Habilitation Thesis

Researches on Increasing the Performances of Renewable Energy Sources

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Abstract

This habilitation thesis presents the most important professional and scientific results in the field of renewable energy that I obtained after the public presentation of my PhD thesis, which took place in 1999, to the present. The habilitation thesis contains four sections:

• motivating request of the habilitation certificate in Electrical Engineering;
• directions and research skills of the applicant;
• the statement of the work and the scientific and technical research results;
• the career directions that require the habilitation.

The first section describes the reasons for the habilitation certificate request in Electrical Engineering. The next section presents my main research directions in which I worked during 1999- 2015, after the thesis public presentation, namely:

- Research on increasing the performances of the low-power autonomous wind power stations.
- Research on increasing the performances of the photovoltaic systems for electricity production.

In the area of increasing the performances of low-power autonomous wind power stations I have acquired the following competences:

- Modeling of the three-phase asynchronous generators with double feeding used in the construction of the wind power stations.
- Control of priority and non priority loads connected to the output terminals of a three-phase induction generator with wound rotor.
- Study of three phase synchronous generators with permanent supermagnets used in the construction of wind power stations.
- Intelligent energy management system for the energy produced by wind power stations.

In the area of increasing the performances of the photovoltaic systems for electricity production I have acquired the following competences:

- Modelling autonomous photovoltaic systems
- Developing MPPT control algorithms of the autonomous photovoltaic systems
- Developing control algorithms for photovoltaic systems with data acquisition and control board CompactRIO 9074.
- Case study of a hybrid wind-photovoltaic system using the program HOMER.

The third section presents the results of my research work based on research directions that I have approached. In the performance increase area of autonomous wind power stations I have worked on the modeling three-phase asynchronous generators used in their construction as well as the design and the implementation of the synchronous generators with permanent supermagnets that can be used in their construction. I have also developed control algorithms in real-time for priority and non priority loads connected to the output terminals of asynchronous generators in the componence of the low-power wind power stations.

I have also developed an intelligent system for real time energy management of the energy produced by wind power stations. Concerning the performance increase in the area of photovoltaic systems for electricity production I worked for the photovoltaic systems modeling and the development of the control algorithms of fophotovoltaic systems with data acquisition and control board CompactRIO 9074. In this area I have developed control algorithms in the programming LabVIEW environment for tracking the maximum power transfer point (MPPT) between photovoltaic panels and batteries used to store electricity.

It should be noted that this research was conducted in three inter-university scientific cooperation contracts financed by the Francophone University Agency in Bucharest and Montreal in collaboration with internationally renowned professors from universities in France, Canada, Lebanon, Syria and Moldova such as: PhD Jean Francois Brudny, PhD Nichita Cristian, PhD Ilinca Adrian, PhD Hanny Yasser, associate professor PhD Pusca Remus, associate professor PhD Mazen Ghandour and associate professor PhD Ilie Nuca. My activity of research and development, as candidate during my scientific and professional development has been consistent and dynamic. The results can be summarized as follows:

- Books published: 9;
- Articles and patents ISI Thomson Reuters: 7;
- Articles published after 1999 BDI index: 20;
- Articles published after 1999 in journals and conference volumes (non indexed): 30;
- Research contracts after 1999 under my responsibility: 5;
- Research contracts after 1999 where I worked as a member: 3;

The last section presents directions for career development that require certification of candidates in electrical engineering. Therefore, I will accord particular importance for future collaborations to be oriented to the field of renewable energy and the research findings to be transferred to firms that produce the equipment needed for new renewable sources of electricity. Possible solutions to the problems identified as being insufficiently treated so far, will provide a strong motivation to continue the research activity in the field of renewable energy.

REZUMAT

În cadrul tezei de abilitare au fost prezentate cele mai importante rezultate profesionale şi ştiinţifice în domeniul surselor regenerabile de energie pe care le-am obţinut după susţinerea publică a tezei mele de doctorat, care a avut loc în anul 1999, şi până în prezent. Teza de abilitare conţine patru secţiuni:

- motivarea solicitării atestatului de abilitare în Inginerie electrică;
- direcţiile şi competenţele de cercetare ale solicitantului;
- memoriu tehnico-ştiinţific al activităţii şi rezultatelor de cercetare;
- direcţii de dezvoltare a carierei care necesită abilitarea

In prima secţiune sunt prezentate motivele care au stat la baza solicitării atestatului de abilitare în Inginerie electrică. În secțiunea următoare sunt prezentate principalele mele direcţii de cercetare în care am lucrat în perioada 1999- 2015, după susţinerea publică a tezei de doctorat şi anume:

- Cercetari prvind cresterea performantelor centralelor eoliene autonome de putere mică
- Cercetari privind cresterea performanțelor sistemelor fotovoltaice de producere a energiei electrice

In domeniul creșterii performanțelor centralelor eoliene autonome de putere mică am dobândit următoarele competenţe:

- Modelarea generatoarelor asincrone trifazate cu dublă alimentare utilizate în construcția centralelor eoliene
- Controlul sarcinilor prioritare și non prioritare conectate la bornele unui generator asincron trifazat cu rotor bobinat
- Studiul generatoarelor sincrone trifazate realizate cu super magneți permanenți utilizate în construcția centralelor eoliene
- Sisteme inteligente de gestiune a energiei produse în centralele eoliene

In domeniul cresterii performanţelor sistemelor fotovoltaice de producere a energiei electrice am dobândit următoarele competenţe:

- Modelarea sistemelor fotovoltaice autonome
- Elaborarea algoritmilor MPPT de comandă a sistemelor fotovoltaice autonome
- Elaborarea algoritmilor de comandă a sistemelor fotovoltaice cu placa de achiziţie date şi comandă CompactRio 9074
- Studiu de caz a unui sistem hibrid eolian-fotovoltaic cu ajutorul programului HOMER.

In a treia secțiune sunt prezentate rezultatele activității mele de cercetare în funcție de direcțiile de cercetare pe care am fost orientat. În domeniul Creșterii performanțelor centralelor eoliene autonome am lucrat la modelarea generatoarelor asincrone trifazate utilizate în construcția lor și la proiectarea și realizarea unor generatoare sincrone cu supermagneți permanenți ce pot fi utilizate în construcția centralelor eoliene autonome de putere mică. Tot în acest domeniu am conceput algoritmi de control în timp real a sarcinilor prioritare și non prioritare conectate la bornele de ieșire a generatoarelor sincrone din construcția centralelor eoliene de putere mică. De asemenea am realizat un sistem inteligent de gestiune a energiei produse în centralele eoliene în timp real. În domeniul Cresterii performanţelor sistemelor fotovoltaice de producere a energiei electrice am lucrat pentru modelarea sistemelor fotovoltaice si pentru elaborarea algoritmilor de comandă a sistemelor fotovoltaice cu placa de achiziţie date şi comandă CompactRio 9074. De asemenea în acest domeniu am elaborat algoritmi de control în mediul de programare LabVIEW pentru urmărirea punctului maxim de transfer de putere (MPPT) dintre panourile fotovoltaice și bateriile de acumulatori utilizate pentru stocarea energiei electrice. Trebuie mentionat că aceste activități de cercetare le-am desfășurat în cadrul a trei contracte de cooperare științifică interuniversitară finanțate de Agenția Universitară a Francofoniei din București și din Montreal în colaborare cu profesori universitari de renume internațional de la Universități din Franța, Canada, Liban, Siria și Republica Moldova cum ar fi: prof. dr. ing. Jean Francois Brudny, prof. dr. ing. Nichita Cristian, prof. dr. ing. Ilinca Adrian, prof. dr. ing. Hanny Yasser, conf. dr. ing. Puscă Remus, conf. dr. ing. Mazen Ghandour și conf. dr. ing. Nucă Ilie. Activitatea de cercetare și dezvoltare desfășurată în timpul evoluției mele științifice și profesionale este consistentă și dinamică. Rezultatele pot fi sintetizate după cum urmează:

- cărţi publicate: 9;
- lucrări publicate și brevete de invenție indexate ISI Thomson Reuters: 7;
- lucrări publicate după anul 1999 indexate BDI: 20;
- lucrări publicate după anul 1999 în reviste și volume de conferințe (neindexate): 30;
- contracte de cercetare după anul 1999 la care am fost responsabil: 5;
- contracte de cercetare după anul 1999 la care am fost membru: 3;

În ultima secțiune sunt prezintate direcțiile de dezvoltare a carierei care necesită abilitarea mea în domeniul Ingineriei electrice. Prin urmare, voi acorda o importanță deosebită pentru ca viitoarele colaborări să fie orientate spre domeniul surselor regenerabile de energie iar rezultatele cercetărilor să fie transferate spre firmele producătoare de echipamente necesare pentru realizarea de noi surse regenerabile de energie electrică. Soluțiile posibile, pentru problemele identificate ca fiind insuficient tratate până acum, vor prezenta o motivație puternică pentru a continua activitatea de cercetare în domeniul surselor regenerabile de energie.

A. MOTIVATION OF THE REQUEST OF THE HABILITATION CERTIFICATE IN ELECTRICAL ENGINEERING

In a dynamic and growing society, any sector of activity requires motivated and competent workforce. Forming a competent professor is a complex and lengthy process that must be based on the accumulation of large amounts and variety of information. For a successful academic career, the teaching activities must be harmoniously combined with research. In order to achieve a technology transfer from academia to industry and a continuous updating of training programs a permanent exchange of knowledge and information between the two areas mentioned above should exist. Beside activities of teaching and research a university professor must carry out activities of management and mentoring [1]. The rapid growth in the volume of information in all areas and accelerated development of process equipment require continuous adaptation of the purpose of research and development strategies to this dynamic information. As a research project manager the professor needs the ability to manage human and material resources and the efficient use of the existing infrastructure, in order to achieve his project objectives. Coordination of research team involves both direction and guidance to young researchers and the distribution of tasks and evaluation results. Particular attention should be paid to recruitment activities of young researchers in the purpose of setting up new research teams [2].

In this context, obtaining the habilitation certificate in electrical engineering for conducting the doctoral work is an important step in the professional development of the candidate. Obtaining this certificate by the candidate will have a positive impact on teaching and research activities on the staff of Renewable Energy of the Department of Energy, Mechatronics and Computer Science. In this way, the collective of the Renewable Energy will be able to address complex research topics of national and international interest. It will also enhance the activity of the collective for attracting new projects financed by the European Union and thus the collaborations with the research teams of universities from France and Italy will expand. All these activities will aim at increasing the energy efficiency of renewable electricity. By increasing the amount of electricity produced by renewable sources the environmental pollution will be significantly reduced.

Also, the research results will be published in the form of articles in volumes of international conferences or journals internationally recognized. Results of research conducted in the area of performance increase of wind power stastions will be capitalised by applying them into the manufacture of synchronous generators with permanent super magnets with improved performance, compared to synchronous generators with permanent magnets from the current production. The results of research conducted in the area of energy performance of photovoltaic systems will capitalize by introducing control algorithms for the orientation of the photovoltaic panels systems in function on the position of the sun and control algorithms for tracking the point of maximum power transfer of photovoltaic panels and electrical storage batteries used in photovoltaic systems. All these results will lead to an expansion of collaboration between the collective of Renewable Energy from the Department of Energy, Mechatronics and Computer Science and companies in the industrial environment in Bacau or at national level.

B. RESEARCH DIRECTIONS AND COMPETENCES OF THE APPLICANT

Competencies developed on the basis of the activity undertaken since obtaining the title of doctor are grouped as follows:

1. Professional competences

- Advanced knowledge in electrical engineering in general and renewable energy in particular:
  - Modeling of doubly fed asynchronous generators used in the construction of wind power stations
  - The control of the priority and non priority loads connected to output terminals of a three-phase induction generator with wound rotor.
  - Study of the three phase synchronous generators with super permanent magnets used in the construction of wind power stations
  - Intelligent management system of the energy generated by wind power stations
  - Modelling of the autonomous photovoltaic systems
  - Development of the control algorithms of the photovoltaic systems with data acquisition and control board CompactRIO 9074.
- Advanced skills in the use of software for modeling, simulation and design of photovoltaic and wind systems to produce electricity.
- High capacity for identifying, defining and solving problems in electrical engineering in general, and in photovoltaic and wind systems in particular.

2. Transversal competences

- Ability to manage human and material resources.
- Project management skills - AUF.
- Ability to use information and communication technologies.

C. THE ACTIVITY AND THE RESEARCH RESULTS

The Habilitation Thesis presents the most important professional and scientific results obtained by the candidate after the receipt of a PhD diplome from the Technical University "Gh. Asachi "Iasi, as confirmed by Order of the Minister of National Education. No. 3772 dated 05/05/1999. The main directions of research of the activity of the candidate during 1999 - 2015 were:

- Researches on increasing the performances of low-power autonomous wind power stations
- Researches on increasing the performances of photovoltaic systems for electricity production.

In area of the increasing of performances of autonomous wind power stations I have worked on modeling three-phase generators used in their construction and the design and implementation of synchronous generators with permanent super magnetic that can be used in the construction of low-power autonomous wind power. In this area I have also developed control algorithms in real-time of non priority and priority loads connected to the output terminals of synchronous generators in the construction of the low power wind power stations. I have also conducted an intelligent system of the energy management generated in wind power stations in real time. In the area of increasing performances of photovoltaic systems for electricity production I worked for the modeling of photovoltaic systems and the development of control algorithms of photovoltaic systems with data acquisition and control board CompactRIO 9074.

Within 2005-2012 I received two fellowships of one month each and I obtained, through competition, three contracts of inter-university scientific cooperation from the Francophone University Agency in Bucharest and Montreal. The first fellowship was at the University of Rimouski in Quebec, Canada during the interval 16 September to 16 October 2005. The research program "*Système de gestion de l'énergie électrique automatisée produit dans les centrales Eoliennes*" for this fellowship has been conducted in **Laboratoire de recherche en energy eolienne** (LREE) and coordinated by Professor **Amadou Diop**. In this period of time I addressed several research topics in the area of wind power stations such as: control of the loads connected to the terminals of the electrical generators in the construction of wind power stations, control of the three-phase asynchronous generators with wound rotor, using the frequency static converters, data acquisition systems for measuring the parameters of a wind power station. The second fellowship was at the University of Le Havre in France during 1st of September to 30th of September 2009. The research program "Système photovoltaïque -éolien de production de l'énergie électrique" for this fellowship has been conducted in the **Laboratoire GREAH - Groupe de Recherche en Electrotechnique et Automatique du Havre** under the direction of Professor **Nichita Cristian.** The research topics addressed during the fellowship were: modeling and simulation of photovoltaic systems, wind, maximizing power transfer from solar panels to consumers, increasing performances of hybrid systems for producing electricity. In the interval between the two fellowships I worked on two international research contracts in the same field of research. For the first research contract "Système de gestion de l'énergie intelligent électrique produit par des centrales Eoliennes" I was contract responsible on behalf of the "Vasile Alecsandri" University of Bacău. The contract was carried out within 1.01.2006 - 31.12.2007. Partner universities under this contract were: Université d'Artois from Bethune from France and the Technical University of Moldova from Chisinau, Moldova.

At this contract I worked with PhD **Jean Francois Brudny** - director of the **Laboratoire des Systèmes Electriques et Environnement (LSEE)** as co-responsible of the contract for the Université d'Artois and with the associate PhD **Ilie Nuca - vicedean of the Faculty of Electrical Engineering** as co-responsible of the contract from the Technical University of Moldova in Chisinau. The objectives of this research contract were:

1) Modeling of the driving systems of the wind power stations.
2) Simulation of the driving systems of the wind power stations.
3) The study of a data acquisition system for measuring the parameters of a wind power station.
4) Analysis and processing of simulation results.
5) The development of a method for measuring the operating parameters of wind power station.
6) Conducting an experimental stand.
7) Analysis and the treatment of results.

Under this contract three fellowships have been awarded for PhD students of one month duration each at the University of Artois, France. At the second research contract "Jumelage eolienne énergie et stockage d'avec diesel compress air" the responsible of the contract has been PhD **Adrian Ilinca** from Université du Quebec a Rimouski from Canada. The contract was financed by the Francophone University Agency of Montreal from Canada. The contract was carried out within 1.01.2008-31.12.2009. I have been working on this contract as co-responsible from the "Vasile Alecsandri" University of Bacău. The other partner universities in this contract were: Université Libanaisse from Lebanon, Université d'Alepp from Syria and Ecole Centrale de Lyon from France.

At this research contract I collaborated with professor Mr. **Adrian Ilinca** - director of the **Laboratoire de recherche en energie eolienne** (L.R.E.E) from Université du Quebec a Rimouski, associate PhD **Ghandour Mazen** - member of the **Département d'Electricité et Electronique** as co-responsible of the contract from Université Libanaise and professor **Yasser Hayyani** - dean of the **Faculty of Engineering** as co-responsible of the contract from the Université d'Alepp. The objectives of the contract have been of researching, developing, designing and manufacturing a power plant composed of: a wind power station, an electrogenic group and a system for producing and storing compressed air (JEDSAC system). This association is characterized by high rates of penetration of wind energy by allowing the complete stop of the electrogenic group, while the electricity production of the wind power is high as the demand. This allows a significant reduction in fuel consumption and emissions of greenhouse gases. This association (JEDSAC), as proposed in this project, was never a commercial application and there were no studies in the literature on the conception and design of such a system. The third research contract "Système photovoltaïque – éolien de production de l'énergie électrique" was obtained in 2010 by competition from the Francophone University Agency in Bucharest. At this contract I was responsible on behalf of the "Vasile Alecsandri" University of Bacău. The contract was carried out in 2010-2012. Partner universities under this contract were: Université du Havre from France, Université Libanaise from Lebanon and Université d'Alepp from Syria. At this contract I collaborated with Professor **Nichita Cristian** - member of the **Laboratoire GREAH** as co-responsible of the contract from Université du Havre, associate doctor engineer Mr. **Ghandour Mazen** - member of **Département d'Electricité et Electronique** as co-responsible of the contract from Université Libanaise and professor **Yasser Hayyani** - dean of the **Faculty of Engineering** as co-responsible of the contract from the Université d'Alepp.

The objectives of the contract were: 1) modeling of the photovoltaic systems and wind power stations for electricity generation. 2) Simulation of the photovoltaic systems and wind power stations and the development of the control algorithms. 3) Study of the data acquisition system for measuring the parameters of a photovoltaic system - wind. 4) Analysis and treatment of the results obtained by simulation. Chosing the optimal control strategies for implementation. 5) The development of a method for measuring the operating parameters of photovoltaic systems – wind power stations. 6) Building an experimental stand. 7) Analysis and treatment of the results. Under this contract three fellowships have been awarded for PhD students of one month duration each, one at the "Vasile Alecsandri" University of Bacău and two at "Université du Havre" in France. This paper is divided into four chapters. The first chapter presents the context of the work of research and how to address it. Chapters 2 and 3 present the research results obtained from the activities of the two research directions mentioned above. The last chapter summarizes my personal contributions and defines the plan of development of the career.

C. I. CONTEXT OF THE WORK

It can be said that researches into renewable sources of electricity are now growing, and they open new perspectives. Since December 1997 the White Paper for a Community Strategy and Action Plan "Energy for the future: renewable sources" defined the strategy in the field and launched the "Campaign for starting" investment. The strategic objective proposed by the White Paper was to achieve by 2010, 12% share through the contribution of renewables sources at the total energy consumption in the EU countries. The most important piece of legislation in this field is Directive 2001/77 / EC of 27 September 2001 on the promotion of electricity produced by renewable sources on the energy market. Given these directives, the efforts of researchers in the field of renewable energy both from the European Union and from our country have increased in the past 10 years. For renewable electricity production the following areas have been established:

- New methods and technologies for increasing the energy conversion efficiency and decreasing electricity production costs for renewable energy sources: wind, solar, biogas etc.
- New methods and quality assurance technologies of the electricity from renewable sources;
- Development of new technologies adapted to different regional conditions; autonomous and hybrid sources for renewable electricity in remote areas.

The research objectives in this area are:

- Reducing production cost of electricity produced by wind farms and solar plants
- Improving the quality of electricity produced by wind farms and solar plants.
- Scientific substantiation of solutions for the implementation of renewable energy sources integrated into smart grids to ensure reliability requirements of systems of the production.

