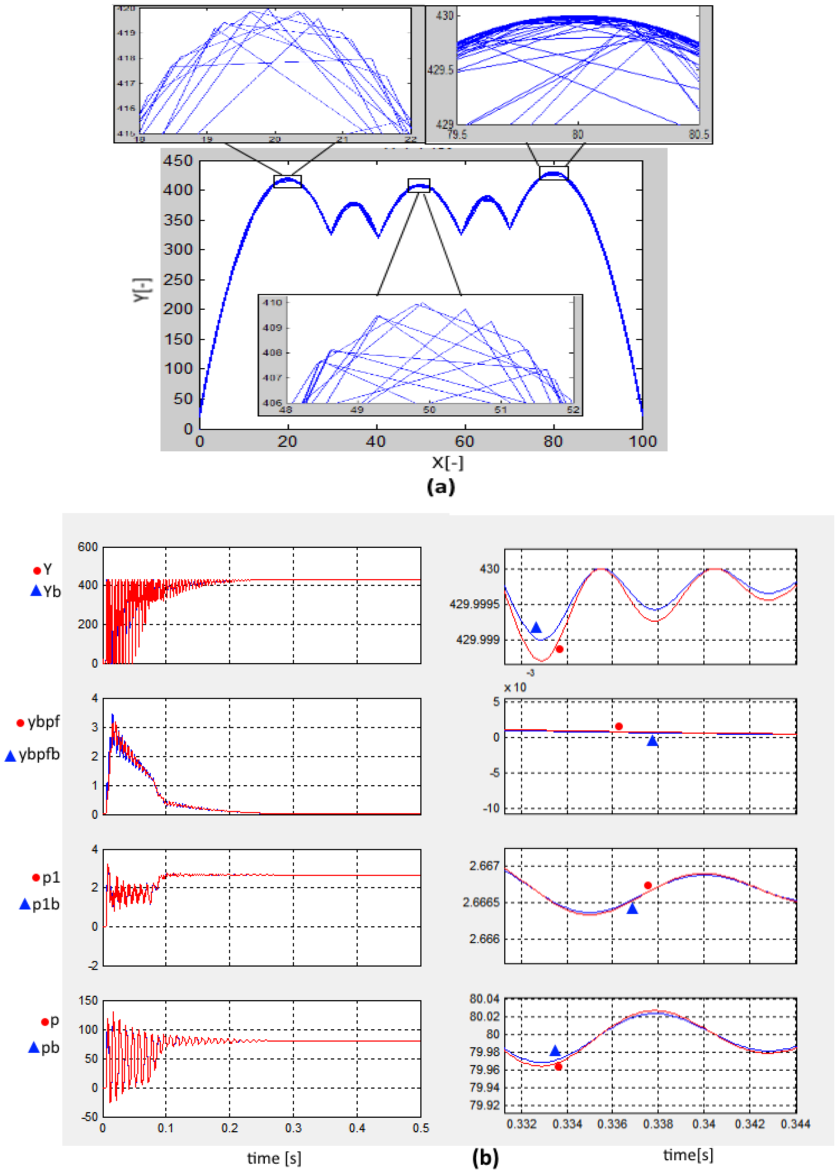

Fig. 5.9 *GMPP search simulation results using G1PESC and G2PESC schemes (magnified on the right) [126]*

The simulation results for the two global schemes based on ES control show that after the GMPP search phase the signals are almost identical, their difference tending to zero, concluding that the performances for both schemes are similar.

5.4 Comparison between the global PESC scheme based on a BPF filter (G1PESC) and the Perturbe & Observe (P&O) algorithm.

The simulation was done for a PV panel at different test sequences and real irradiation profile. The results of the simulation for a sunny day and a cloudy day are highlighted in Fig. 5.18 și Fig. 8.19.

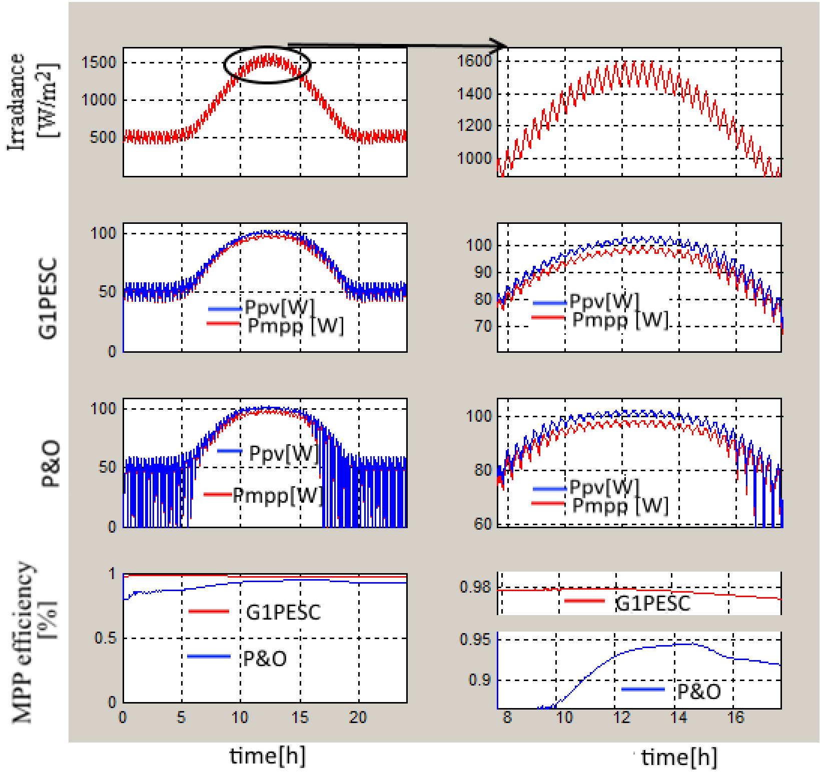

***Fig. 5.18** Simulation diagram for a sunny day (magnified on the right)*

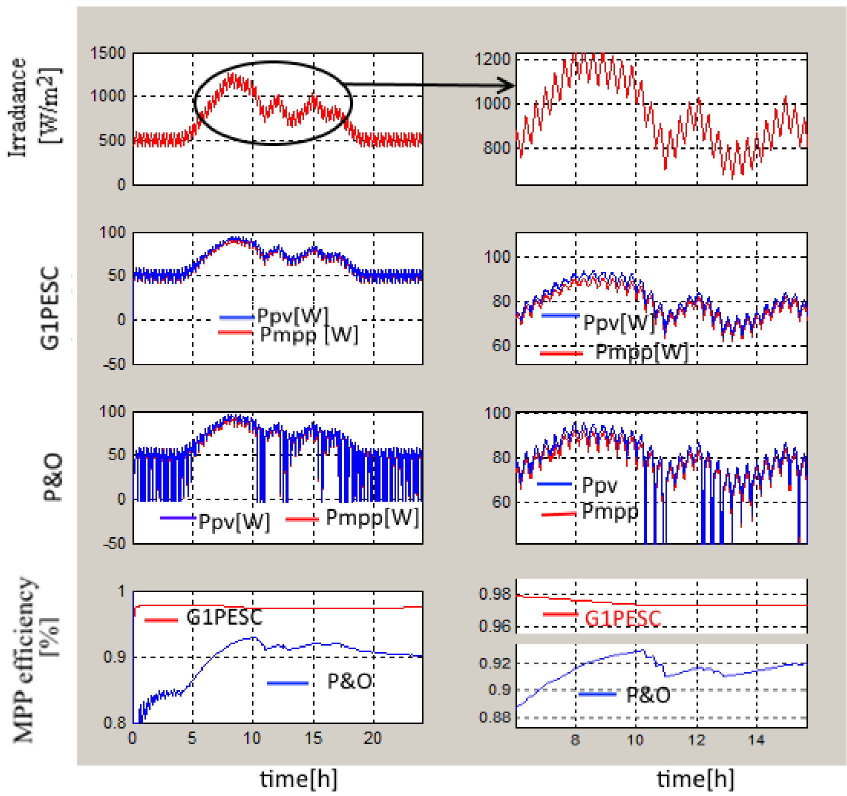

***Fig. 5.19** Simulation diagram for a cloudy day (with magnification on the right)*

Conclusions

From the analysis of the simulation results for the two schemes (G1PESC and G2PESC), it results that in the GMPP search phase there are higher oscillations for G1PESC, after which the signals are almost identical, their difference tending to zero. This denotes similar performance for the two schemes.

In the second stage, the performances of G1PESC and P&O were tested for a real profile (sunny day, cloudy day). The simulation results show good results for the G1PESC algorithm obtaining a high efficiency of 98% compared to the P&O algorithm which has an efficiency of 92%. The G1PESC algorithm has small oscillations in case of rapid weather changes, unlike P&O which has large oscillations and cannot track the maximum power point during rapid weather changes.

Chapter 6

Load following control technique for optimized energy management of a hybrid power source (HPS) based on a fuel cell (Fuel Cell-FC) and renewable energy sources (RES)

A hybrid power system based on renewable energies consists of: renewable energy sources, conventional energy sources, energy storage components, power converters and direct current or alternative current consumers.

6.2 Case study for an FC/RES HPS architecture

In the case study, two topologies were studied: the Air-LF topology and the Fuel-LF topology, which uses a fuel cell flow control strategy (air and hydrogen) based on Load following mode control.

Objectives

The objectives of this case study are the following: 1) modeling the FC/RES HPS configuration; 2) presentation of the performances of the two strategies: Air-LF and Fuel-LF for constant or variable load profile, without or with renewable energy sources; analysis of energy efficiency ($Fuel_{eff}$) and fuel consumption for both topologies.

6.2.9 Performance indicators and optimization function

The performance indicators used are: fuel efficiency ($Fuel_{eff}$), fuel cell efficiency (η_{sys}) and fuel consumption ($Fuel_T$) during an operating cycle:

$$Fuel_{eff} = P_{FCnet}/FuelFr \quad (6.18)$$

$$\eta_{sys} = P_{FCnet}/P_{FC} \quad (6.19)$$

$$Fuel_T = \int FuelFr(t)dt \quad (6.20)$$

Differences in performance indicators are described by the equations:

$$\Delta P_{FCnet} = P_{FCnet1} - P_{FCnet2} \quad (6.21)$$

$$\Delta \eta_{sys} = \eta_{sys1} - \eta_{sys2} \quad (6.22)$$

$$\Delta Fuel_{eff} = Fuel_{eff1} - Fuel_{eff2} \quad (6.23)$$

$$\Delta Fuel_T = Fuel_{T1} - Fuel_{T2} \quad (6.24)$$

Where: indices 1 and 2 represent the results obtained for the topology (Air-LF) respectively (Fuel-LF).

Apart from other optimization techniques, the optimization function considered in this case study is a mixed function given by the relation [158,159,160]:

$$k_{net}P_{FCnet} + k_{fuel}Fuel_{eff} \quad (6.25)$$

The parameters k_{net} și k_{fuel}, are considered for three cases: case A: k_{net}=0.5, k_{fuel}=0; case B: k_{net}=0.5, k_{fuel}=25; case C: k_{net}=0.5, k_{fuel}=50.

6.2.10 Results

Simulation results for constant load (7kW) without renewable energy sources (k_{net}=0.5, k_{fuel}=0) are shown in Fig. 6.14.

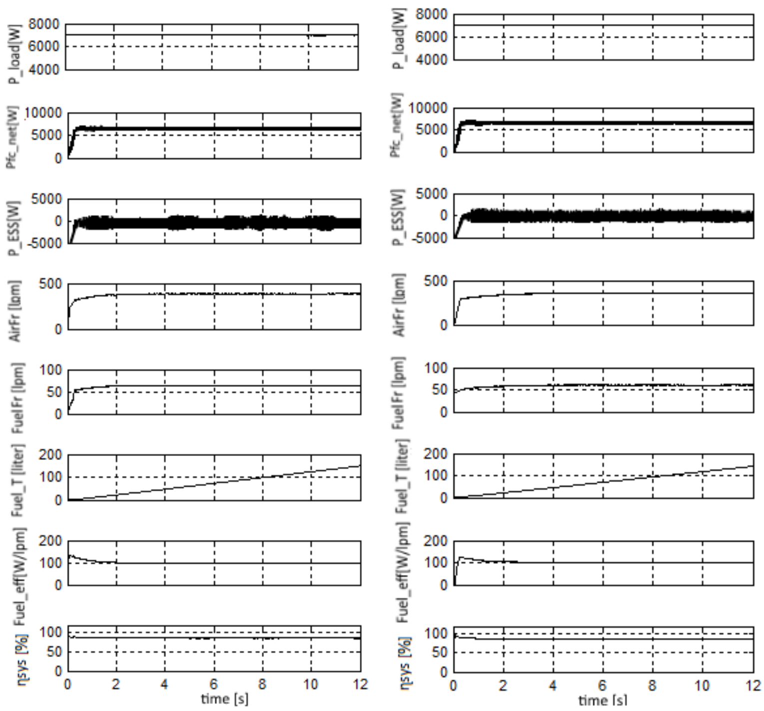

Fig. 6.14 *Simulation results for FC / RES HPS topology at constant load (7kW)*

without renewable energy sources, (Air-LF) on the left, (Fuel-LF) on the right

The differences of the performance indicators are presented in Fig. 6.15 - 6.18 to compare the two topologies.