The degree of success of these objectives would entail increasing the amount of electricity produced from renewable sources. This growth will also depend on the selling price of this type of energy. A component of wind and solar power with definite influence for these objectives is the command. Reducing the cost of electricity requires inter alia:

- Increase the reliability and robustness of wind power stations and solar power stations.
- Manufacture of lighter wind generators and performance photovoltaic panels
- Increased energy efficiency
- Robustness of the control algorithms designed.

In this context it falls and the habilitation thesis: Researches on increasing the performances of renewable energy sources. Research related to this thesis addresses some of the many problems related of performances to wind power and solar power and requires intense theoretical and experimental investigations.

By introducing of elements of the artificial intelligence in the control of wind power stations and solar power station decreases cost of electricity produced by them and increase the quality. Internationally, experimental researches are carried out in various research laboratories to develop strategies for extracting the maximum power of the electric generators used in wind power stations. In [3] for the synthesis of controllers from the command structure of a wind power station constructed with MADA, the poles allocation method is used. The work [4] presents an algorithm to extract maximum power from a wind power station equipped with a synchronous generator, developed on the basis on neural networks. The work [5] presents an algorithm of a numerical control for a static converter DC / DC connected between the photovoltaic panel and load.

These numerical controls or analog controls play an important role in the channel of the conversion of solar energy as they maximize the power from the output of these generators, for different values of load. From the bibliographic study of the current state in area, results that there are not references, reported a unified treatment of the use the artificial intelligence elements in the control of electrical generators used in wind power stations with the variable speed or static converters of type DC / DC or DC / AC. The motivation of the proposed theme approach consists of the development of intelligent algorithms for hybrid systems control of energy production that will be validate on a test stand and will be used in future for the command structures of the hybrid systems in the industrial production of electricity. Among the CD units involved in the field I have established collaborations with the University of Quebec of Rimouski from Canada, the University d'Artois from France, Technical University of Moldova in Chisinau and the University of Le Havre from France.

C.II. INCREASING THE PERFORMANCES OF THE LOW-POWER AUTONOMOUS WIND POWER STATIONS

2.1 Wind energy

Wind energy is nowadays an important renewable source for electricity production. For the conversion of wind energy into electricity the wind power stations are used. In order to install wind power stations in a given geographical area, the wind energy potential of the area has to be determined.

2.1.1 Wind power potential

Wind energy is a converted form of the solar energy, which is transmitted to the atmosphere through heating from the surface of the earth. Finding the size of the wind power potential is more difficult and less accurate than the solar energy potential. Thus the theoretical wind potential for the whole terrestrial atmosphere can be determined based on a global energy balance. This balance has quite many unknown issues, because of the limitations of the mathematical models of the world system. It is accepted in principle that approx. 2% of the solar energy falling upon the earth is ceded in atmosphere [6]:

$$E_A = 0.02 \cdot E_s \tag{2.1}$$

Instead, the allocation of this quota in different parts of the world is more difficult to determine, because the influence of air movements can be felt over large areas. In order to capture wind energy it is necessary to know the characteristics of air currents that have direct influence on the construction of conversion facilities. The main parameters being considered are:

- wind speed
- wind direction
- annual wind duration (depending on speed).

In order to determine the energy production of the wind collector it is required to measure the wind speed at small time intervals or continuous recording of it. Wind speed is also characterized by variations depending on altitude, due to friction of the air layer with the ground and the influence of different obstacles. Wind direction is especially important for determining how to place wind collectors in larger assemblies. During the measurement of wind speed and its direction, the following can be determined:

- *The frequency of air movement* can be expressed in number of hours during a year when wind speed exceeds a certain value. Considering the lower wind speed that could be used by conversion facilities ($v = 3\,\mathrm{m}\ /\ \mathrm{s}$), it was found that over 50% of the territory of our country presents wind conditions.

-*Wind power* can be derived from the kinetic energy of a stream of air at a constant speed:

$$E = \frac{mv^2}{2} \tag{2.2}$$

In this relation m is the mass of air that passes through the surface of a wind collector within an interval t.

$$m = \rho \cdot S \cdot v \cdot t = q \cdot t \tag{2.3}$$

and $q = \rho \cdot S \cdot v$ is the mass of the flow of air through the collector surface. The power of the air stream is obtained by dividing the wind energy to t (2.2), thus:

$$P = \frac{\rho \cdot S \cdot v^3}{2} = q\frac{v^2}{2} \tag{2.4}$$

If $S = 1\text{m}^2$, knowing that $\rho = 1.226\,\text{kg/m}^3$, a quick calculation of the power relation wil result:

$$P = 0.613 \cdot \left(\frac{v}{10}\right)^3 \ (\text{kW/m}^2) \tag{2.5}$$

2.1.2 Classification of the wind collectors

Wind collectors are built in various forms in order to improve the efficiency of wind power plants. By the position of the collector shaft with respect to the wind direction there are [7]:

- Collectors with horizontal axis, with the axis of rotation parallel to the direction of the wind;
- Collectors with vertical axis, with the axis perpendicular to the wind direction.

2.1.3 The conversion of wind energy into other forms of energy

The main areas of application of mechanical energy derived from wind turbine shaft are:
- pumping water for irrigation, water supply, etc… The accumulation of water pumped into the pool followed by turbin is relative to lower pool; it can produce energy in an unconventional arrangement, through which it can compensate wind energy fluctuations.
- Compressing air for various purposes, including for the needs of a gas turbine used during peak load in energy systems. - Production of heat by friction; heat can be accumulated in solid or liquid materials and used when needed. Practically, it is preferable the friction in a viscous liquid, by means of a stirrer, whose wear is much less than the friction between the solids.
- Production of electricity or for storage or for direct supply to consumers. For collectors of major wind energy, conversion is the only way to consider for the production of electricity. The block diagram of such a plant is presented in Fig. 2.1.

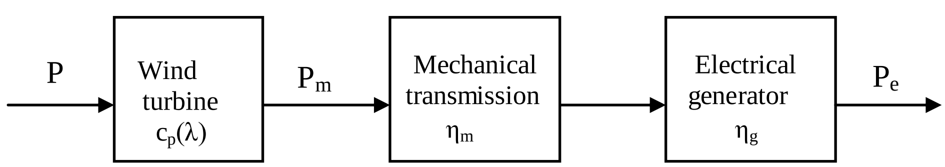

Fig. 2.1 Block diagram of conversion into electricity

Intermediate link from mechanical transmission is sometimes shown to adapt the turbine speed at the requirements of electric machine by changing the transmission ratio. It can also comprise a brake mechanism for limiting the transmitted power of the electric generator. The electric power is determined, [6]:

$$P_e = c_p(\lambda) \cdot \eta_m \cdot \eta_g \cdot P_v \tag{2.6}$$

Since both the wind power and power factor are variable in time, the energy produced in a period t is determined by integration, [6]:

$$E = \eta_m \cdot \eta_g \cdot \int_0^t P_v(t) \cdot c_p(t) \cdot dt \tag{2.7}$$

There are several ways to convert into electricity:
a) *Production of direct current* with a current generator or an alternator associated with a rectifier. The second variant is preferred because it is easier to deal with the electrical parameters regulation, it is lighter (an alternator is 2.5 times lighter than a dynamo of the same power) and it can provide the rated power on a wide range of speed. The energy produced can be stored electrochemically and then distributed at a constant voltage. This system is still rarely used because the DC consumers are less numerous.
b) *Alternative current production with synchronous generators*. In this case, the synchronous generator can be operated either at variable speed or at a constant speed. The variant with variable speed can be selected when the energy produced is provided for a network separated from the energy system. Since the use of random variable frequency is very difficult, it is suitable only for usage in electric heating. The variant with constant speed involves the need to maintain a constant speed of the generator, so the existence of sufficient means of adjusting both the wind turbine and mechanical transmission. Although the energy produced can be delivered to the energy system, the difficulty of ensuring a fixed speed makes this process to be used at a low extent.
c) *Alternative current production with asynchronous generators*. Asynchronous machines driven at a higher speed than synchronous generator speed will become generators of electricity. The frequency is imposed by the network to which it is connected, from which the reactive energy, needed to create the rotating magnetic field, is absorbed. The power developed by the generator depends on the speed. This solution is more suitable and therefore it is used in most of the cases to the largest installed capacity. There is no need for speed adjustment, it is rigid and its installation is simple.

2.2 Electrical machines and wind energy conversion systems

There are several types of electrical machines on the market, that can be used as generators in wind power stations but which require specific characteristics [8]. In the wind industry both AC electrical machines are currently used: asynchronous and synchronous machines. Asynchronous machines are used in different versions, such as asynchronous machines with squirrel cage and wound rotor induction machines.

2.2.1 Squirrel cage asynchronous machines (SCAM)

A wind energy conversion system developed with squirrel-cage induction generator is shown in Figure 2.2. Capacitor banks are used for reactive power compensation [8]. This wind power plant operates at a fixed rotational speed. Therefore, it is necessary to insert a mechanical multiplier of speed between the turbine and the asynchronous machine.

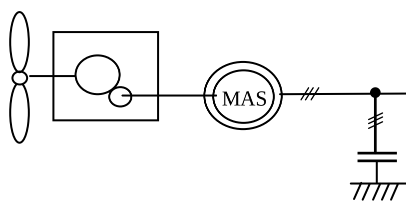

Fig. 2.2 Wind system made with squirrel cage asynchronous machine (fixed rotational speed)

A wind energy conversion system with a squirrel cage induction generator which operates at variable speed is shown in Figure 2.3. Capacitor banks are replaced with static frequency converters either widely, or only to compensate the reactive power at high wind speeds. The first configuration has the advantage of being able to vary the rotation speed of the wind power station for the whole range the wind speed variation.

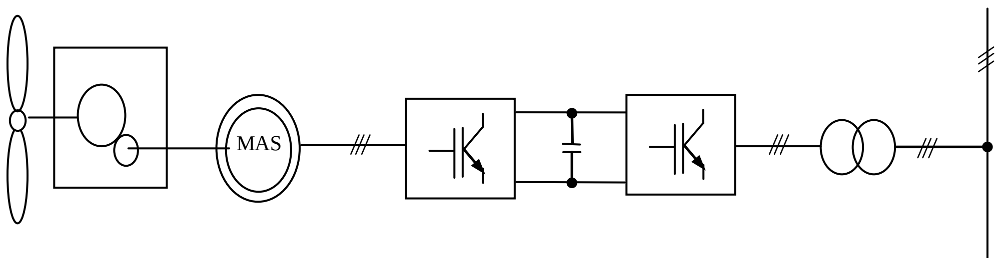

Fig. 2.3 Wind system with squirrel cage asynchronous machine at variable frequency

2.2.2 Doubly fed asynchronous machine (DFAM)

A wind energy conversion system developed with induction generator with wound rotor is shown in Figure 2.4. The stator of the generator is connected directly to the network, usually through a transformer. Instead cage, these induction machines have a wound rotor. The basic idea is to control the rotor resistance using a static frequency converter of high power and thus controlling the sliding of the machine on a range of variation of 10%.

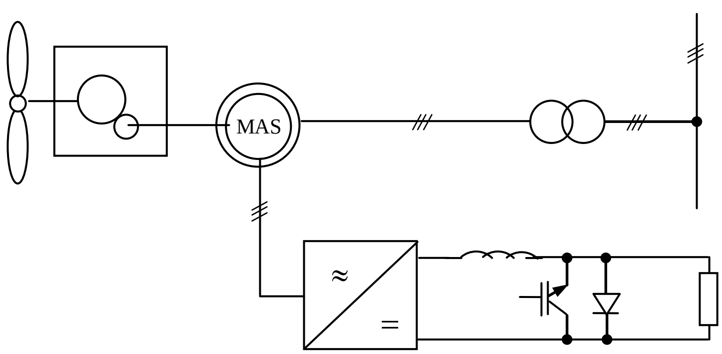

Figure 2.4 Wind systems with asynchronous machine with wound rotor - the variation of rotation speed by adjusting of the rotor resistance

Another very interesting solution to obtain a change in the speed of rotation of about 30% around of the synchronous speed consists of coupling the rotor of the generator with double feed to the network by two three-phase PWM inverters, the rectifier and the other one in the inverter (see Figure 2.5). They allow the control of the output power of generator by using converters designed at 25% of the rated power of the generator.

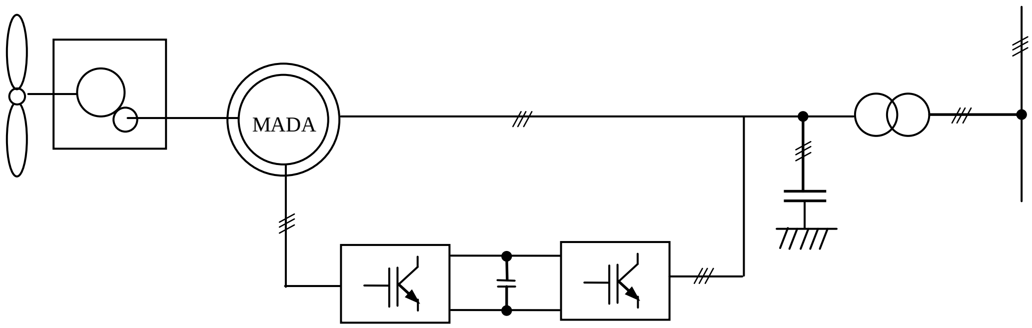

Fig. 2.5 Wind system with double fed asynchronous machine - adjusting the speed of rotation through the feed channel

2.2.3 Synchronous generator

Development of magnetic materials allows the construction of permanent magnet synchronous machines that have become competitive in terms of cost. These types of machines have a large number of poles and enable the development of considerable mechanical couples. A wind energy conversion system performed with permanent magnet synchronous machine is shown in Figure 2.6, [7], [8].

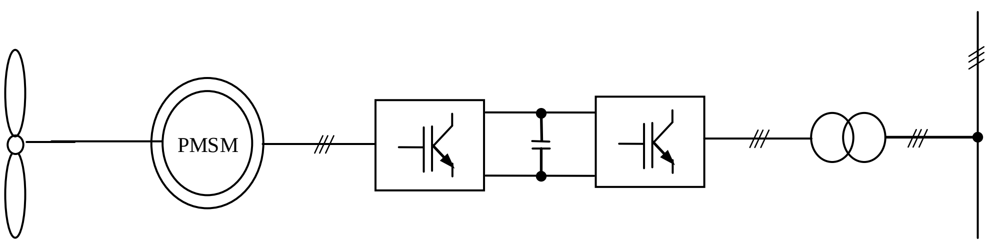

Fig. 2.6 Wind system realized with permanent magnet synchronous machines

Another solution (Figure 2.7) consists of placing the diode rectifier placed directly behind the generator. Optimizing of management of energy is only possible if the power supply voltage of the excitation winding is adjustable. The disadvantages of this solution are: the use of an excitation circuit with rings and more complex control strategies

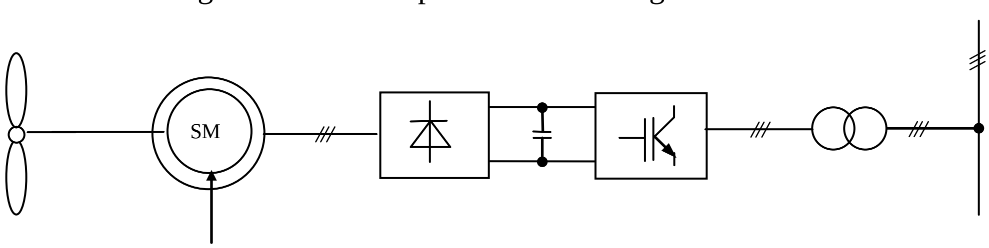

Fig. 2.7 Wind system with synchronous machine and diode rectifier

2.3. The control of the double feed asynchronous machine

The control of double feed asynchronous machines is based on three characteristics:
- Extraction algorithm of maximum power for double feed asynchronous machines used as a generator.
- Vectorial control of the double feed asynchronous machines
- PWM control of the static frequency converter

The algorithms for extracting maximum power of the double fed asynchronous generators are presented in the papers [9], [10], [11]. For the vector control of double fed asynchronous machines a mathematical model of an induction machine with stator flux orientation is presented. PWM control of a static frequency converter used to feed the winding rotor of the asynchronous machine with double feed is presented in the papers [12], [13].

2.3.1 Model of a double feed asynchronous machine (DFAM) with orientation after the stator flux

Electric machines, being practically sinusoidal, are defined by module and phase. They can therefore be represented in a two-dimensional reference system. The reference model chosen here for a wound rotor asynchronous machine is a machine connected to the stator (fixed axis). This reference system is illustrated by α_f and β_f axes, in Figure 2.8. The passage electric machines in this reference system, starting from the reference system associated with three stator and rotor windings made at the crossing an exchange of axes (transformed Park). The particularity of an asynchronous machine with double feed is that it has two currents that can directly control, i_{rd}, i_{rq}, and two currents indirectly controlled i_{sd}, i_{sq}. From $[14]$ the system of differential equations of the machine will result:

$$\frac{d\phi_{1d}}{dt} = u_{1d} - R_1 \cdot i_{1d} + \phi_{1q} \cdot \omega_1 \tag{2.8}$$

$$\frac{d\phi_{1q}}{dt} = u_{1q} - R_1 \cdot i_{1q} - \phi_{1d} \cdot \omega_1 \tag{2.9}$$

$$\frac{d\phi_{2d}}{dt} = u_{2d} - R_2 \cdot i_{2d} + \phi_{2q} \cdot \omega_2 \tag{2.10}$$

$$\frac{d\phi_{2q}}{dt} = u_{2q} - R_2 \cdot i_{2q} - \phi_{2d} \cdot \omega_2 \tag{2.11}$$

If the flow-orientation, obtained model of MADA is simplified, the resulting control device will also be simpler. The vector control of this machine was designed with landmark Park orientation for which the component of the stator flux along the q axis to be zero: $\phi_{1q} = 0$. A simplification of the equations of the asynchronous machine is obtained by considering void the homopolar components:

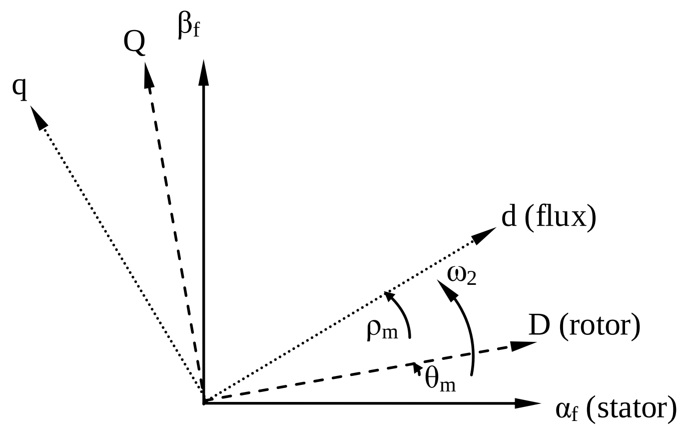

Fig. 2.8 Reference axes systems of an asynchronous machine

$$\frac{d\phi_{1d}}{dt} = u_{1d} - R_1 \cdot i_{1d} \tag{2.12}$$

$$u_{1q} = R_1 \cdot i_{1q} + \phi_{1d} \cdot \omega_1 \tag{2.13}$$

$$\frac{d\phi_{2d}}{dt} = u_{2d} - R_2 \cdot i_{2d} + \phi_{2q} \cdot \omega_2 \tag{2.14}$$

$$\frac{d\phi_{2q}}{dt} = u_{2q} - R_2 \cdot i_{2q} - \phi_{2d} \cdot \omega_2 \tag{2.15}$$