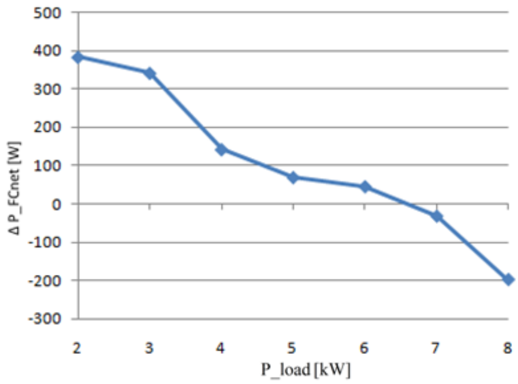

Fig. 6.15 *Differences between net powers (Δ P_{FCnet}) generated by FC*

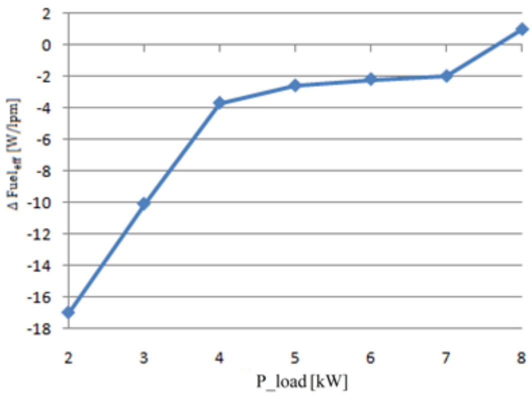

Fig. 6.16 *Differences in fuel efficiency (Δ $Fuel_{eff}$) in the case of the two topologies*

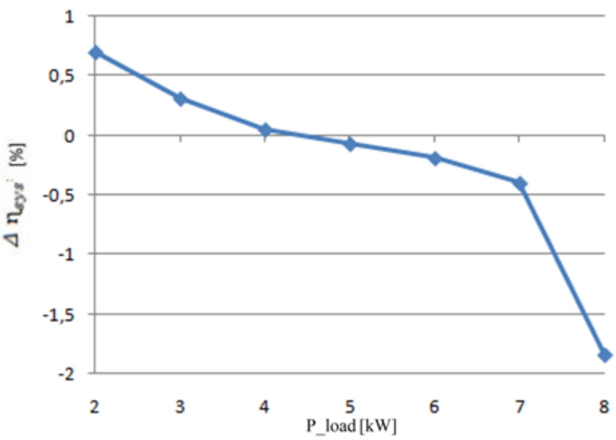

Fig. 6.17 *Efficiency differences (Δ η_{sys}) for the two topologies*

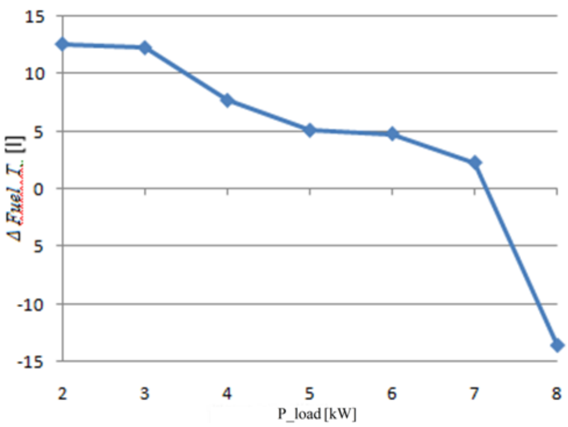

Fig. 6.18 *Differences in fuel consumption ($\Delta\ Fuel_T$) in the case of the two topologies*

The Air-LF topology compared to Fuel-LF has lower fuel consumption ($\Delta Fuel_T < 0$ și $Fuel_{eff} > 0$) at maximum load (între 7.5 kW și 8 kW) and higher energy efficiency ($\Delta\eta_{sys} > 0$și$\Delta P_{FCnet} > 0$) at low load (up to 4.5 kW and 5.5 kW). Both topologies give close results to the nominal load (around 6 kW). The first Air-LF topology is required for a car equipped with a fuel cell running on the motorway and the second Fuel-LF topology is required for a car that climbs a hill.

Next, the optimization function will be considered for case B *(*k_{net}=0.5, k_{fuel}=25*)* and in case C *(*k_{net}=0.5, k_{fuel}=50) to compare the fuel consumption for both topologies.

The results of the constant load simulations, variable load with the same profile of renewable energy sources are performed for both topologies but in the case of B (k_{net}=0.5, k_{fuel}=25) and in case C (k_{net}=0.5, k_{fuel}=50) to compare the fuel consumption for $k_{fuel} \neq 0$. The results obtained are presented in the tables: Table 6.5 and Table 6.6 for different constant load values and the average variable load value. The differences in fuel consumption for different values of P_{load} and $P_{load(AV)}$ are shown in Fig. 6.21 and Fig. 6.22.

Tab. 6.5 *Differences in fuel consumption for case B and C, for the same P_{RES} profile*

	case B: k_{net}=0.5, k_{fuel}=25		**case C: k_{net}=0.5, k_{fuel}=50**	
P_{load}	**$\Delta Fuel_{TB} = Fuel_{T1B} - Fuel_{T2B}$**	**$60 \cdot \Delta Fuel_{TB}/12$**	**$\Delta Fuel_{TC} = Fuel_{T1C} - Fuel_{T2C}$**	**$60 \cdot \Delta Fuel_{TC}/12$**
[kW]	[l]	[lpm]	[l]	[lpm]
6	0,54	2,7	-4,33	-21,65

7	-0,33	-1,65	-3,1	-15,5
8	-2,09	-10,45	-2,97	-14,85
9	-4,7	-23,5	-5,3	-26,5
10	-9,8	-49	-11,9	-59,5