As per [14], the following expressions of the stator current are obtained:

$$i_{1q} = -\frac{L_h}{L_1} \cdot i_{2q} \tag{2.16}$$

$$i_{1d} = \frac{\phi_{1d} - L_h \cdot i_{2d}}{L_1} \tag{2.17}$$

These stator currents are replaced in the equations of the direct components of the flow rotor, [14] :

$$\phi_{2d} = \left(L_2 - \frac{L_h^2}{L_1} \right) \cdot i_{2d} + \frac{L_h}{L_1} \cdot \phi_{1d} = L_2 \cdot \sigma \cdot i_{2d} + \frac{L_h}{L_1} \cdot \phi_{1d} \tag{2.18}$$

$$\phi_{2q} = L_2 \cdot i_{2q} - \frac{L_h^2}{L_1} \cdot i_{2q} = L_2 \cdot \sigma \cdot i_{2q} \tag{2.19}$$

where σ is the dispersion coefficient of the windings d and q:

$$\sigma = 1 - \frac{L_h^2}{L_1 \cdot L_2}$$

By replacing the expressions of the direct component of the stator current (2.16 and 2.17) in the equations (2.12 and 2.13) and then the expression of the direct components of the rotor flux (2.18 and 2.19) in the equations (2.14 and 2.15), it will result:

$$u_{1d} = \frac{R_1}{L_1} \cdot \phi_{1d} - \frac{R_1}{L_1} \cdot L_h \cdot i_{2d} + \frac{d\phi_{1d}}{dt} \tag{2.20}$$

$$u_{1q} = -\frac{R_1}{L_1} \cdot L_h \cdot i_{2q} + \omega_1 \cdot \phi_{1d} \tag{2.21}$$

$$u_{2d} = R_2 \cdot i_{2d} + L_2 \cdot \sigma \cdot \frac{di_{2d}}{dt} + \frac{L_h}{L_1} \cdot \frac{d\phi_{1d}}{dt} - L_2 \cdot \omega_2 \cdot \sigma \cdot i_{2q} \tag{2.22}$$

$$u_{2q} = R_2 \cdot i_{2q} + L_2 \cdot \sigma \cdot \frac{di_{2q}}{dt} + L_2 \cdot \sigma \cdot \omega_2 \cdot i_{2d} + \omega_2 \cdot \frac{L_h}{L_1} \cdot \phi_{1d} \tag{2.23}$$

Equations (2.22 and 2.23) allow determining the rotor currents:

$$\frac{di_{2d}}{dt} = \frac{1}{L_2 \cdot \sigma} \cdot \left(u_{2d} - R_2 \cdot i_{2d} + \omega_2 \cdot L_2 \cdot \sigma \cdot i_{2q} - \frac{L_h}{L_1} \cdot \frac{d\phi_{1d}}{dt} \right) \tag{2.24}$$

$$\frac{di_{2q}}{dt} = \frac{1}{L_2 \cdot \sigma} \cdot \left(u_{2q} - R_2 \cdot i_{2q} - \omega_2 \cdot L_2 \cdot \sigma \cdot i_{2d} - \omega_2 \cdot \frac{L_h}{L_1} \cdot \phi_{1d} \right) \tag{2.25}$$

The electromagnetic torque is determined by the relation:

$$M_{em} = p \cdot \left(\phi_{1d} \cdot i_{1q} - \phi_{1q} \cdot i_{1d} \right) \tag{2.26}$$

With an orientation of the stator flux so that $\phi_{1q} = 0$, a simplified expression is obtained:

$$M_{em} = p \cdot \phi_{1d} \cdot i_{1q} \tag{2.27}$$

The current i_{1q} can not be directly controlled, but using equation (2.16) the component of the rotor current is inserted into the electromagnetic torque expression:

$$M_{em} = -p \cdot \frac{L_h}{L_1} \cdot \phi_{1d} \cdot i_{2q} \tag{2.28}$$

2.3.2. Simulation results

For simulation the program SIMULINK was used, in MATLAB environment. The simulation was performed for a asynchronous machine with double feed having the following nominal parameters, [3]: $P_n = 15$ KW, $n_n = 1440$ rpm, $M_n = 100\ N \cdot m$, $U_{1n} = 220$ V, $U_{2n} = 220$ V, $I_{1n} = 32$ A, $I_{2n} = 2.5$ A, $R_1 = 0.17\ \Omega$, $R_2 = 0.2\ \Omega$, $L_1 = 0.05$ H, $L_2 = 0.05$ H, $L_h = 0.045$ H, p=2. On the basis of the equations (2.20) (2.21) (2.22) (2.23) and (2.28), the SIMULINK block diagram of the simplified model of an asynchronous machine with double feed with the orientation after stator flux is shown in Fig. 2.9. The mathematical model obtained will be used in vector control structures of double feed asynchronous machine used in the construction of wind power stations.

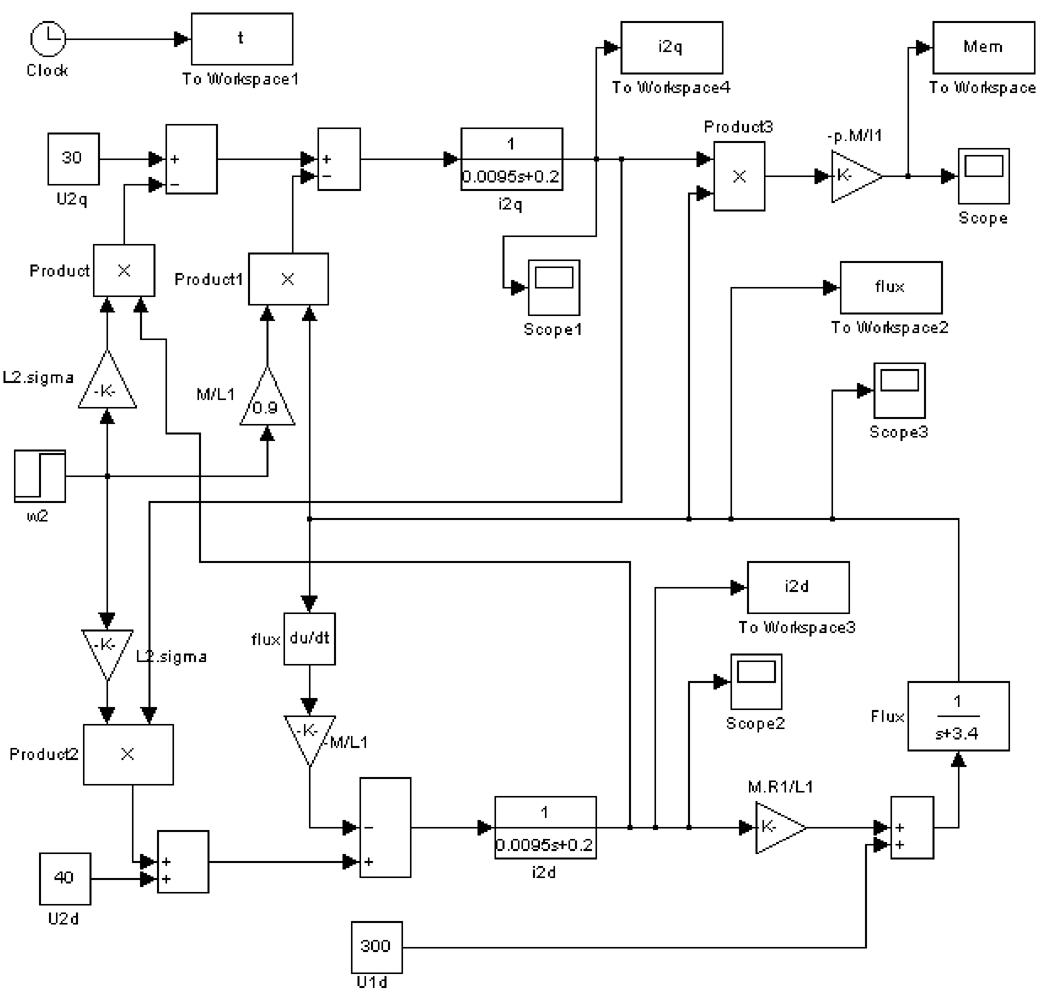

Fig. 2.9 SIMULINK block diagram of the simplified model of the double feed asynchronous machine

2.4. Control system of the load of a three-phase asynchronous generator used in a wind power station

2.4.1 Description of the experimental stand

For controlling the load of three-phase asynchronous generator used in a low-power wind station an experimental stand has been designed and built by me within the Electrical Machines Laboratory of the "Vasile Alecsandri" University of Bacău. A photograph of the experimental stand is shown in Figure 2.10. This stand consists of: 1- three phase asynchronous motor with squirrel cage; 2- three phase asynchronous generator with wound rotor; 3- three phase autotransformer; 4- static frequency converter 1; 5- current encoder; 6- voltage encoder; 7- power factor encoder; 8- static frequency converter 2; 9- Power resistors , 10- control device of the loads connected to the three-phase generator terminals; 11- voltage source which provides the reference voltage to the frequency static converter 8; 12- IBM PC compatible computer; 13- data acquisition board PCI 6251; 14- Consumer 1 consists of a three-phase induction motor; 15- Consumer 2 consists of a three-phase power resistance. Characteristics of these components are presented in the papers [15], [16], [17].

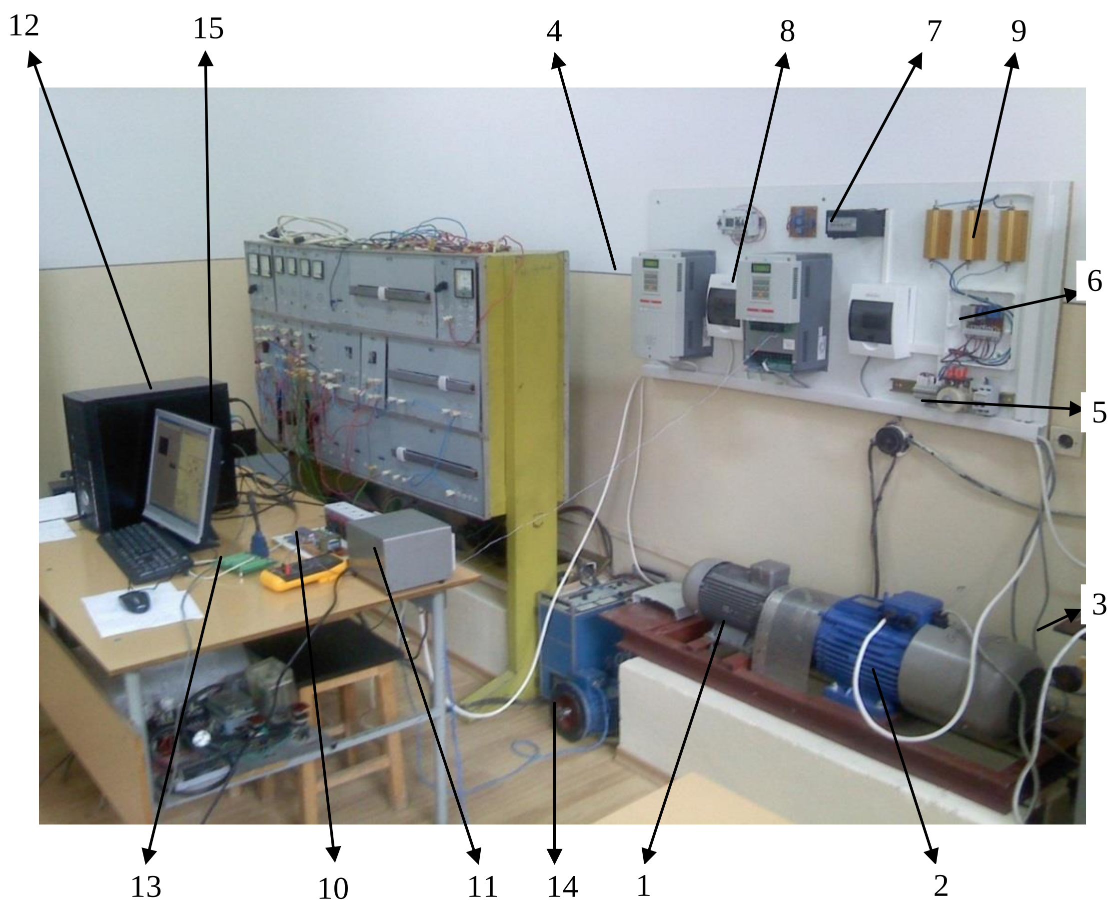

Fig. 2.10 Experimental stand for load control of a three-phase induction generator used in a wind power station

The control device of the loads connected to the three-phase asynchronous generator terminals consists of:
- Circuit breaker for general coupling or uncoupling of the consumers.
- Contactors in the power circuits for consumer connecting.
- Board with intermediary relays for controlling the supply of the contactor coils in the power circuits.
- Voltage double source for supplying the intermediary relay board at + 5 V.d.c. voltage and power contactor coils at + 24 V.d.c. voltage.
- Connectors for the power and for control cables.

The control device of the loads connected to the three-phase asynchronous generator terminals 10 is shown in Figure 2.11.

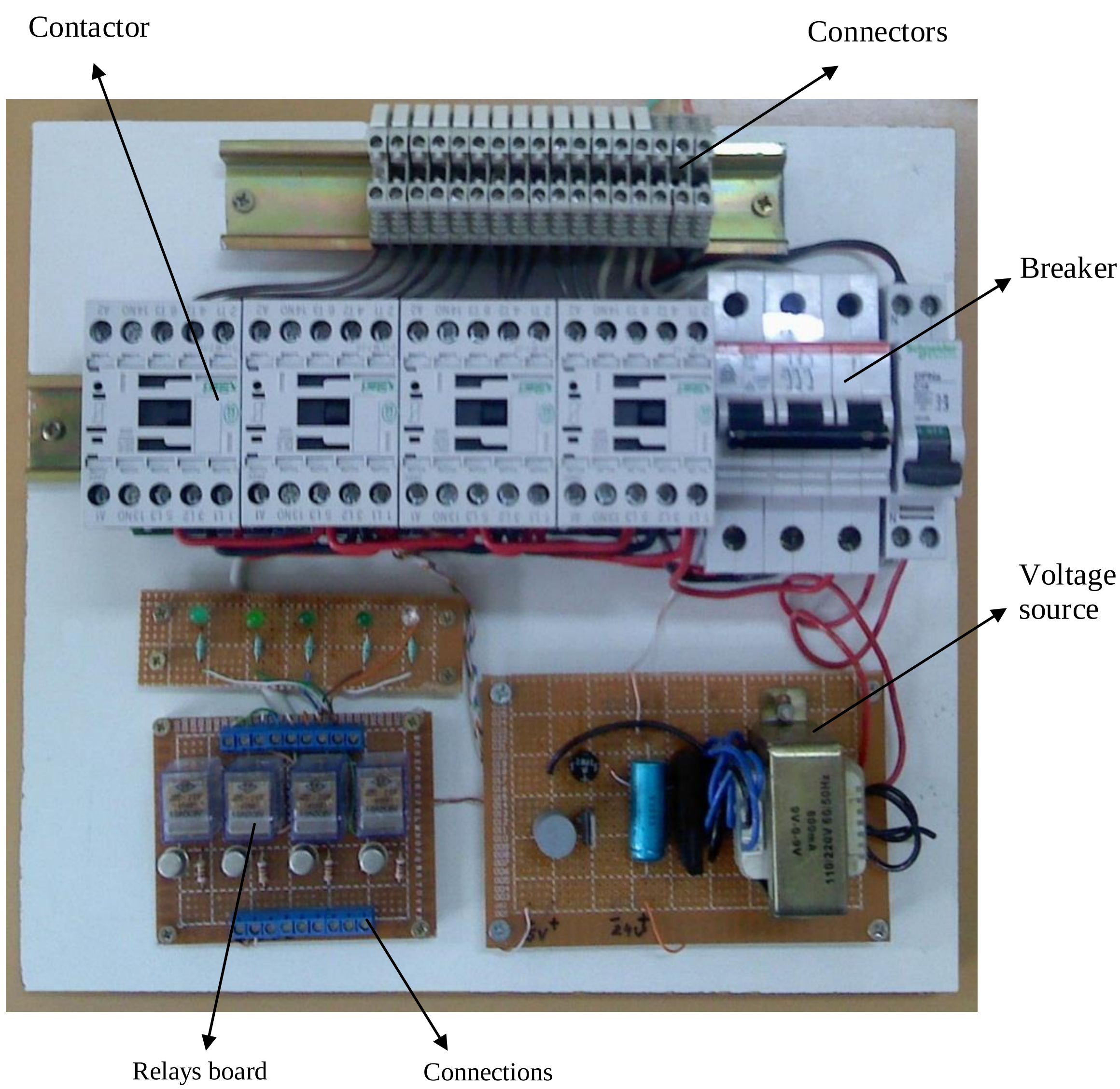

Fig. 2.11 Control device of the loads connected to the three-phase asynchronous generator terminals

2.4.2 Functioning of the experimental stand for controlling the load of the asynchronous generator

The electric diagram of the experimental stand is shown in Fig. 2.12. The operation of the experimental stand was presented in detail in the works [15], [16], [17]. The wind turbine is simulated by three-phase motors with squirrel cage 1, which is fed from the static frequency converter 4. By changing the reference signal of the static frequency converter-1 the speed of rotation of three-phase motor which drives the rotor of three phase asynchronous generator, changes, thus simulating the changes of the wind speed on the wind power station. Through the three-phase autotransformer-3, the three-phase winding of the rotor of the three phase asynchronous generator 2 is powered from the static frequency converter 8.

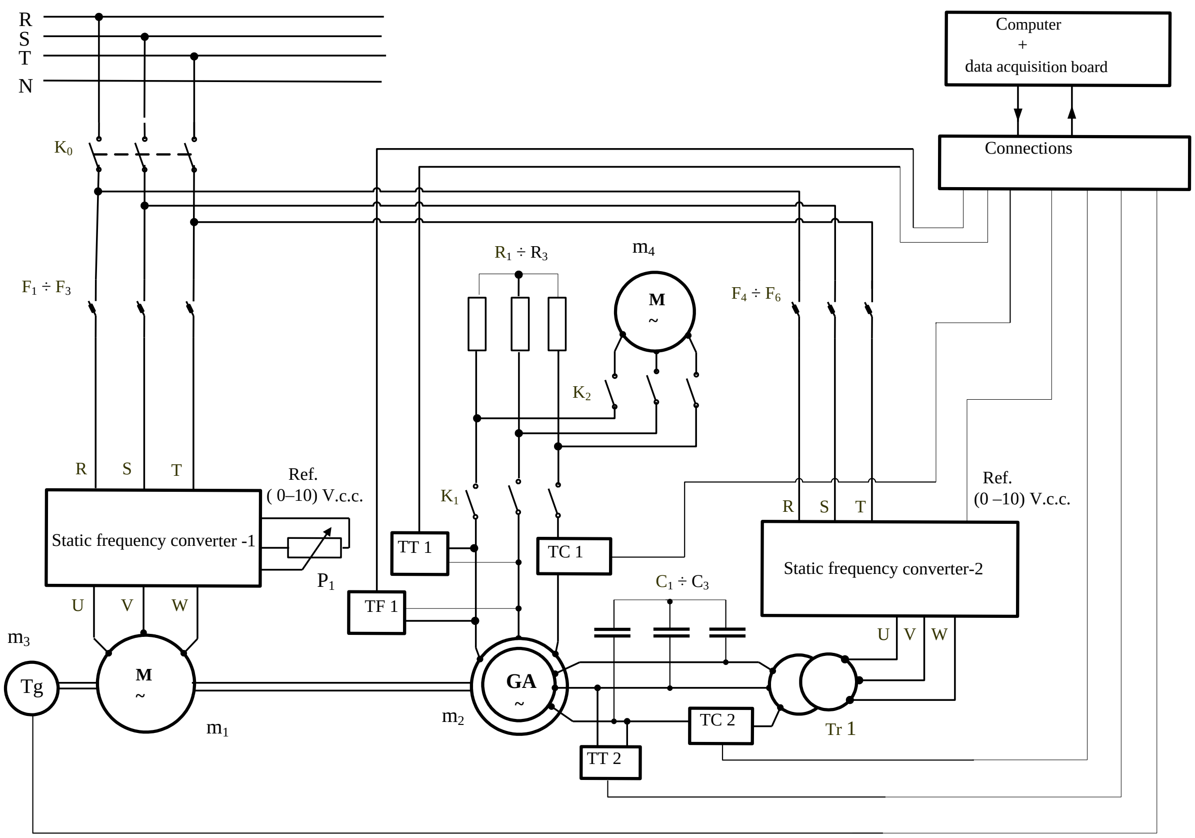

Fig. 2.12. Electric diagram of the experimental stand

Upon the start-up of the three-phase motor a variable three-phase AC voltage will be obtained at the output terminals of the stator windings of the three-phase generator, in relation to the asynchronous motor speed and the current flowing through the phase windings of the rotor of the three-phase asynchronous generator. At the terminals of the stator windings of three-phase generator 2 the consumers 14, 15 are connected through the control device of loads 10. Through this device the connecting or disconnecting of four priority or non-priority consumers from the terminals of the three-phase asynchronous generator 2 can be controlled, depending on the voltage at the output terminals of the generator, respectively the wind speed that will act on the wind turbine.