Tab. 6.6 *Differences in fuel consumption for different $P_{load(AV)}$*

	case B: k_{net}=0.5, k_{fuel}=25		**case C: k_{net}=0.5, k_{fuel}=50**	
P_{load}	**$\Delta Fuel_{TB(LC)}= Fuel_{T1B(LC)}- Fuel_{T2B(LC)}$**	**$60 \cdot \Delta Fuel_{TB(LC)}/12$**	**$\Delta Fuel_{TC(LC)}= Fuel_{T1C(LC)}- Fuel_{T2C(LC)}$**	**$60 \cdot \Delta Fuel_{TC(LC)}/12$**
[kW]	[l]	[lpm]	[l]	[lpm]
6	0,88	4,4	-1,57	-7,85
7	-0,04	-0,2	0,69	3,45
8	-1	-5	-4,9	-7,25
9	-10,9	-54,5	-13,8	-69
10	-20,7	-103,5	-23,9	-119.5

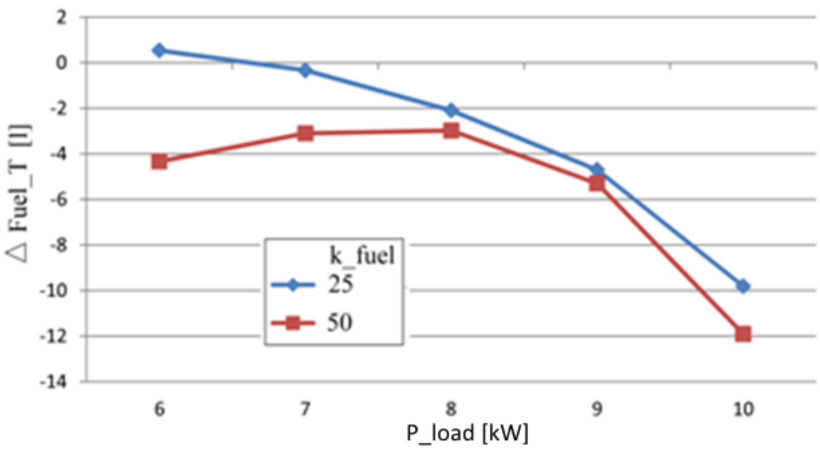

Fig. 6.21 *Differences in fuel consumption ($\Delta\ Fuel_T$) for different P_{load}*

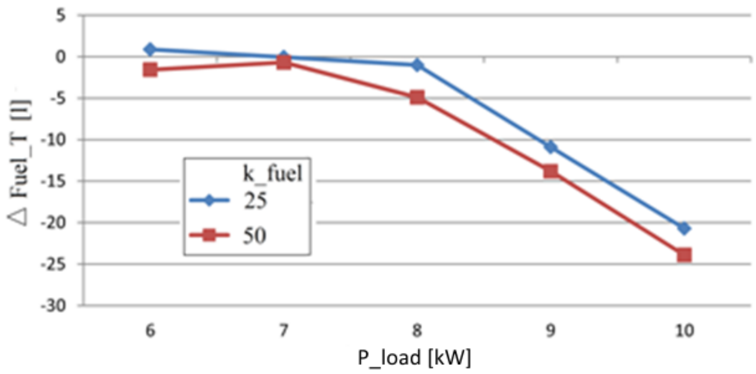

Fig. 6.22 *Differences in fuel consumption ($\Delta\ Fuel_T$) for different $P_{load(AV)}$*

The analysis of the results shows a lower fuel consumption for k_{fuel} =50 than for k_{fuel} =25.

Chapter 7

Optimization of Hybrid Power Systems (HPS)

In recent years, several software tools have been developed for the optimal sizing of an integrated system based on renewable energy sources [163,164]. These software tools used for sizing and modelling hybrid energy systems based on renewable sources include: HOMER, iHOGA, RET-screen, Hybrid 2 [165,166,167,168,169,170,171,172]. Of the software listed above, two of them are frequently applied, namely: HOMER and iHOGA [173,174].

Objective

A case study is presented for a hybrid power system located near Rm. Vâlcea in order to be optimized from a technical and economic point of view.

7.4 Hybrid power system - simulation in HOMER

The hybrid system contains five major components that need to be designed. The components are: photovoltaic panels, wind turbine, Diesel generator, battery, converter and electric charge.

7.5 Results obtained in HOMER

Fig. 7.5 (a) shows the waveforms of 8th of January for the hybrid system, and in Fig. 7.5 (b) the waveforms for charging and discharging the battery.

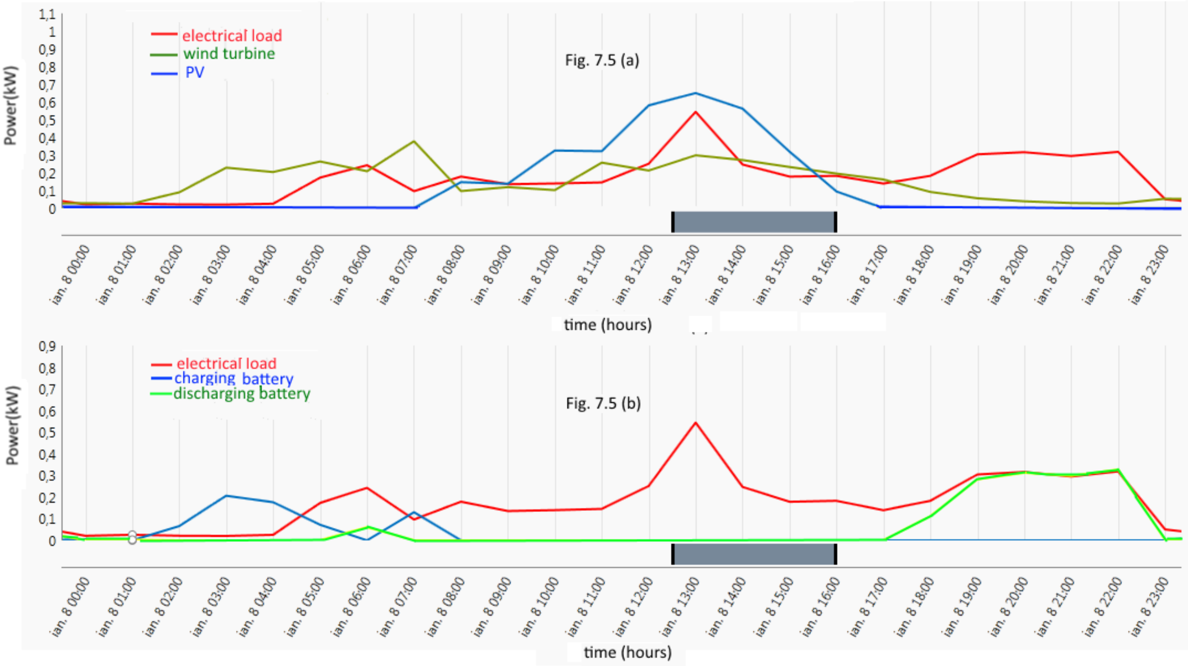

Fig. 7.5 *Waveforms using HOMER software (Fig. 7.5.a - waveforms for the hybrid system, Fig. 7.5.b - waveforms for charging and discharging the battery)*

7.6 Hybrid power system - simulation in iHOGA

As in the case of the HOMER simulator, the hybrid system contains: photovoltaic panels, wind turbine, Diesel generator, battery, converter and electric charge.