The output voltage from the sensor is transmitted to the data acquisition board of the computer via a coupling link. With the help of a program developed in LabVIEW the voltage signal is compared with four benchmarks of 2 V, 4 V, 6 V and 8 V.
When the voltage signal from the sensor voltage is higher than 2 V, the command is given for coupling the first consumer through the numerical output of the data acquisition board, through an intermediary relay board and the contactor from the load circuit. The algorithm continues until all consumers are coupled to the high wind regime of the wind power station. At a decrease of the wind speed, first the non priority consumers will be disconnected. The wiring diagram of the control device for controlling the load connected to the output terminals of the three-phase generator of a wind power plant is shown in Figure 2.13.

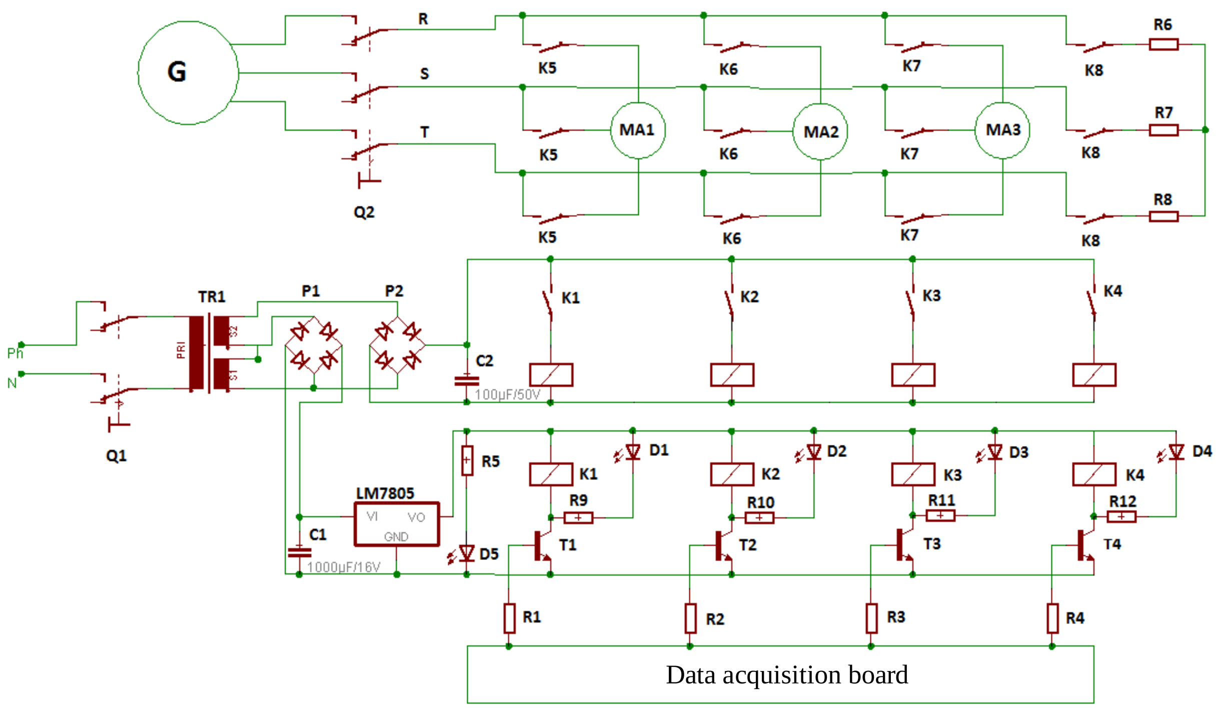

Fig. 2.13 The electrical diagram of the control device of the loads connected to the three-phase asynchronous generator terminals

2.4.3. Experimental determinations

For controlling the connection of the priority and non priority loads a program in LabVIEW programming environment has been developed, whose block diagram is shown in Fig. 2.14 and whose front panel is shown in Fig. 2.15. The front panel allows real-time display of the voltage measured by the voltage encoder at the output terminals of the stator windings of the three-phase asynchronous generator as well as the analog and digital display of this voltage. On the front panel the connection of the consumers to the output terminals of the three-phase generator is signaled by the lamps L1-L4.

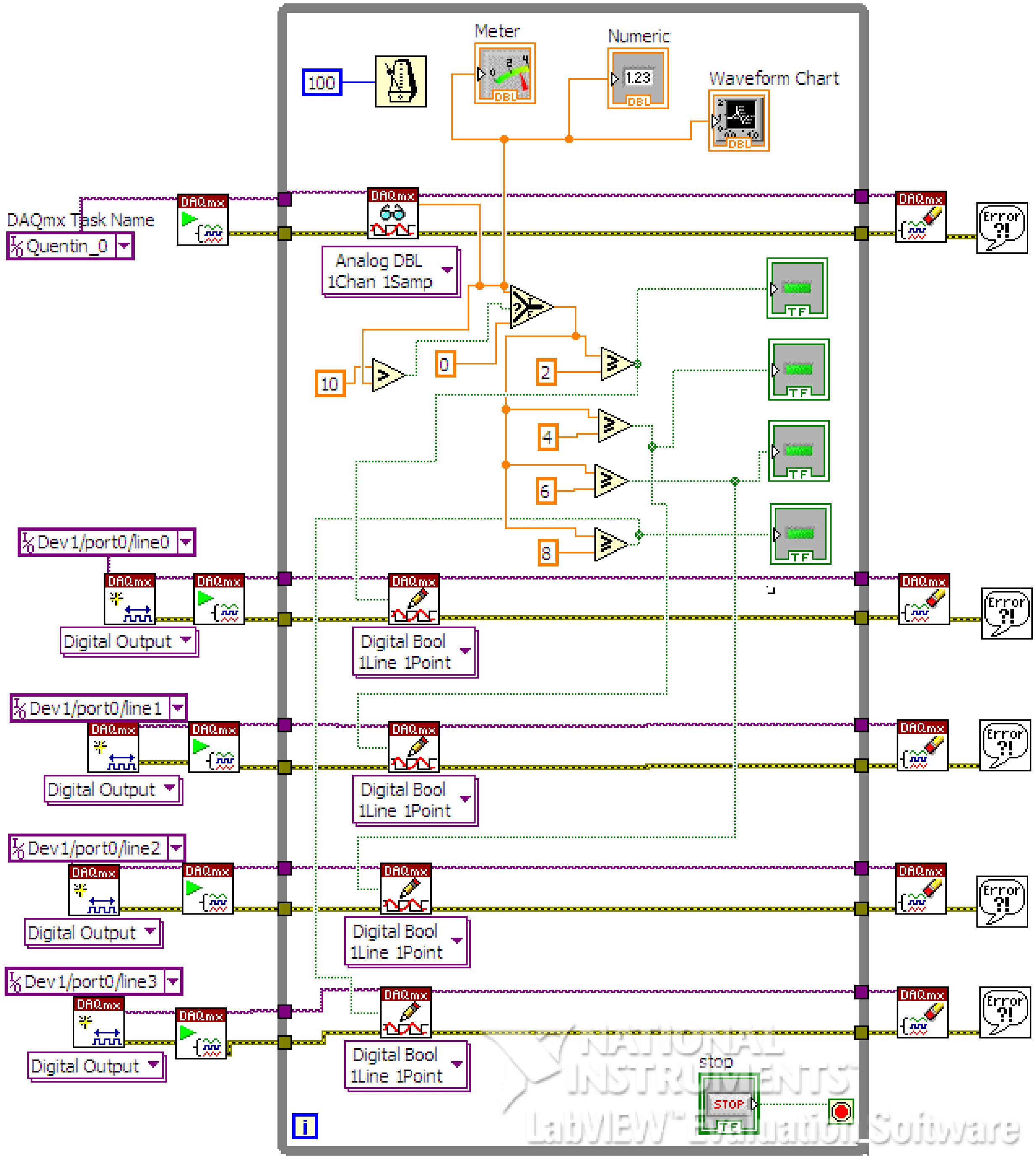

Fig. 2.14 The block diagram of the program for controlling the connection of loads to the three-phase generator asynchronous terminals

For managing of energy produced by a low power wind power station, the signals from the voltage, current and power factor encoders from the output terminals of the three-phase generator are transmitted to the acquisition board of the computer via connection couplers. In the LabVIEW programming environment a program has been developed to measure in real time the active, reactive and apparent power from the output of the three-phase asynchronous generator with wound rotor. The front panel and block diagram are shown in [16].

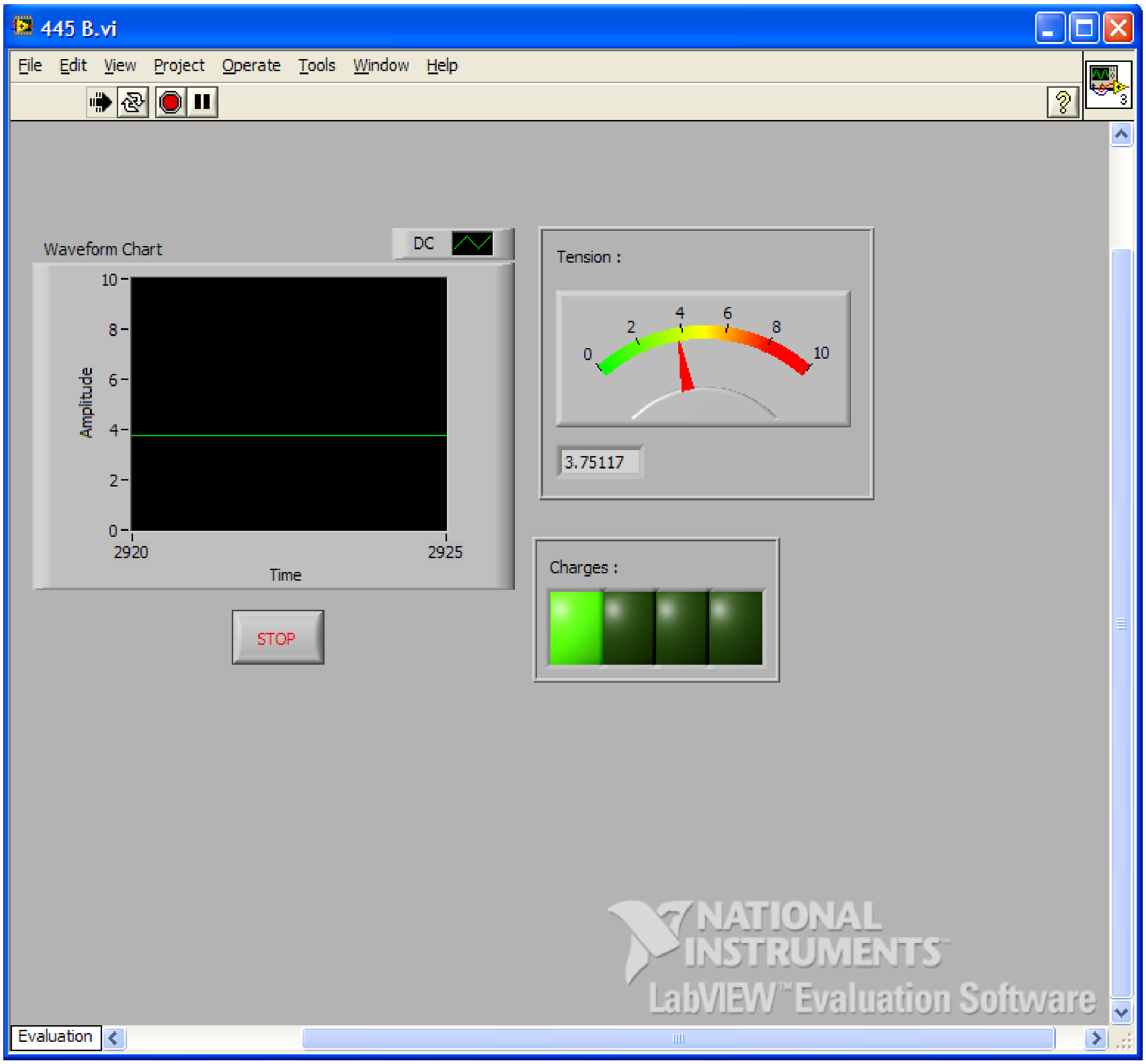

Fig. 2.15 Front panel of the program for connection control of the loads to the three-phase asynchronous generator terminals

Details of these applications are found in [15], [16] and [17]. For calculating the active, reactive and apparent power, the Matscript instruction of the MATLAB [18] program in the application made in LabVIEW is used. In the same area I have published the paper [19]. The modeling of three-phase asynchronous generators used in the construction of wind power stations has been presented by me in the paper [20].

2.5. Synchronous generator with permanent super magnets, of small size and high power

The company ICPE - S. A. Bucharest produces three-phase brushless synchronous generators with permanent magnets in different variants, rated within 400 - 1500 W used in the construction of wind power stations. The disadvantage of these types of generators is the large cross section of the conductor for winding the three-phase stator winding, because of its three-phase connection, that requires a large construction of the stator, resulting in a lower yield of converting the mechanical energy into electrical energy. In the Electrical Machines Laboratory of the “Vasile Alecsandri" University of Bacău, I have designed and built a three-phase synchronous generator of small size and high power in reverse construction, in collaboration with Dipl. Eng. Andone Constantin. For this three-phase synchronous generator of small size and high power we have obtained **the patent no. 125 745** dated **29. 07. 2011** from OSIM (State Office for Inventions and Brands) Bucharest. The aim of the invention was to increase the efficiency of electricity production in various industrial applications, in the power range of 400 through 1500 W, that corresponds to the wind power. A sectional view of this generator is shown in Fig. 2.16.

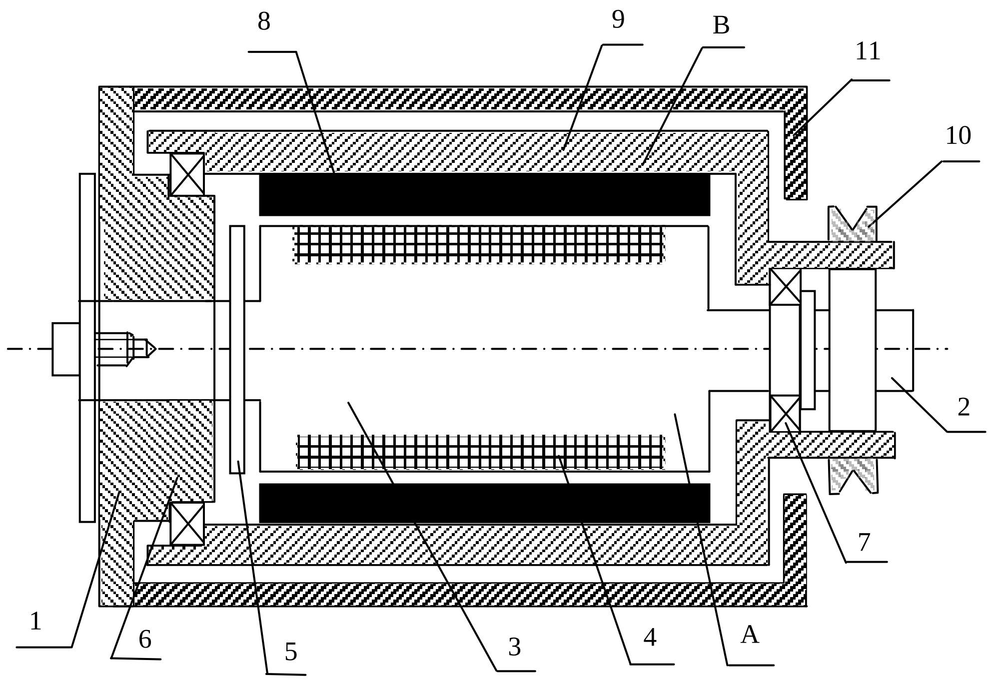

Fig. 2.16 Polyphase synchronous generator of small size and high power

In the construction of the synchronous generator was used supermagnete Neodymium permanent type. Polyphase winding was made of copper. The coils components of the winding are connected in star and the other end connected to a polyphase rectifier made with low power diodes. The diagram of polyphase stator winding is shown in Figure 2.17. Details of the synchronous generator can be found in the work: [21], [22]. Other three-phase permanent magnet synchronous generators are presented in [23], [24], [25] and [26]. For the study of synchronous generators with permanent SuperMagnets was used experimental stand shown in Fig. 2.18. This stand consists of: three-phase synchronous generator with permanent SuperMagnete in the construction reverse (a), universal asynchronous motor (b) flexible coupling (c) dimmer (d), ammeter (e), voltmeter (f), tachometer (g) and load resistance (h). A cross section through the three-phase synchronous generator is shown in Figure 2.19.