7.7 Results obtained in iHOGA

Fig. 9.10shows the waveforms of 8th of January for the hybrid system.

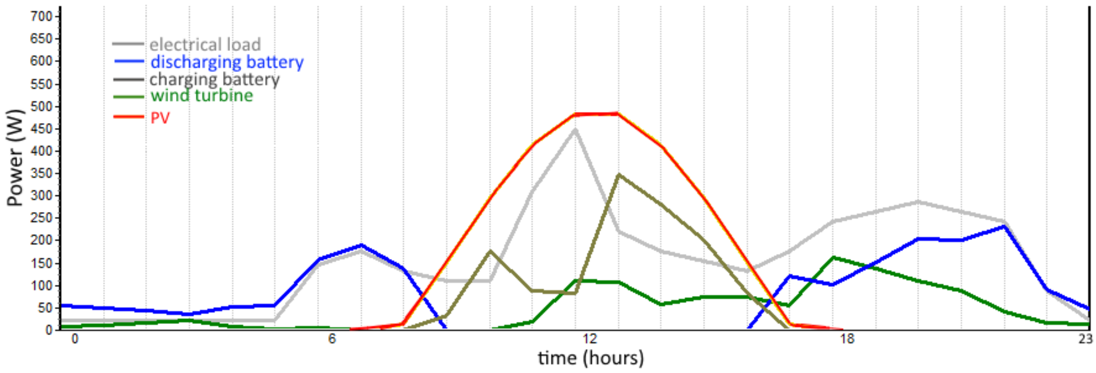

Fig. 7.10 *Waveforms using iHOGA software*

Conclusions

The input data are the same for both analysis software tools used (HOMER and iHOGA). Given the results of the hybrid system sizing, the iHOGA program provides more efficient and reliable design solutions than HOMER.

Chapter 8

Case study for a photovoltaic park

The objective of this chapter is to make a performance analysis for a photovoltaic power plant based on remote control, surveillance, metering and monitoring using SCADA equipment. The data processed by the SCADA system refer to: energies, powers, currents on the three phases, phase voltages, technical condition of the electrical equipment.

Based on the processed data, the main performance indicators of the photovoltaic park are analysed, the energy management of the photovoltaic park can be performed for a longer or shorter period of time.

8.3 Weather data

Weather data are provided using the STM36 weather station located within the photovoltaic park (Fig. 8.8).

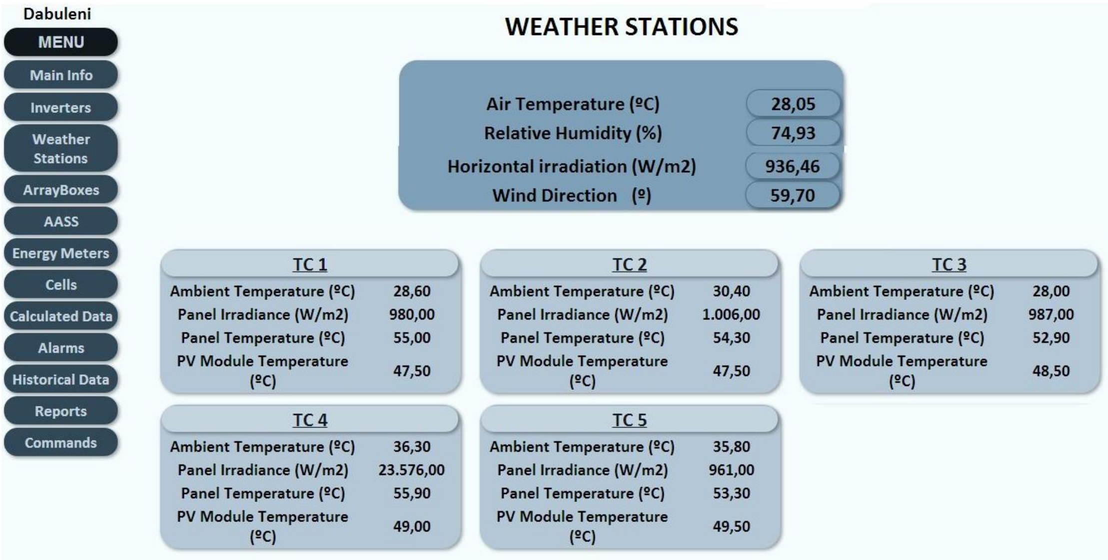

Fig. 8.8 *Weather station data [202]*

8.4 Results

Fig. 8.15 shows the human-machine interface, which provides information about: name, photovoltaic park location, peak power, instant active power, total energy delivered, energy delivered daily), ambient temperature, solar radiation and total availability [203,205].

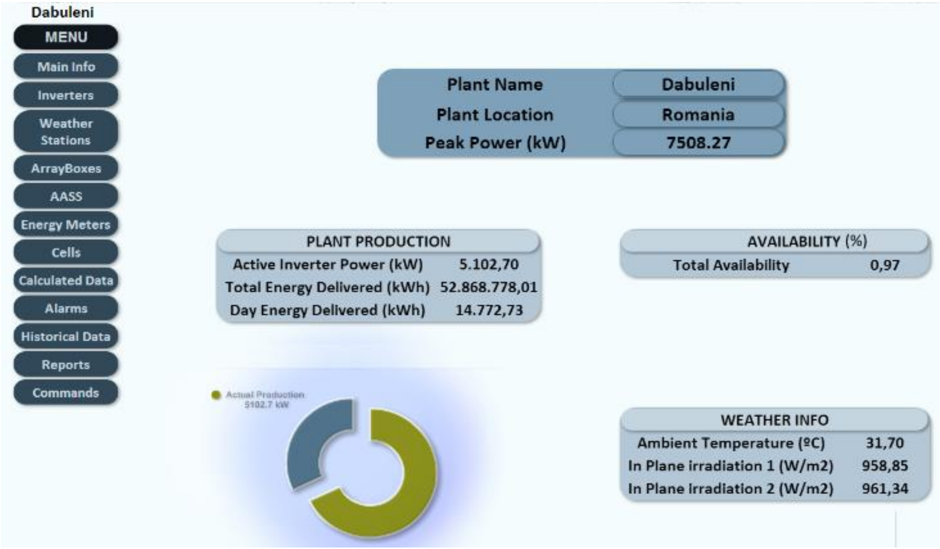

Fig. 8.15 *Human interface – machine [203]*

Fig. 8.16 shows the diagram of powers, currents and voltages for all connection strings of photovoltaic panels.