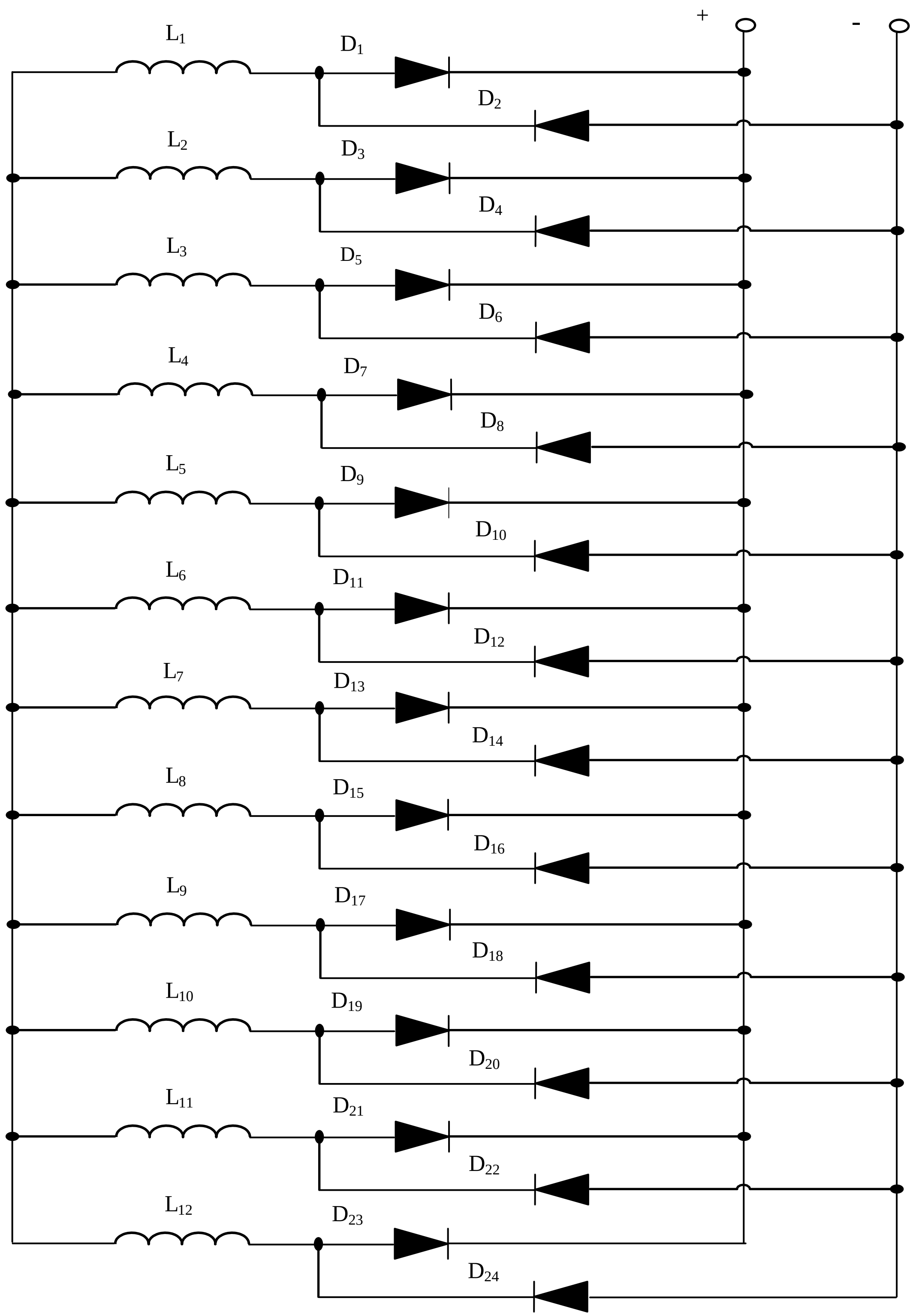

Fig. 2.17 The polyphase winding of the synchronous generator with small size and high power

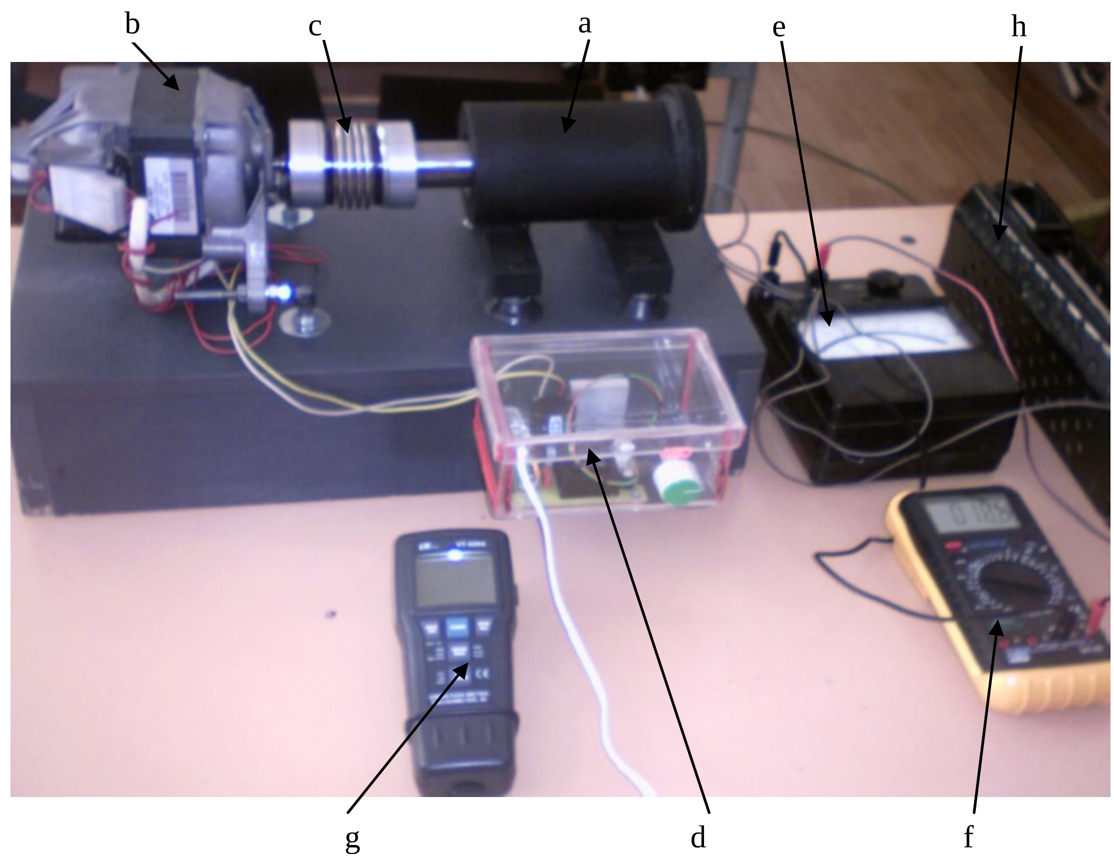

Fig. 2.18 Experimental stand

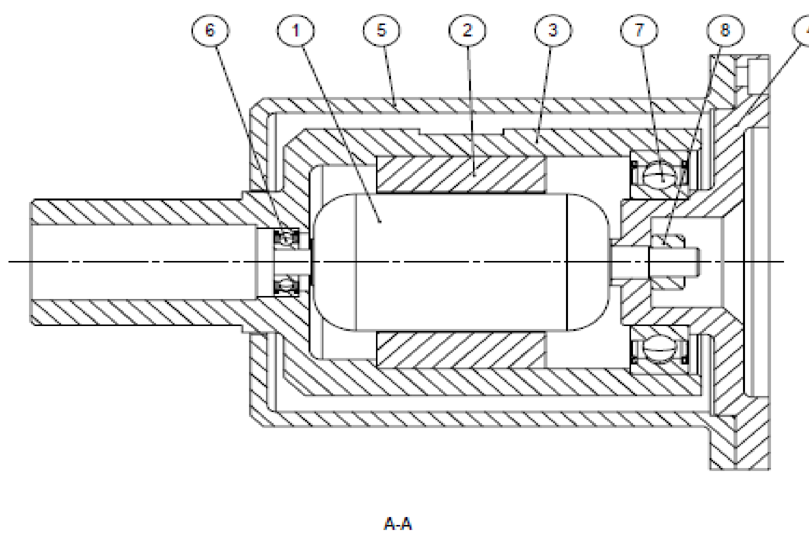

Figure 2.19 Cross sections of the three-phase synchronous generator

1- stator, 2- rotor , 3- box rotor, 4- ring, 5-fairing, 6- bearing 607 2Z , 7- bearing 6007 2Z, 8 - hex nut

The stator of the three-phase synchronous generator with permanent supermagnetic is shown in Fig. 2.20. The stator shaft is fixed to the ring (4) by means of hexagon nuts (8). The bearings are fixed on the stator shaft (6) and (7) for supporting and driving the rotor in rotation. The three-phase synchronous generator rotor is shown in FIG. 2.21. It consists of the box (3) in that secures the permanent super magnets. Permanent super magnets are neodymium type. The polarity of the permanent supermagenet is alternating, having a heteropolar rotor as result.

Fig. 2.20 Generator stator

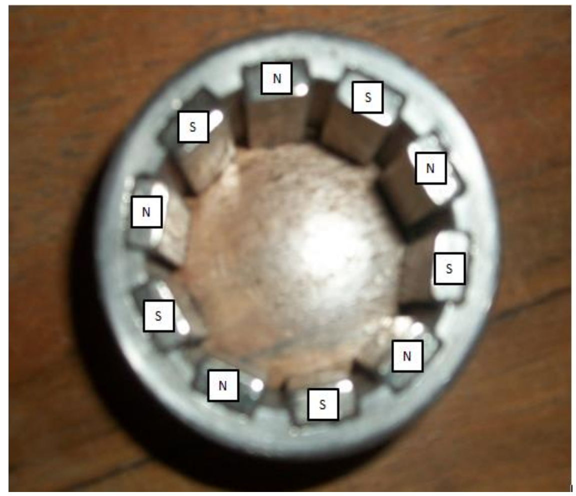

Fig. 2.21 Generator rotor

By means of the experimental stand the following characteristics of the synchronous generator with permanent ssuper magnets have been obtained :

4.1. The idle running diagram of the three phase asynchronous generator, U=f(n); U is the voltage measured at the terminals between two phases of the generator and n is the speed of the synchronous generator. The resulting values are presented in Table 2.1 and the related diagram is shown at Fig. 2.22.

Table 2.1

U (volt)	8	10	15	18	21	27	33	38	45
n (rpm)	522	586	765	898	1083	1380	1652	1933	2220

4.2. The load running diagram of the three phase synchronous generator U = f(I); U is the voltage on terminals measured between two phases of the generator and I is the current intensity through the load resistor Rs and through the respective windings at a constant speed generator rotor , n= 2536 rpm. The resulting values are shown at Table 2.2 and the related diagram at Fig. 2.23.

Table 2.2

U (volt)	21,4	17,3	12,2	7	1
I (A)	6,5	7,5	8,25	9	10

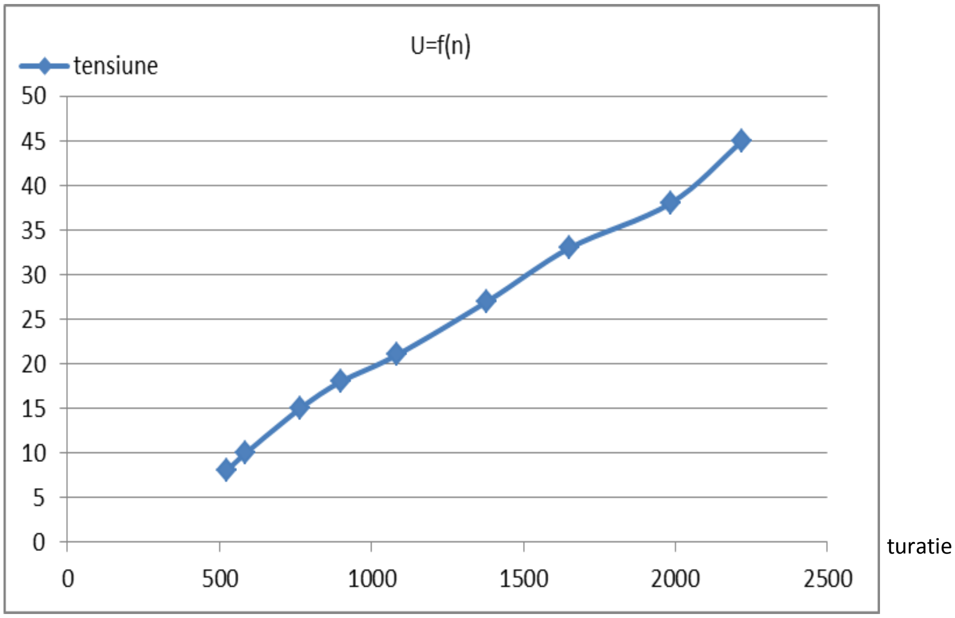

Fig. 2.22 Diagram of idle running of the three phase synchronous generator

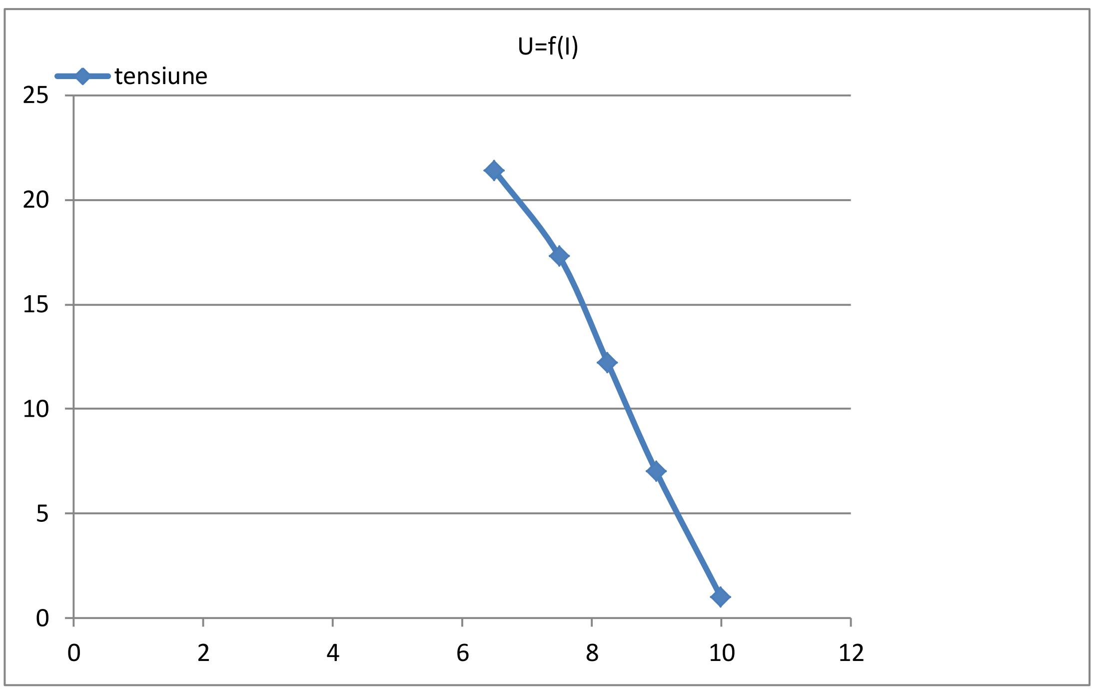

Fig. 2.23 Diagram of load running of the three phase synchronous generator

These results have been published in the paper indexed Thomson Reuters ISI [27]. In the LabVIEW programming environment I have designed a speed control system of three-phase motors which can be used for the stand that simulates the operation of the wind power station. In this context, I have published the paper [28].

C.III INCREASING THE PERFORMANCES OF THE PHOTOVOLTAIC SYSTEMS FOR THE PRODUCTION OF THE ELECTRICAL ENERGY

3.1. Modeling of the PV generator

The model with a diode is a classical model in the literature [29, 30, 31, 32 and 33]. This implies a current generator for modeling of flow incident light, a diode for the phenomen of polarization of the cell and two resistors (parallel and serial) for the loss. The photovoltaic cell is shown in the figure below (Fig. 3.1).

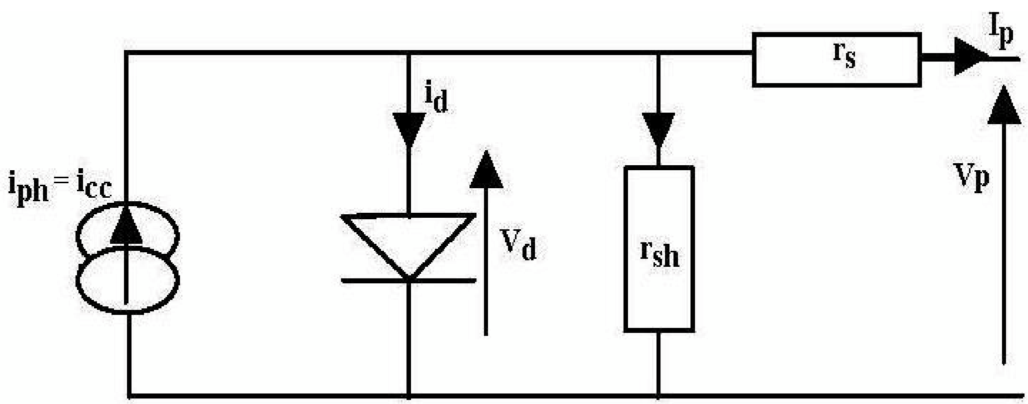

Fig. 3.1 Electrical diagram equivalent to a photovoltaic cell

This model has four variables, Figure 3.2. The two input variables are: E_s- radiation intensity in the plan of the modules (W / m²) and T_j – cell junction temperature (° C). The two output variables are: I_G- current supply by the group of modules (A) and V_G-the voltage at the terminals of the group of modules (V).

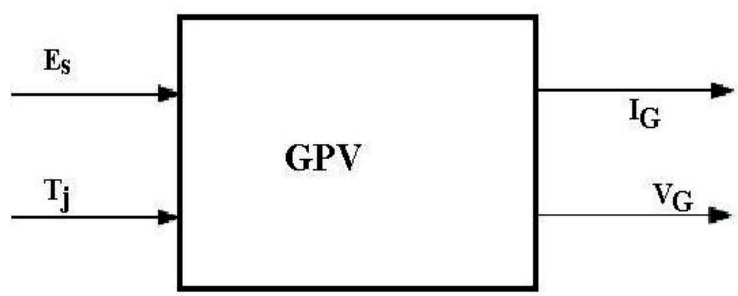

Fig. 3.2 Block diagram of the PV generator

The characteristic equation for a group of photovoltaic modules is obtained from the electrical equivalent circuit shown in Figure 3.1.

$$I_G = I_{ph} - I_d - I_{sh} \tag{3.1}$$

The current, I_{ph} is directly dependent on the radiation intensity and temperature of the modules and can be determined with the relation, [31]:

$$I_{ph} = P_1 \times E_s \times \left[1 + P_2\left(E_s - E_{sref}\right) + P_3\left(T_j - T_{jref}\right)\right] \tag{3.2}$$

Where: $E_{sref} = 1000\ W/m^2$, is the reference radiation intensity, $T_{jref} = 25\ ^0C$ reference temperature of modules. P_1, P_2 and P_3 are constant parameters. The polarization current of the junction PN, I_d is given by relation:

$$I_d = I_{sat} \times \left[exp\left(\frac{q}{k \cdot A \cdot n_s \cdot T_j}(V_G + R_s \cdot I_G)\right) - 1\right] \tag{3.3}$$

where: I_{sat} is the saturation current; k Boltzmann's constant ($1.38\ 10^{-23}$ J/K) ; q elementary charge ($1.6\ 10^{-19}$ C); A - ideal factor of the junction. The current of saturation of the diode is:

$$I_{sat} = P_4 \times T_j^3 \times exp\left(E_g/k \times T_j\right) \tag{3.4}$$

where: E_g is the energy difference and P_4 is a constant parameter. Finally, the current through the resistor in parallel is written as:

$$I_{sh} = \frac{V_G}{R_{sh}} \tag{3.5}$$

The final equation may be written:

$$\begin{aligned} I_G &= P_1 \times E_s \times \left[1 + P_2\left(E_s - E_{sref}\right) + P_3\left(T_j - T_{jref}\right)\right] - \frac{V_G}{R_{sh}} \\ &-P_4 \times T_j^3 \times exp\left(-\frac{E_g}{k \cdot T_j}\right)\left[exp\left(\frac{q}{k \cdot A \cdot n_s \cdot T_j}(V_G + R_s \cdot I_G)\right) - 1\right] \end{aligned} \tag{3.6}$$

A default function of the form of below is obtained:

$$I_G = f\left(I_G, V_G,\ E_s,\ T_j\right) \tag{3.7}$$

with 7 determined parameters P_1, P_2, P_3, P_4, A, R_s and R_{sh}. Resistance in series connection must to be of low value and resistance in parallel should be very high, so the maximum current to be supplied to the load, [31]: P_1 = 0,0036; P_2 = 0,0001; P_3 = - 0,0005; P_4 = 70,843; A = 1; R_s = 0,614 Ω; R_{sh}= 151,16 Ω.

3.2 Simulation of a solar cell in PSIM

The electrical model of Fig. 3.1 is easily adaptable to any type of software system [32]. It uses for modeling an exemple of multi-crystalline silicon cells, the PSIM simulation software. Figure 3.3 shows the elements of the equivalent circuit diagram presented above.

A non-linear resistor was used to reproduce the actual characteristic of the diode, respectively PN junction.