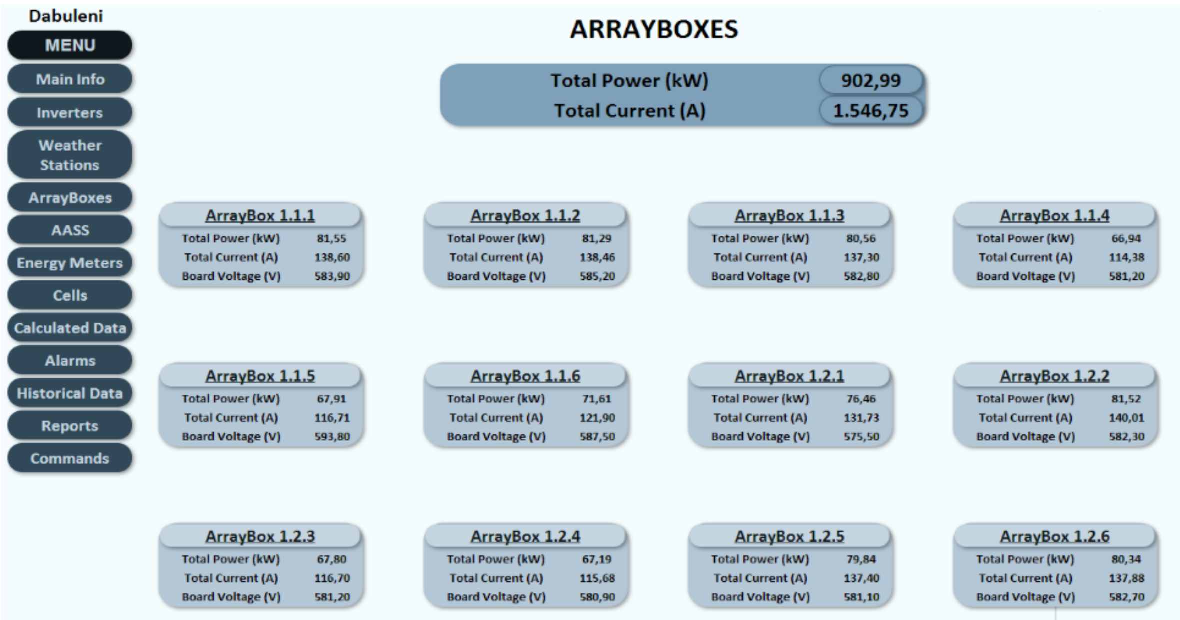

Fig. 8.16 *Diagram of powers, currents and voltages for all strings of photovoltaic panels*

Information about malfunctions, park efficiency and availabilitydaily or monthly photovoltaics are also shown graphically. The production of energy produced and estimated, the availability of the photovoltaic park, the load factor, the performance ratio, the energy of solar radiation are given tabularly and the comparative analysis is carried out between what has been achieved and what has been estimated.

8.4.1 Maintenance based on the results obtained

The processing of the data obtained by the SCADA system allows the implementation of a corrective and preventive maintenance plan of the photovoltaic park based on defects in the equipment during the operation of the installations.

1. PV MODULES – VISUAL INSPECTION
2. CLEANLINESS OF THE MODULES
3. THERMOGRAPHIC INSPECTION
4. INVERTERS. GENERAL CONDITIONS
5. INVERTERS. OTHER WORKS
6. INVERTERS. THERMOGRAPHIC INSPECTION AND EARTH CONNECTION
7. STRUCTURE
8. STRING AND COMBINER BOXES
9. DC & AC CABLING
10. GROUNDING NETWORK
11. ENERGY METERS
12. METEOROLOGICAL STATIONS
13. CLEANING OF PYRANOMETERS
14. CIVIL INFRASTRUCTURES; FENCE AND ROADS
15. VEGETATION CONTROL
16. TERRAIN CONDITION, DRAINAGE SYSTEM, TRENCHES AND MANHOLES
17. SECURITY SYSTEMS
18. TRANSFORMATION CENTERS AND SWITCHING CENTERS
19. CHECKING THE SENZOR SYSTEM
20. SCADA
21. DIESEL GENERATOR

Fig. 8.36 *Installations where the maintenance plan is to be carried out*

Conclusions

With the help of the SCADA system, the photovoltaic power plant is monitored remotely, monitors and supervises electrical, mechanical parameters and determines the efficiency and reliability of the photovoltaic park.

On the basis of the data stored by the SCADA system, the maintenance plan and prophylactic checks may be established during a calendar year.

Chaper 9
Conclusions

This chapter presents the results obtained, the original contributions, the list of original works as well as the prospects for further development.

9.1 Results obtained and original contributions

The following is a summary of the results and contributions for the field addressed in the paper.

Specific objectiv	Results obtained	Results published in scientific papers
OS1	Two theoretical analyzes were performed: an overview of the construction, the principle of operation of the solar cell, the issue of extracting maximum power from a photovoltaic system, modelling photovoltaic cells using one-diode model and the double diode model, the current-voltage and power-voltage characteristics. The efficiency analysis for different PV panel connection configurations; respectively a comparison between different algorithms for tracking the maximum power point.	ECAI 2014 - Energy efficiency analysis of various topologies, control techniques and technologies used for photovoltaic panels. Scientific report no. 1 - Energy efficiency analysis of different topologies, techniques and technologies used for photovoltaic panels.
OS2	A simulation interface was created for a cell, module or PV area, based on the mathematical equations used to model the component elements of a photovoltaic installation, which allowed the simulative testing of the proposed algorithms. The interface is made in the Matlab-Simulink simulation environment. With the help of the interface different types of PV modules used in the construction of photovoltaic parks can be analyzed, studied, can also be used to train technical staff operating in photovoltaic parks on	SGEM 2017 - Simulation interface of photovoltaic (PV) cell, PV module, and PV array using Simulink.

	the characteristics of current-voltage, power-voltage for different values of solar radiation and temperature as well as on the behaviour in partial shading conditions for one or more PV modules.	
OS3	A comparative analysis of the maximum power point tracking (MPPT) techniques was made using the following algorithms: the P&O algorithm and two algorithms proposed by the thesis author based on the ES control (aESC and mESC). The performance of the three algorithms was tested on a PV module built of 36 cells connected in series.	ECAI 2015 - Performance comparison of three MPPT algorithms: aESC, mESC and P&O. AGIR Bulletin - Comparison of the performances of the search algorithms of the maximum power point of photovoltaic systems. Scientific report no. 3 – Comparison analysis of maximum power point tracking (MPPT) techniques. JEEECCS 2015 - On the micro-inverter performance based on three MPPT controllers.
OS4	A comparison was made between the G1PESC scheme based on one BPF filter and the global G2PESC scheme based on two BPF filters.	ECAI 2016 - Performance of the Global MPPT Algorithms a brief overview and case studies. Scientific Report No. 4 - Global MPPT Techniques (GMPPT).
OS5	A case study was performed for an FC / RES HPS architecture. The analysis of two topologies (Air-LF and Fuel-LF) is presented for constant load profile without renewable energy sources, constant	Energy Conversion and Management 2019 - Hydrogen saving through optimized control of both fueling flows of the Fuel Cell Hybrid Power System under a variable load demand and an

	load profile with renewable energy sources and variable load profile with renewable energy sources to decide which topology it's better.	unknown renewable power profile. ICATE 2018 - On the energy efficiency of standalone fuel cell/renewable hybrid power sources. ECAI 2018 - Renewable (REW) / Fuel Cell (FC) Hybrid Power System with mitigation of the REW variability by the FC fuel flow control. Scientific report no. 5 - Control technique with load tracking for an optimized energy management of a hybrid power source (HPS) based on a fuel cell (Fuel Cell-FC) and renewable energy sources (RES). SGEM 2018 - Energy efficiency for renewable energy application.
OS6	A case study was conducted on the sizing of a hybrid power system based on renewable energies using HOMER and iHOGA applications.The same case study was designed under the same environmental and load conditions using the two HOMER and iHOGA software. The results are presented in both tabular and graphical form for a better view of the differences between them. A comparative analysis was also done, showing the	ECAI 2017 - Design of hybrid power systems using HOMER simulator for different renewable energy sources. RESRB 2017 - Comparative analysis of Hybrid Power Systems based on HOMER and iHOGA simulators.

	advantages and disadvantages, to allow the investor to choose the most convenient solution.	
OS7	A case study was performed for a photovoltaic park using the SCADA system in order to achieve its energy management. The case study refers to a photovoltaic plant located in a plain area of Romania.	ECAI 2020 - Comparative study regarding the integration of photovoltaic sources in agriculture. ECAI 2020 - The design of the graphical interface for the SCADA system on an industrial platform. POWER SYSTEMS - Microgrid arhitectures, control and protection methods.
OS8	Development of a system for measuring the human electromagnetic field, which can be used to analyze the influence of electric fields (generated for example by a PV plant) on people close to the field source (operating personnel in a photovoltaic plant).	ECAI 2020 - Determining Human Presence through the Analysis of the Electric Field using MATLAB environment.

9.3 List of original works

The results obtained by the author in fields relevant to the doctoral thesis were disseminated by participating in conferences and scientific communication sessions and by publishing articles, including the following:

Published in ISI WOS listed journals

1) Nicu Bizon, Ioan Cristian **Hoarcă**, Hydrogen saving through optimized control of both fueling flows of the Fuel Cell Hybrid Power System under a variable load demand and an unknown renewable power profile, **Energy Conversion and Management**, Vol. 184, pp. 1-14, March 2019, **Impact Factor: 8.208 (2019)**, **WOS:000461728300001**

Published in ISI WOS indexed conferences

2) **Hoarcă** Cristian, Raducu Marian, Energy efficiency analysis of various topologies, control techniques and technologies used for photovoltaic panels Part I: On the PV modeling and problem of extracting the maximum power, **ECAI 2014** - International Conference 6th Edition on Electronics Computers and Artificial Intelligence, 23-25 Oct, 2014, Pitesti, România, **WOS:000380489500049**
3) **Hoarcă** Cristian, Raducu Marian, Constantinescu Luminita-Mirela, Energy efficiency analysis of various topologies, control techniques and technologies used for photovoltaic panels Part II: Maximum power point tracking algorithms, **ECAI 2014** - International Conference 6th Edition on Electronics Computers and Artificial Intelligence, 23-25 Oct, 2014, Pitesti, România, **WOS:000380489500050**
4) **Hoarcă** Cristian, Raducu Marian, Performance comparison of three MPPT algorithms: aESC, mESC and P&O, **ECAI 2015** - International Conference 7th Edition on Electronics Computers and Artificial Intelligence, 25-27 June, 2015, Bucharest, România, **WOS:000370971100023**
5) **Hoarcă** Cristian, Bizon Nicu, Performance of the Global MPPT Algorithms - a brief overview and case studies, **ECAI 2016** - International Conference 8th Edition on Electronics Computers and Artificial Intelligence, June 30-July 02, 2016, Ploiesti România, **WOS:000402541200061**
6) **Hoarcă Cristian**, Bizon Nicu, Badita Alexandru. **WOS:000425865900123 Hoarcă Cristian**, Bizon Nicu, Badita Alexandru. **WOS:000425865900123 Hoarcă** Cristian, Bizon Nicu, Badita Alexandru, Design of hybrid power systems using HOMER simulator for different renewable energy sources, **ECAI 2017** - International Conference 9th Edition on Electronics Computers and Artificial Intelligence, June 29-July 01 , 2017, Targoviste, România, **WOS:000425865900123**
7) **Hoarcă** Cristian, Enescu Florentina, On the energy efficiency of standalone fuel cell/renewable hybrid power sources Part I: Simulation results for constant load profile without RES power, **ICATE 2018 -**

International Conference 14th Edition on Applied and Theoretical Electricity, 04-06 Oct, 2018, Craiova, România, **WOS:000487278600031**