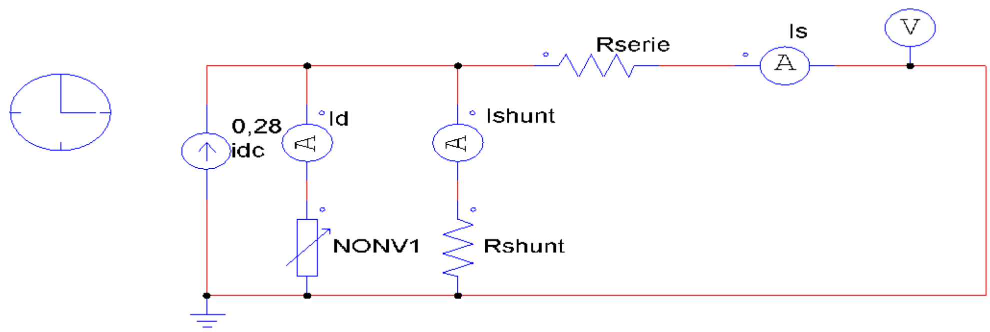

Figure 3.3 The electrical equivalent circuit of a solar cell under PSIM

With this simplified installation, the static characteristics of a photovoltaic cell exposed to solar radiation and at a constant temperature can be simulated along time, regardless the technology. It is sufficient to modify the model parameters in order to obtain good characteristics. Simulation results for the two different values of the supply of current are shown in the following figures:

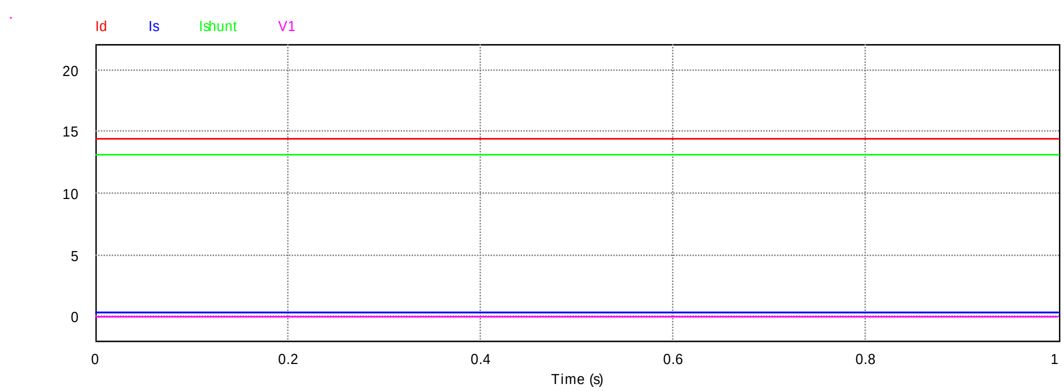

Figure 3.4 The characteristic of simulated current for a current source Idc = 0,028 A

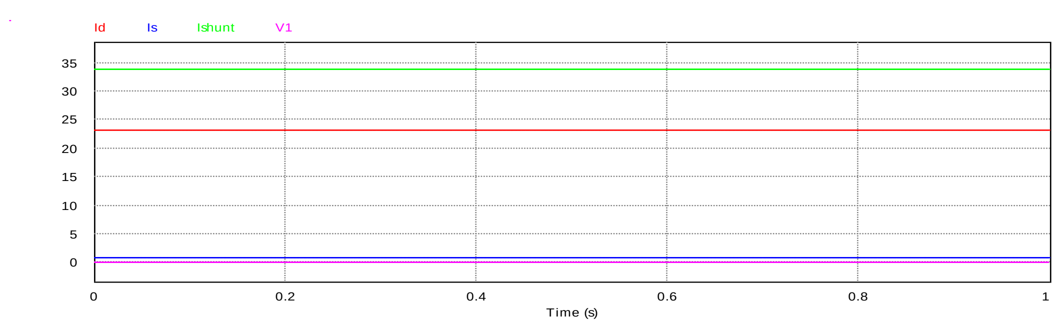

Figure 3.5 The characteristic of simulated current for a current source Idc = 0,058 A

3.3 MPPT control algorithms of the autonomous photovoltaic systems

3.3.1 Generalities

For the convertion of the solar energy into electricity the systems with photovoltaic modules are used more and more. The solar energy is often stored using batteries. The continuous improvement of manufacturing technologies of photovoltaic panels has led to the need to develop battery charging algorithms designed to ensure a fast and safe charging. Through effective monitoring of the charging process damage to the battery is prevented. Photovoltaic systems only use a fraction of the solar radiation and certain wavelengths, to produce electricity. The difference in energy received at the surface of photovoltaic panels is converted into heat, increases the temperature of photovoltaic cells components by decreasing their efficiency. To increase the energy productivity of photovoltaic systems, optimizing algorithms for battery charging are used, that allow obtaining a maximum transfer of power from the solar power plant. For reaching the maximum power transfer in a photovoltaic system, a DC-DC converter between the PV generator and the load of the user is necessary, which must provide the optimum charging voltage and current. The transfer of maximum power is achieved by providing a continuous DC-DC converter such as to maximize the conversion efficiency, regardless the load to which it is connected, the light intensity, the temperature or the solar panel area. Research activities that I have carried out and presented in [34], [35], [36] and [37] aimed at obtaining maximum power available at the terminals of a photovoltaic system. There are several types of control algorithms for DC-DC converters such as:

- MPPT algorithm “Perturbe & Observe”
- MPPT algorithm "Incremental conductance"

3.3.2 Maximum power point

For a photovoltaic panel the voltage-current characteristic (IU) depends mainly on the intensity of solar radiation and the temperature of the cells. For various meteorological parameters there is the operating characteristic of the PV generator shown in FIG. 3.6. The operating point (PF) is at the intersection of the IU diagram with the load diagram from the terminals of the PV generator, Figure 3.6. This operating point is generally different from the maximum power point (MPP). Maximum Power Point (MPP) is the operating point to which between the generator and the load the maximum power is transferred. The maximum power point depends on the operating conditions of the PV generator, and the electrical characteristics of the load from its terminals. Systems tracking the maximum power point aimed at maintaining the operating point as close to the MPP. A photovoltaic system operates at the maximum power point if the following conditions are met (3.8) [38], [39], [40]:

$$\begin{aligned} U_{PV} &= U_{opt.} \\ I_{PV} &= I_{opt.} \\ R_{PV} &= R_S = \frac{U_{opt.}}{I_{opt.}} \end{aligned} \tag{3.8}$$

The block diagram of a photovoltaic system used to achieve a maximum power transfer between the PV generator and the receiver is shown in Fig. 3.7.
DC-DC converters are divided into several categories such as:

- Converters DC-DC increasing the voltage (boost- fig. 3.8)
- Converters DC-DC decreasing the voltage (buck- fig. 3.9)

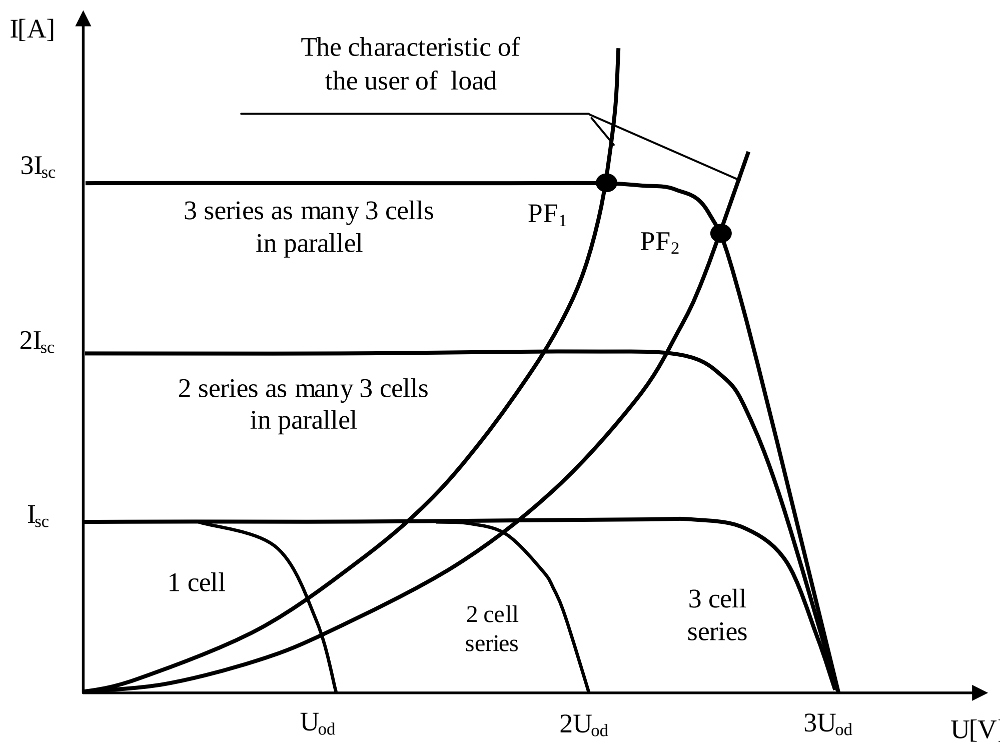

Fig. 3.6 The determination of the operating point for a photovoltaic system

Continuous adaptation of the PV generator load is performed by the DC-DC converter using a control signal in the impulses modulated in width PWM. This signal is applied on the base of the MOSFET transistor with short switching time. The duty cycle of the PWM control signal is calculated based on the algorithm of tracking the maximum power point.

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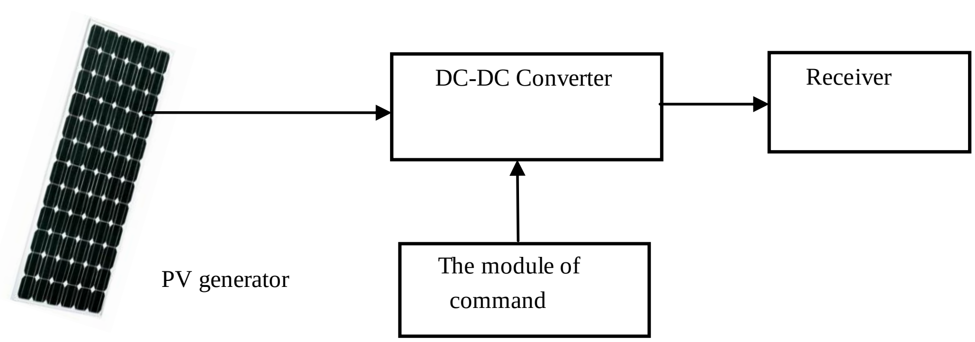

Fig. 3.7 Block diagram of a photovoltaic system

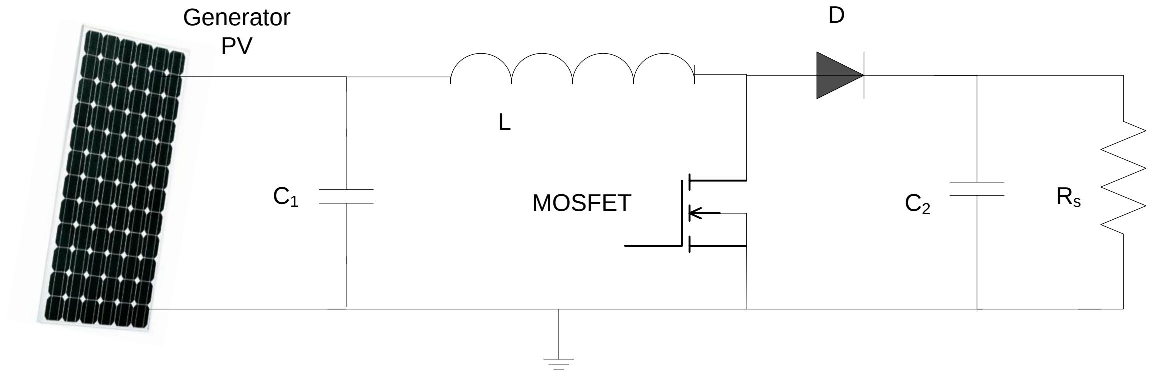

Fig. 3.8 The principle scheme of a DC-DC converter type Boost

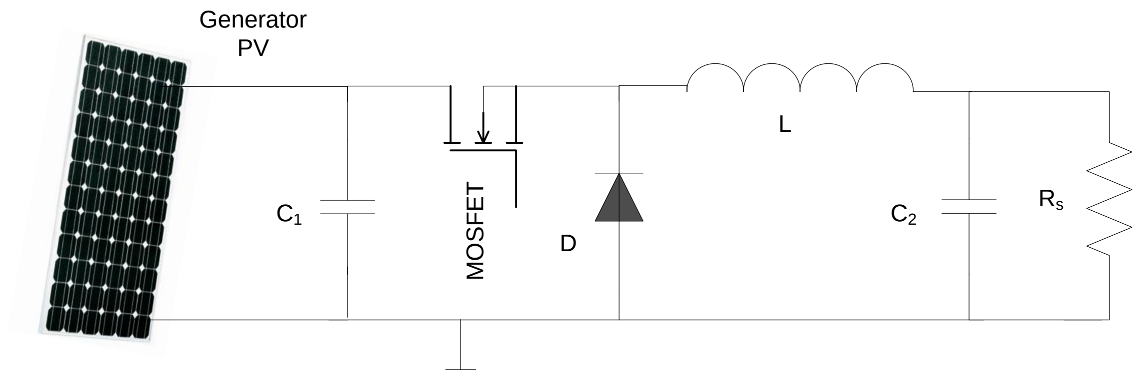

Fig. 3.9 The principle scheme of a DC-DC converter type Buck

3.3.3 MPPT algorithm "Perturbe & Observe"

The logical diagram of the algorithm is shown in FIG. 3.10. Maximum Power Point MPP is determined by repeated tests.

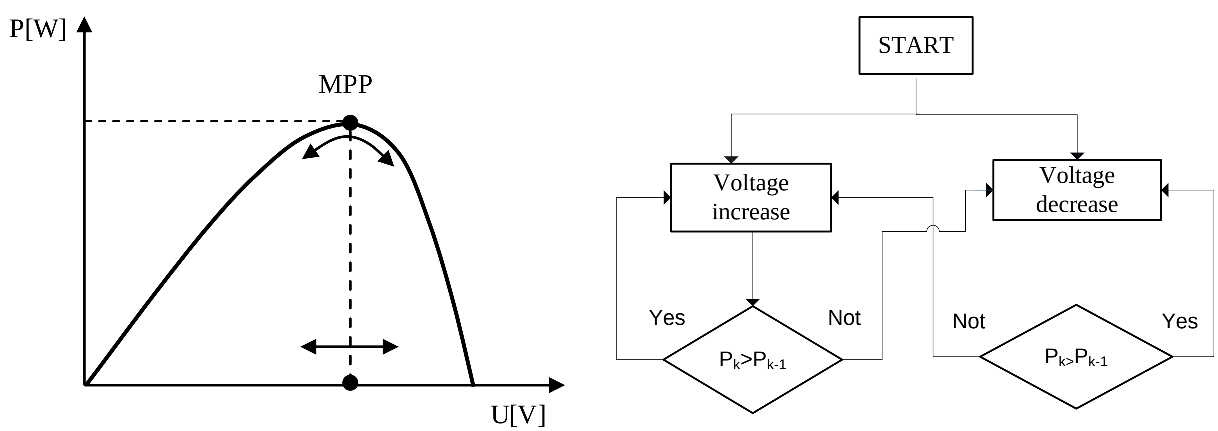

Fig. 3.10 MPPT algorithm "Perturbe & Observe"

The changes in voltage or current at the terminals of the generator and the electric power being delivered are compared, in this case, to the electric power in the previous step. If the power in the present step is higher, the disturbance has been done in the right direction. If not, the next disturbance will be in the opposite direction. Usually, the operating voltage used on the DC / DC converter will oscillate around the value corresponding to the maximum point of operation.

3.3.4 MPPT algorithm "Incremental conductance"

This algorithm is based on the pursuit of the value of the derivative power in relation to voltage and setting the result to zero [38].

$$\frac{dP}{dU} = \frac{d(UI)}{dU} = I + U\frac{dI}{dV} = 0 \tag{3.9}$$

Maximum point of operating corresponds to the solution of the above equation. From the equation of the derivative of power with respect to zero voltage, it results:

$$-\frac{I}{U} = \frac{dI}{dU} \tag{3.10}$$

$-I/U$ is the opposite of the instantaneous conductance of the photovoltaic panel, while the right side is the incremental conductance, namely current change versus voltage (dI/dU). At the functioning in maximum power point two quantities must be equal in absolute size, $\frac{dI}{dU} = -\frac{I}{U}$. For the operating point to get settled into the maximum power point, the following algorithm will be used: *a)* from the equation (3.10) the following set of inequalities will be determined:

$$\frac{dI}{dU} = -\frac{I}{U} \quad \left(\frac{dP}{dU} = 0\right) \quad \text{(3.11.a)}$$

$$\frac{dI}{dU} > -\frac{I}{U} \quad \left(\frac{dP}{dU} > 0\right) \quad \text{(3.11.b)} \tag{3.11}$$

$$\frac{dI}{dU} < -\frac{I}{U} \quad \left(\frac{dP}{dU} < 0\right) \quad \text{(3.11.c)}$$

b) The equations 3.11 (b and c) are used to determine the direction that should be a shift in the operating point to the MPP.

c) The algorithm is repeated until the condition (3.11.a) is satisfied.

Once MPP MPPT reached, it will continue to operate until there is a change in the measured current. This change in current is correlated with the change of solar radiation on the photovoltaic panel. The logical diagram of the iterative algorithm is shown in Figure 3.11.

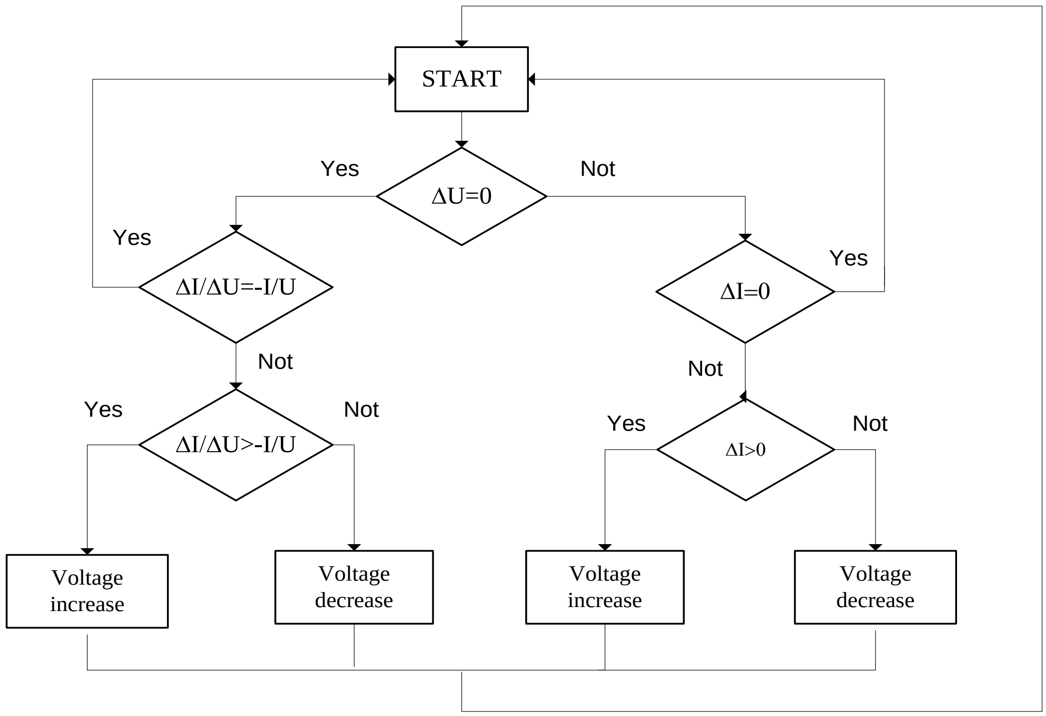

Fig. 3.11 MPPT algorithm "Incremental Conductance"

3.3.5 Real-time simulation of photovoltaic systems with MPPT

For real-time simulation of a photovoltaic system with MPPT the experimental stand shown in Fig. 3.12 has been used. This experimental stand is composed of a control board Compact RIO 9074, [37] and a portable computer. The stand has been built in the laboratory of Electrical Machines of "Vasile Alecsandri" University of Bacău.

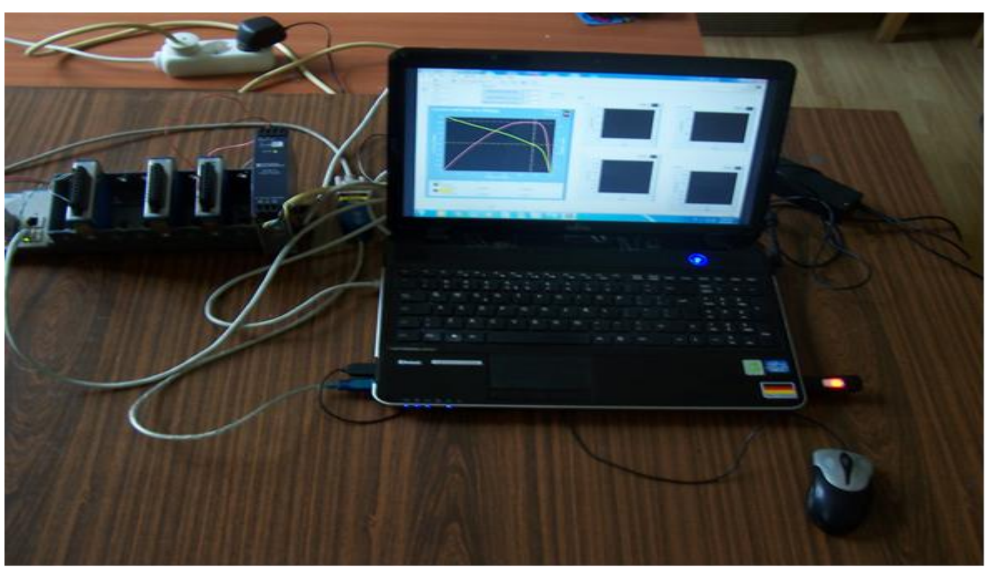

Fig. 3.12 Experimental stand

To implement the MPPT algorithm "Incremental conductance" a program was developed in 2013 LabVIEW. The related block diagram is shown in Fig. 3.13.

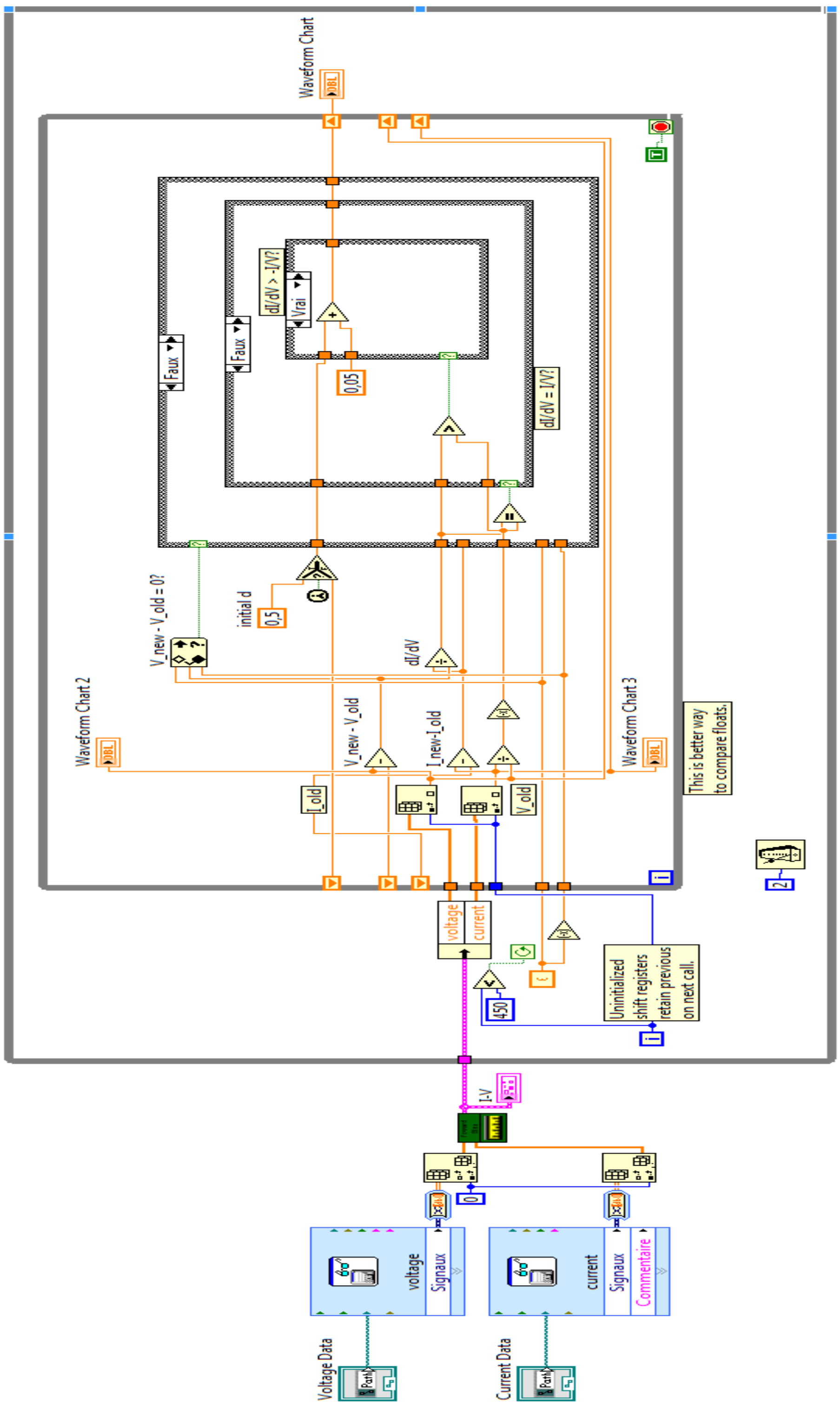

Fig. 3.13 The block diagram of the program developed in LabVIEW

The input parameters are voltage and current, respectively IU curve parameters for different values of solar radiation. In our application the parameters have been extracted from the data sheet of photovoltaic panels for the following values of solar radiation: 200, 400, 600, 800 and 1000 W / m^2. Performance parameters such as filling factor (ratio of maximum power that can be obtained from the product of open circuit voltage and short-circuit current), Voc open circuit voltage , Isc short-circuit current, and power parameters, such as the characteristics of the global maximum point (MPP) Imp, Vmp and Pmax and most importantly, the overall efficiency are shown in Figure 3.14.

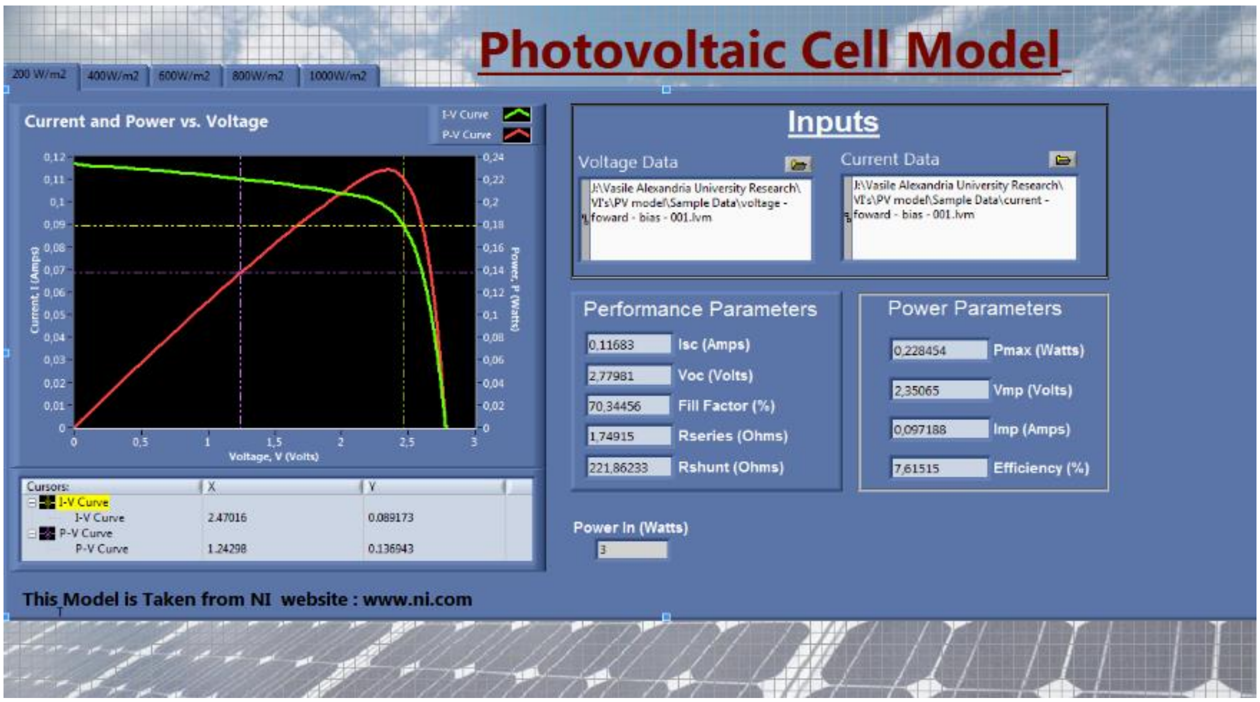

Fig. 3.14 Performance parameters for different values of the solar radiation

3.3.6 Photovoltaic system with MPPT of industrial type

In the laboratory of Electrical Machines an experimental stand for a photovoltaic system with MPPT of industrial type has been built. It is shown in Fig. 3.15. The experimental stand is composed of the following components:

1 - Photovoltaic panels;
2 - Solar regulator;
3 - Batteries to store electricity;
4 - 24 V D.C. / 220 V A. C. inverter;
5 - Switch;
6 - Electromagnetic vibrator pump;
7 - Reservoir
8 - Ammeter
9 – Watt meter
10 - Electric lamps.

Photovoltaic panels are of type BS-185-5M6.1. The characteristics of the photovoltaic panels are: each photovoltaic module is formed of 72 silicon single crystal cells of 125 mm x 125 mm each, connected in series. The frame of the photovoltaic modules is made of aluminum angle bar 35 mm x 35 mm with a thickness of 1.5 mm. Dimensions of photovoltaic modules are: - Length: 1580 mm; - Width: 808 mm; - Thickness: 46 mm and weight of 15.5 kg. Technical performances of the modules are: - nominal power produced: 170-190 W; - Guaranteed minimum power: - minimum 90% of the rated power for a period of over 10 years; - At least 80% of the rated power for a time period of over 25 years. The solar WRM 15 (Figure 3.16) manufactured by the company Western is a complete solution for making photovoltaic systems off - grid for feeding road signaling systems, for lighting systems and for battery recharging. This model of regulator uses the MPPT (Maximum Power Point Tracking) technology, [30], [31] that has a circuit of search of the maximum power of the photovoltaic module: regardless the battery voltage and condition, WRM 15 always detects the point of maximum power and maximizes the energy extracted for charging the battery. Technical characteristics of WRM 15: - MPPT technology; - Voltage photovoltaic modules 0-100 V; - 450 W maximum power mode; - 18 programs for consumers; - Automatic detection 12/24 V; - Overvoltage protection; - Reverse battery protection; - Overload protection on the output.

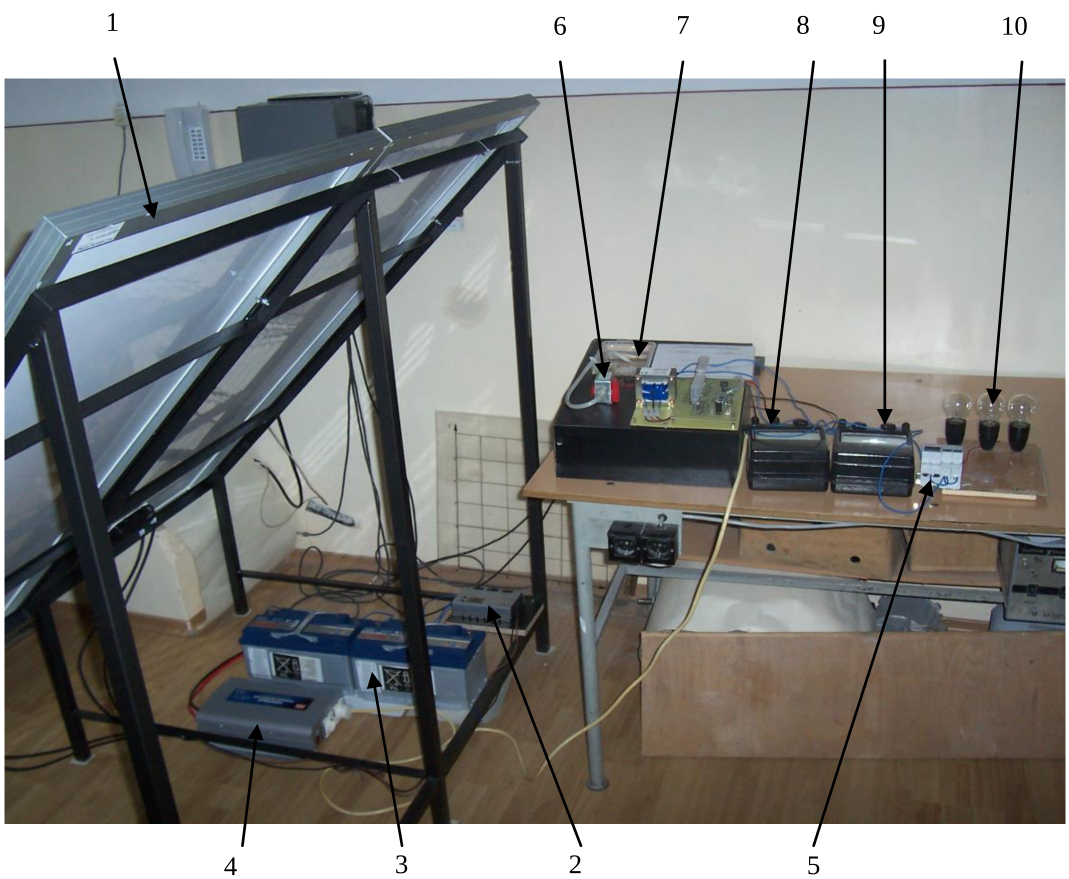

Fig. 3.15 Experimental stand for photovoltaic system with MPPT of industrial type

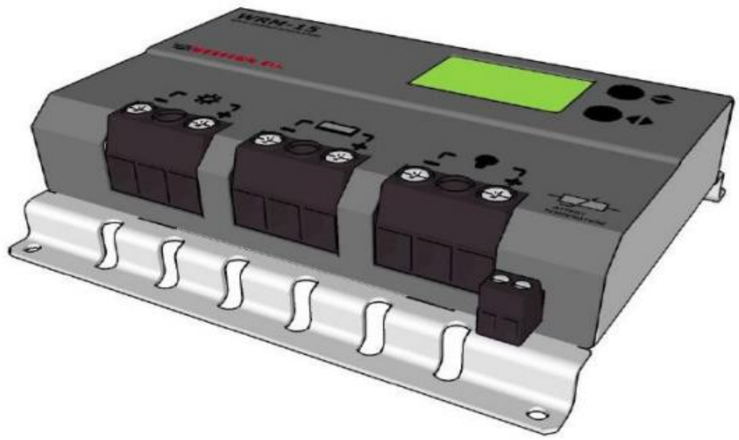

Fig. 3.16 Solar regulator WRM 15A

The electromagnetic vibrator pump is manufactured by ULKA, model E, type EX5.
Characteristics of electromagnetic vibrator pump ULKA EX5 are:

- Power supply: - 230 V.a.c. ;
- The frequency 50 Hz;
- Power: 48 W;
- Flow rate: 2 l / min.

Characteristics of electric lamps are:

- Voltage: 220 V.a.c.
- Power input: 100 W

With the help of the experimental stand the operating mode at load of the PV system has been studied. The electric lamps and the electromagnetic vibrator pump have been successively connected to the inverter output voltage and the power delivered by the photovoltaic panels has been measured for each case. These results are presented in [34].

3.3.7 Photovoltaic system with DC / DC converter controlled with CompactRIO 9074

For the photovoltaic system presented above I renounced the MPPT device of industrial type and used a DC / DC converter of buck type controlled through the board CompactRIO 9074, in the LabVIEW programming environment. A photograph of the respective experimental stand is shown in FIG. 3.17. The buck converter DC / DC has been built in the laboratory of Electrical Machines of the "Vasile Alecsandri" University of Bacău. The converter input voltage is 36 V d. c. and the output voltage is 24 V.d.c. It functions on the principle of the commutation and consists of a field effect transistor IRF 9045, a power diode MBR 1060, a coil of inductance L = 100 mH and the filter capacitors at the input and the output of the converter. The power transistor is controlled by a PWM output signal supplied by the NI 9072 module from the acquisition and control board Compact RIO 9074. To control the battery charging voltage from the solar panel an application in LabVIEW 2013 has been issued. Through this application a PI control algorithm has been implemented for the battery charging voltage. The block diagram in LabVIEW software is shown in Fig. 3.18 and front panel in Fig. 3.19.

Fig. 3.17 Experimental stand for the photovoltaic system with DC / DC converter

The experimental results have been presented in [35]. Solar energy conversion systems and control algorithms for a photovoltaic system are presented by other researchers in [38], [40], [41], [42], [43], [44].

3.3.8 Study case of a hybrid photovoltaic-wind system with the Homer program, [45]

3.3.8.1 Using of HOMER program

For the design and analysis of hybrid systems for electricity generation the HOMER program has been used. Homer program can be used both for hybrid systems connected to the network and independent systems, [46]. The case study was conducted for a photovoltaic-wind hybrid system built at the University of Le Havre. HOMER program compares the different technology offerings in the design of the hybrid electricity production. In the resources section, it may be noticed that the Homer program displays the corresponding buttons for the necessary energy sources (solar and wind sources), Figure 3.20. The schematic diagram of the hybrid system being analyzed is shown in Figure 3.21. The components of the system are presented in Figure 3.22.