8) **Hoarcă** Cristian, Enescu Florentina, On the energy efficiency of standalone fuel cell/renewable hybrid power sources Part II: Simulation results for variable load profile with different renewable energy sources profiles (RES), **ICATE 2018** - International Conference 14th Edition on Applied and Theoretical Electricity, 04-06 Oct, 2018, Craiova, România, **WOS:000487278600061**
9) Bizon Nicu, Mazare Alin Gheorghita, Oproescu Mihai, Lopez-Guede Jose Manuel, Varlam Mihai, **Hoarcă** Cristian, Renewable (REW) / Fuel Cell (FC) Hybrid Power System with mitigation of the REW variability by the FC fuel flow control, **ECAI 2018 -** International Conference 10th Edition on Electronics Computers and Artificial Intelligence, 28-30 June, 2018, Iasi, România, **WOS:000467734100086**
10) Bizon Nicu, Lopez-Guede Jose Manuel, **Hoarcă** Cristian, Culcer Mihai, Iliescu Mariana, Fuel Cell (FC) Hybrid Power System with mitigation of the load power variability by the FC fuel flow control, **ECAI 2018 -** International Conference 10th Edition on Electronics Computers and Artificial Intelligence, 28-30 June, 2018, Iasi, România, **WOS:000467734100034**

Book chapters

11) Enescu Florentina Magda, Bizon Nicu, **Hoarcă** Cristian, Energy management of the grid connected PV array, **Power Systems, Chapter 11 of book: Microgrid arhitectures, control and protection methods**, Springer Verlag London Limited, 2019, ISBN 978-3-030-23722-6, https://doi.org/10.1007/978-3-030-23723-3_11

Published in SCOPUS indexed magazines

12) **Hoarcă** Cristian, Bizon Nicu, Ștefănescu Ioan, Simulation interface of photovoltaic (PV) cell, PV module, and PV array using Simulink, **SGEM 2017** – International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, 29 June 2017

through 5 July 2017, Albena, Bulgaria. Paper:. Volume 17, Issue 42, 2017, pp. 545-556, ISSN: 13142704

13) **Hoarcă** Ioan Cristian, Enescu Florentina Magda, Bizon Nicu, Energy efficiency for renewable energy application, **SGEM 2018** - International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, Volume 18, Issue 4.1, 2018, Pages 325-332, 2-8 July, 2018, Albena, Bulgaria, ISSN: 13142704

Published in magazines indexed in other international databases (Copernicus, Google Scholar, etc.)

14) **Hoarcă** Cristian, Raducu Marian, On the micro-inverter performance based on three MPPT controllers JEEECCS 2015 - Journal of Electrical Engineering, Electronics, Control and Computer Science - **JEEECCS 2015**, Vol. 1, nr. 1, pp. 7-14

15) Cristian Ioan **Hoarcă**, Marian Răducu, Simona Maria Răboacă, Comparison of the performance of the algorithms for finding the maximum power point of photovoltaic systems, **AGIR bulletin no. 1** , pp. 95-103, January-March 2017, ISSN 2247-3548.

Published in international conferences

16) **Hoarcă** Cristian, Bizon Nicu. **Hoarcă** Cristian, Bizon Nicu, Comparative analysis of Hybrid Power Systems based on HOMER and iHOGA simulators, **RESRB 2017** - 2nd Renewable Energy Sources - Research and Business conference, 19 - 21 June, 2017, Wrocław, Poland

Papers published EEE Xplore indexed conferences (in the process of indexed in ISI WOS).

17) **Hoarcă** Cristian, Determining Human Presence through the Analysis of the Electric Field using MATLAB environment, **ECAI 2020** - International Conference 12th Edition on Electronics Computers and Artificial Intelligence, 25-27 June, 2020, Bucharest, România.

18) **Hoarcă** Cristian, Enescu Florentina Magda, Bizon Nicu, Comparative study regarding the integration of photovoltaic sources in agriculture, **ECAI 2020** - International Conference 12th Edition on Electronics

Computers and Artificial Intelligence, 25-27 June, 2020, Bucharest, România.

19) **Hoarcă** Cristian, Bizon Nicu, Enescu Florentina Magda. **Hoarcă** Cristian, Bizon Nicu, Enescu Florentina Magda, The design of the graphical interface for the SCADA system on an industrial platform, **ECAI 2020** - International Conference 12th Edition on Electronics Computers and Artificial Intelligence, 25-27 June, 2020, Bucharest, România.

9.4 Prospects for further development

Considering the content and structure of the doctoral thesis, I further propose a list of the main research issues that require further development:

1. Implementation of the maximum power point tracking algorithms (MPPT Algorithms) proposed in the thesis within some research projects for FC/RES HPS.
2. Development of new software solutions for tracking the maximum global power point (GMPPT Algorithms).
3. Implementation of the proposed energy management strategies for hybrid power sources (HPS) based on renewable energies (RES) and fuel cells (FC).
4. Carrying out feasibility studies regarding the implementation of FC / RES HPS.

Scientific reports

1) Scientific report no.5: Control technique with load tracking for an optimized energy management of a hybrid power source (HPS) based on a fuel cell (Fuel Cell-FC) and renewable energy sources (RES), author : Hoarcă Ioan Cristian, Coordinator Prof. Dr. Eng. Nicu Bizon, Guidance - evaluation Commission: Prof. Dr. Eng. Adriana Florescu, CPI Dr. Eng. Mihai Culcer, Lecturer Dr. Eng. Mihai Oproescu.
2) Scientific report no. 4: Global MPPT techniques (GMPPT), author: Hoarcă Ioan Cristian, Coordinator Prof. dr. Eng. Nicu Bizon, Guidance - evaluation commission: Prof. dr. Eng. Ion Liță, Prof. dr. eng. Adriana Florescu, CPI dr. eng. Mihai Culcer.

3) Scientific report no. 3: Comparative analysis of the techniques for following the maximum power point (MPPT), author: Hoarcă Ioan Cristian, Coordinator Prof. Dr. Eng. Nicu Bizon, Guidance - evaluation Commission: Prof. Dr. Eng. Gheorghe Brezeanu, Prof. Dr. Eng. Adriana Florescu, Lecturer Dr. Eng. Mihai Oproescu.
4) Scientific report no. 2: Modeling a hybrid power source (HPS) based on renewable energy sources (RES) and energy storage devices (ESD), author: Hoarcă Ioan Cristian, Coordinator Prof. Dr. Eng. Nicu Bizon, Guidance - Evaluation Commission: Prof. Dr. Eng. Adriana Florescu, Lecturer Dr. Eng. Mihai Oproescu, Lecturer Dr. Eng. Gabriel Iana.
5) Scientific report no. 1: Analysis of the energy efficiency of different topologies, techniques and technologies used for photovoltaic panels, author: Hoarcă Ioan Cristian, Coordinator Prof. Dr. Eng. Emilian Lefter, CPI Dr. Mihai Culcer, Sl. dr. eng. Cicerone Marinescu.

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