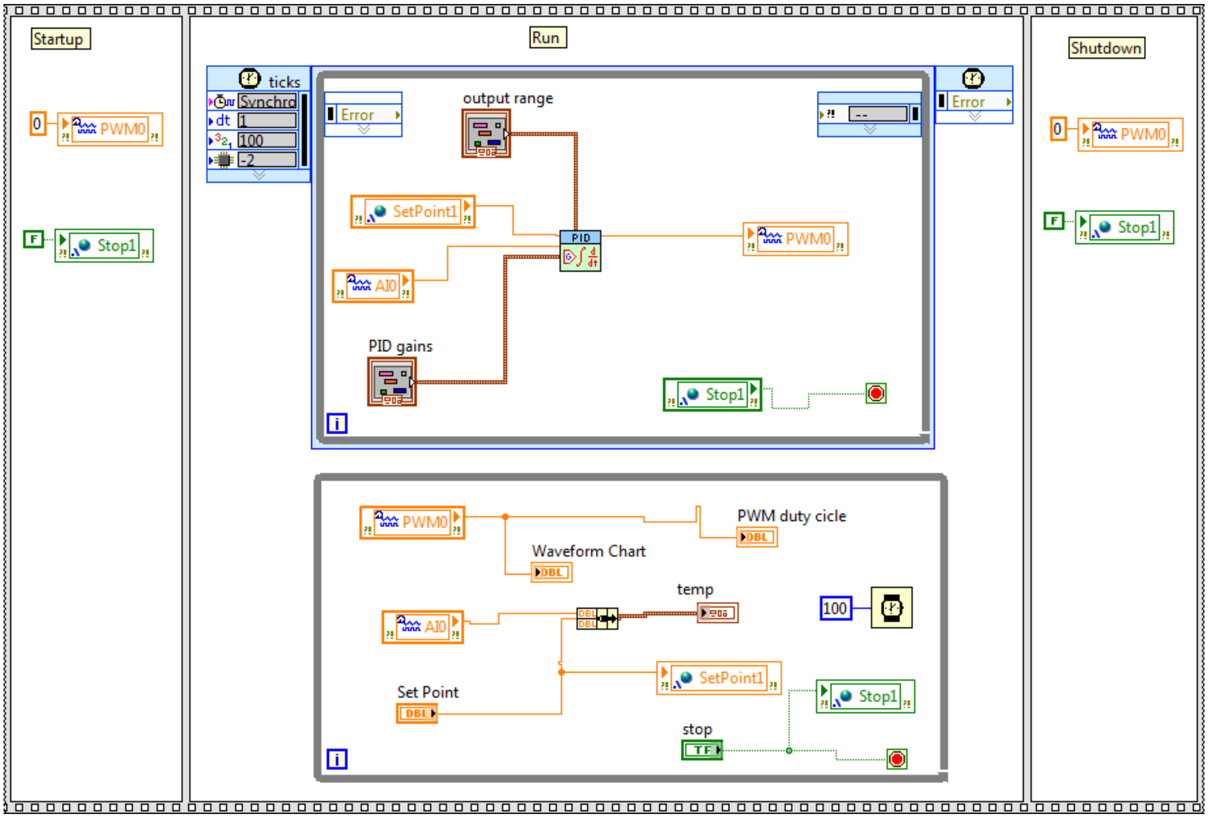

Fig. 3.18 The block diagram for the photovoltaic system with DC / DC converter

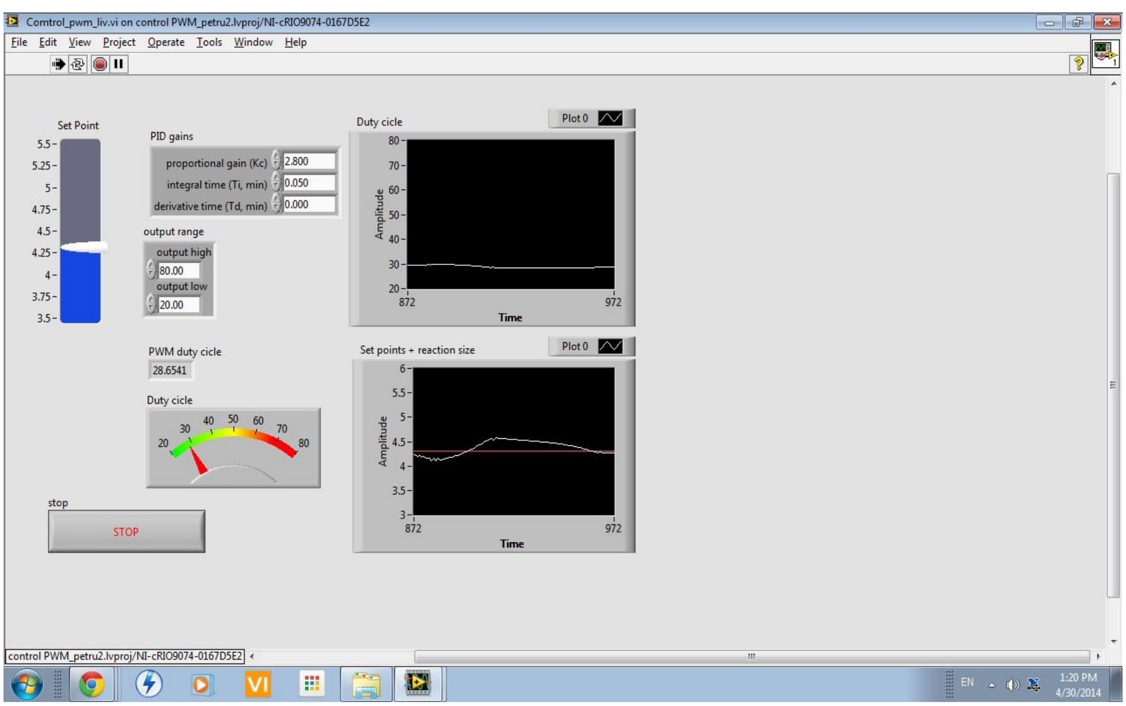

Fig. 3.19 The front panel for the photovoltaic system DC / DC converter

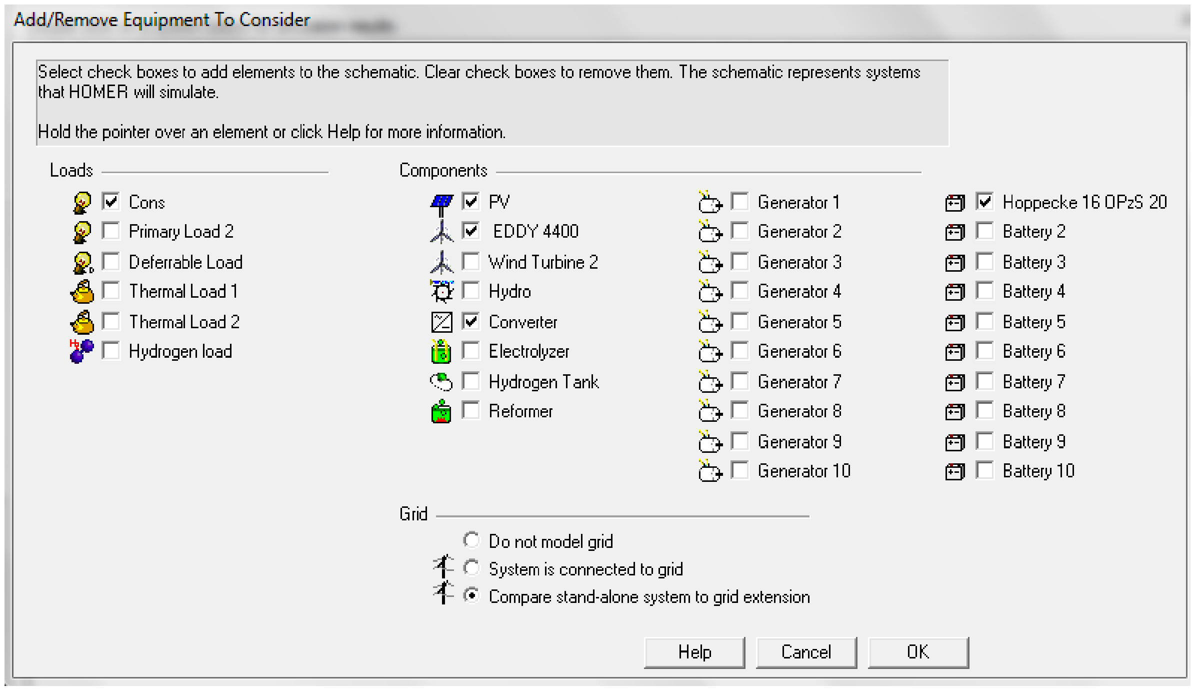

Fig. 3.20 Chosing the components with HOMER

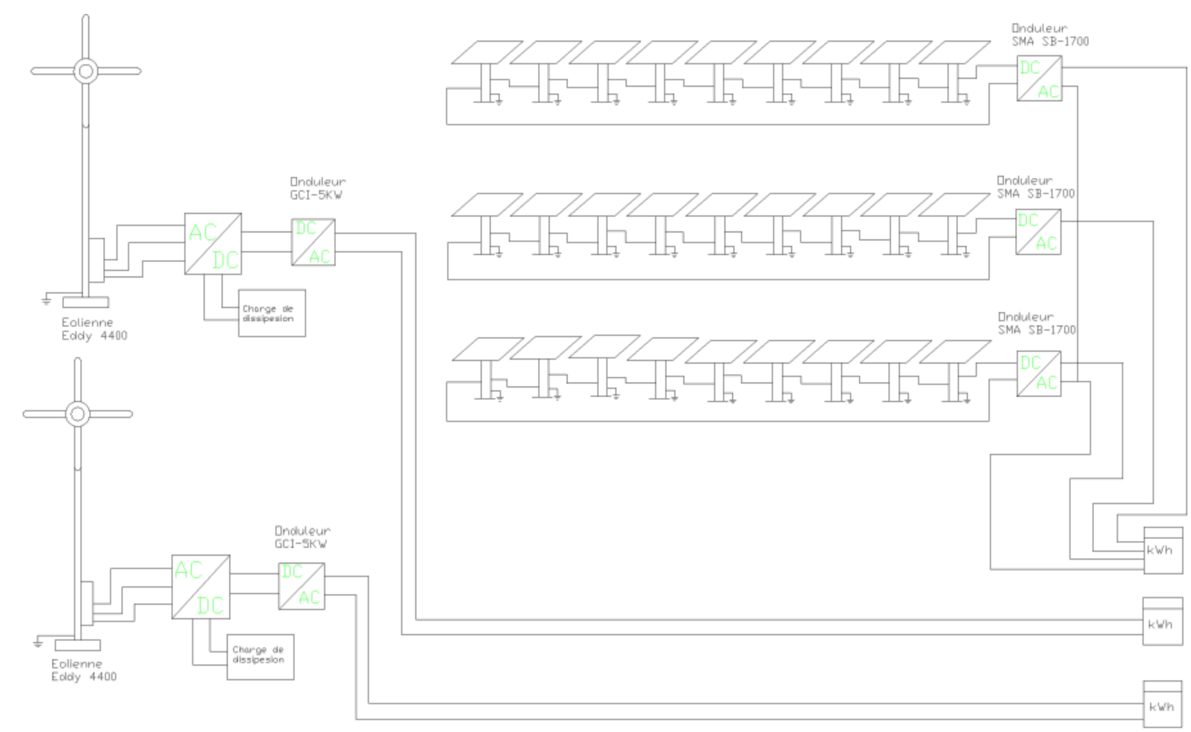

Fig. 3.21 The electrical diagram of the fotovoltaic- wind hybrid system

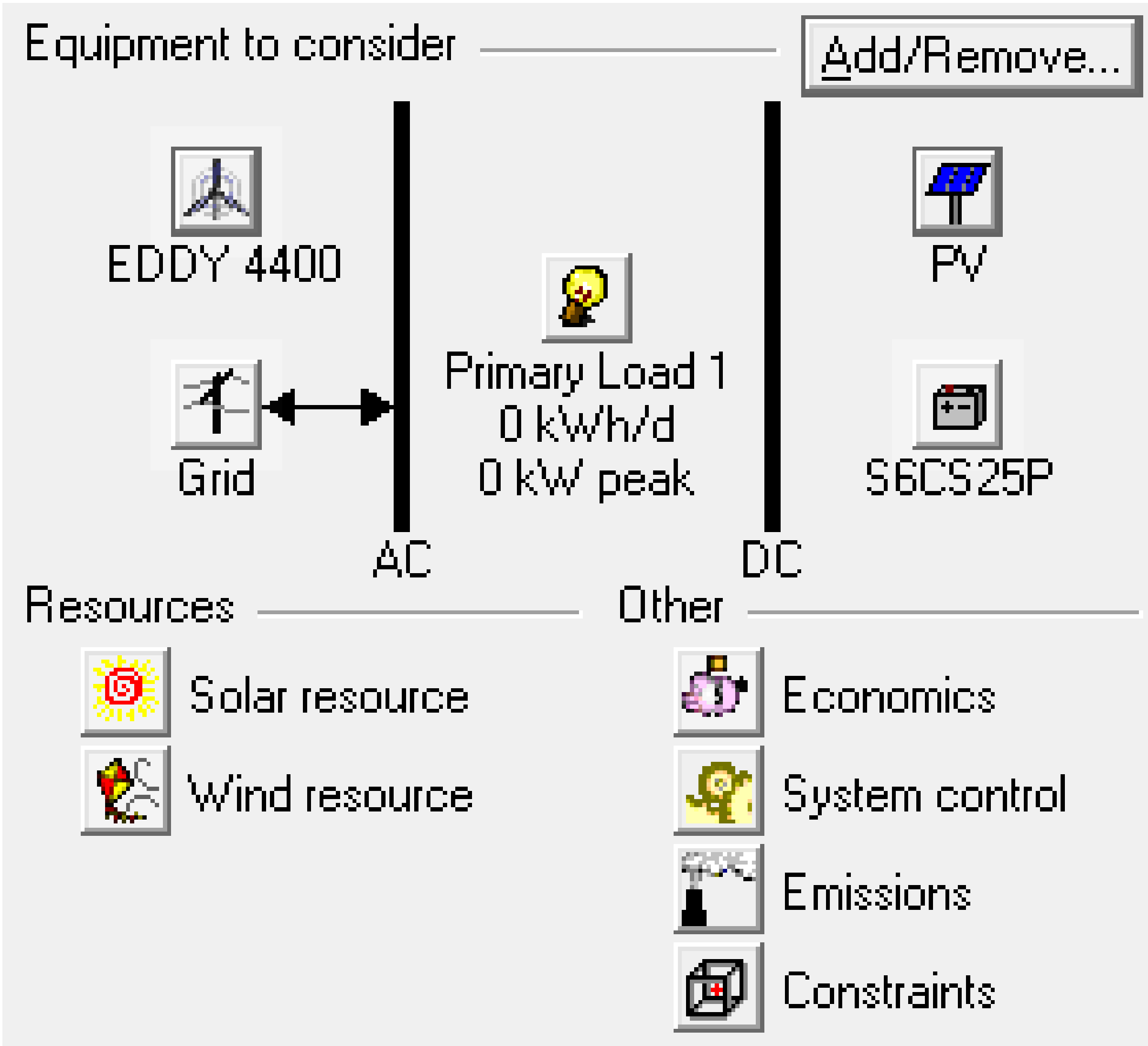

Fig. 3.22 Components of the system

3.3.8.2. Case Study

HOMER software was used to simulate the operation of a hybrid system of energy production. This system is on the roof of the building Bellot of the University of Le Havre, located in Docklands, between basins Paul batting and Eure. The wind - photovoltaic system consists of:

- 27 photovoltaic panels of type 48M200 with an installed capacity of 5.4 KW
- Two wind turbines Eddy 4400 with an installed power of 8 KW
- 8 inverters of type Sunny Boy 1700
- 24 batteries with a capacity of 1000 AH

Figure 3.23 shows the average output power of the PV system. On the horizontal axis the months of the year is represented and the vertical axis shows the average power.

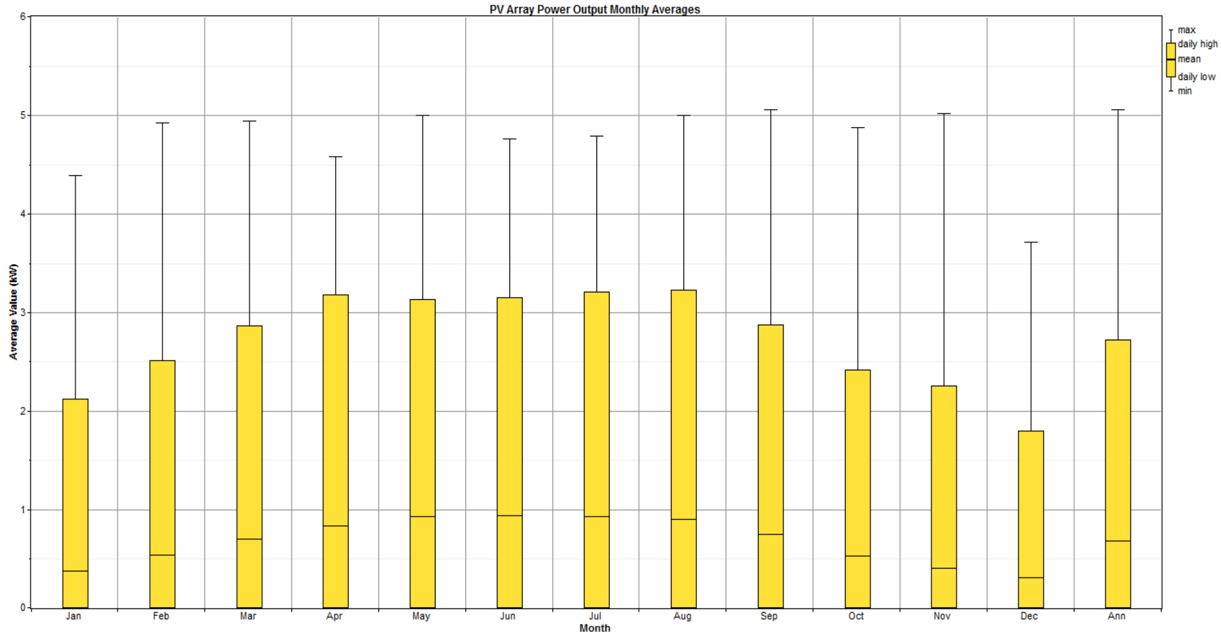

Fig. 3.23 Average output power of PV

Fig. 3.24 shows the average output power of the wind turbines. The horizontal axis shows the months of the year and the vertical axis shows the average power.

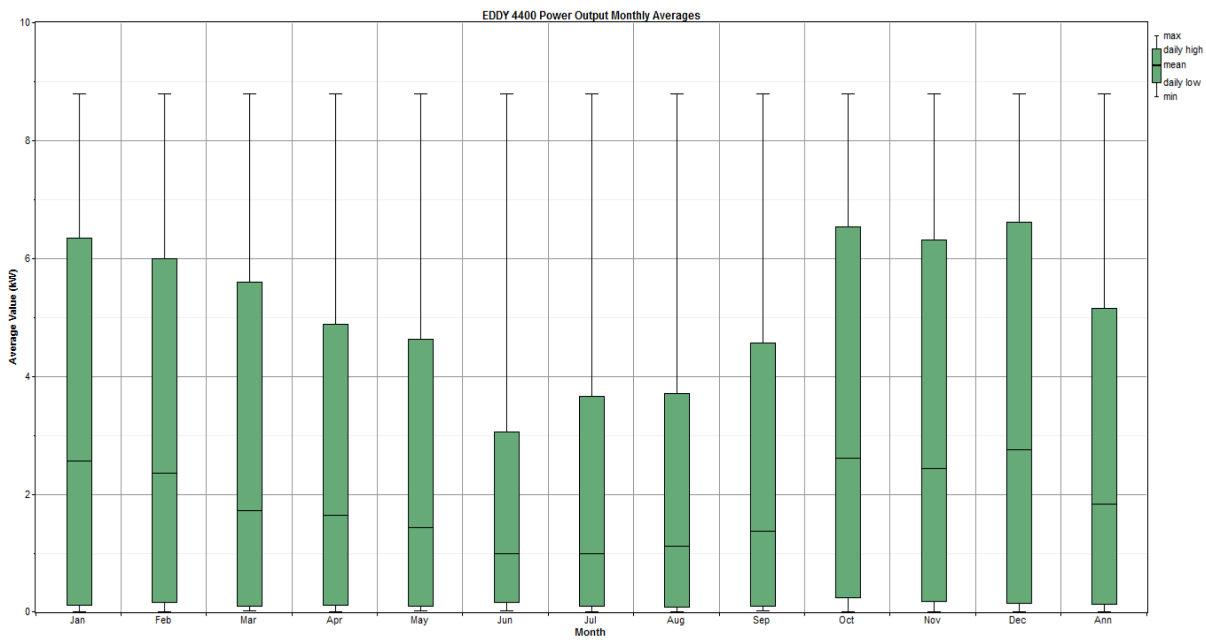

Fig. 3.24 Power at the output of the wind power stations

Simulation results will be used for comparison with data from the real system in order to find solutions to improve the energy efficiency by adding possibly solar panels and / or other renewable energy sources.

4. Conclusions

My activities of research and development, during my scientific and professional evolution, are consistent and dynamic. The results can be summarized as follows:

- Books published: 9;
- Publications and patents ISI Thomson Reuters: 7;
- Works published after 1999 BDI index: 20;
- Works published after 1999 in journals and conference volumes (unindexed): 30;
- Research contracts after 1999 that I was responsible for: 5;
- Research contracts after 1999 to which I was a member: 3;

I have conducted an activity of collaboration at the elaboration of the doctoral thesis of the student Mihaila Lucian in 2014. This activity demonstrates that I am ready to obtain the title of the ability to coordinate and guide my PhD students.

D. Directions of development of career that require the habilitation

The researchs carried out are rigorously directed having a central main objective. Consequently, I shall give a special importance to the future collaborations oriented in the field of renewable energy and the research results to be transferred to the firms that produce the equipment needed for the development of new renewable sources of electricity. The possible solutions envisaged by myself, for the problems identified as being insufficiently treated so far, will present a strong motivation to continue my research activity in the field of renewable energy.

On short-term (2 years) the career objectives can be grouped as follows:

- Preparation of at least 3 doctoral students per year;
- The expansion of the group of Renewable sources and attracting more students to attend their specialization within the Industrial Energetics Department at the Faculty of Engineering of "Vasile Alecsandri" University of Bacău;
- Preparation, as coordinator, of at least two calls for proposals for the Horizon 2020 program;
- Develop a high-level laboratory equipped for simulation and testing of electrical machines used in the construction of low-power wind power plants.

On long-term (5 years) career objectives envisaged:

- Contributions to modernize the teaching and research activities of the research group in the field of renewable energy;
- Extending the collaboration with universities from France and other European Union countries.
- Increasing the number of participations of our university as coordinator / partner in international research and teaching projects at national and international;
- Increasing the attractiveness of the research activity in our university by promoting a better work and by increasing the number of research projects;
- Extending the collaboration with industrial companies in the field of renewable energy.

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