University POLITEHNICA of Bucharest
Doctoral School of ELECTRICAL ENGINEERING

DOCTORAL THESIS
- SUMMARY-

RESEARCH ON ELECTRICAL EQUIPMENT AND MACHINERY FOR WIND ENERGY SYSTEMS

PhD student: eng. Alexandru-Marius VIIȘOREANU
PhD supervisor: Prof. PhD. Eng Constantin GHIȚĂ

Bucharest 2022

CONTENTS

INTRODUCTION

The current trend is to move away from polluting sources by 2050 and develop renewable energy sources. In specialized literature there are estimates of the installed power needed in different sources for this scenario to be viable [1].

Tab.1. Worldwide energy generated from different energy sources and future trends

Zero emissions scenario by 2050 [TWh]						
	2010	2019	2020	2030	2040	2050
Total energy generated	21520	26959	26762	37316	56553	71164
Renewable	4250	7114	7593	22817	47521	62333
- Solar – photovoltaic	32	681	833	6970	17031	23469
- Solar CSP*	2	13	13	204	880	1386
- Wind	342	1421	1596	8008	18787	24785
- Hidro	3446	4236	4347	5870	7445	8461
- Biofuel	360	672	709	1407	2676	3279
- Geotermal	68	91	94	330	625	821
Nuclear	2756	2790	2692	3777	4855	5497
Hydrogen and ammonia	-	-	-	875	1857	1713
Fossil fuels with CCUS**	-	1	1	459	1659	1332
Fossil fuels	14480	17019	16440	9358	632	259
- Coal	8671	9911	9467	2947	0	0
- Natural gas	4843	6356	6257	6222	626	253
- Oil	966	752	716	189	6	6

*CSP = with the concentration of direct solar radiation

**CCUS = carbon capture, use and storage

We can say that electricity produced by wind turbines has a future and we need to focus our attention on methods of optimising wind farms to achieve the best possible techno-economic parameters.

PURPOSE OF THE DOCTORAL THESIS

Achieving an appropriate cost-effectiveness parameter for wind farm projects requires rigorous documentation, design and optimisation. To this end, the paper presents both the economic, political and environmental motivations for implementing wind farm solutions, as well as recommendations related to wind measurements and current computer-based methods for optimizing the location and choosing the optimal turbine design for this proposed location.

ACKNOWLEDGEMENTS

In gratitude, I would like to thank all those who have supported me in this work. The present work was developed with the help of the Department of Material Machines and Electric Drives of the Faculty of Electrical Engineering of the Polytechnic University of Bucharest.

I am pleased to bring special thanks and deep gratitude to Professor Dr. Constantin GHIȚĂ, the scientific supervisor of the thesis, for his competent guidance and help throughout the realization of this doctoral thesis. At the same time, I would like to thank the Committee for the supervision of my doctoral activity, which included Prof. Dr. Eng. Tiberiu TUDORACHE, Prof.dr.eng. Ion - Daniel ILINA and Mr. conf.dr.eng. Aurel - Ionut CHIRILA, for their help during the preparation of the scientific reports related to the doctoral thesis and its final editing. Part of the results presented in the doctoral thesis were obtained with the support of the Human Capital Operational Programme, Priority Axis 6 - Education and Competences within the project "Development of entrepreneurship skills of doctoral students and postdoctoral students - key to career success" (A-Success) MySMIS Code: 125125

Last but not least, I would like to thank my family for their continuous support and encouragement to complete this PhD thesis.

CHAPTER 1
GENERAL INFORMATION ON WIND ENERGY

1.1. WIND ENERGY USE IN THE WORLD

At the end of 1984, 8469 wind turbines were already operating in the state of California, USA, with a total capacity of about 550 MW. They were built in areas with strong winds and grouped in so-called 'wind farms'. In Europe, the growth in installed wind power capacity took off between 1998 and 2003, with an increase of around 39% per year. [2].

The European Commission has now set an ambitious target of achieving climate neutrality by 2050, adopting a series of actions including the development of renewable energy sources. Directive 2009/28/EC on energy from renewable sources sets out a general policy on the promotion and production of energy from renewable sources [3], [4].

According to a 2021 report by the Global Wind Energy Council [5], 2020 was a record year for wind energy, historically the best year globally in terms of capacity growth, 53%

increase in installed capacity over the previous year and a newly installed capacity of 93 GW. This brings the total installed wind power globally to 743 GW up 14% on 2019.

Fig. 1.1 shows the installed onshore and offshore wind power capacity worldwide in 2020 for the main wind energy using countries.

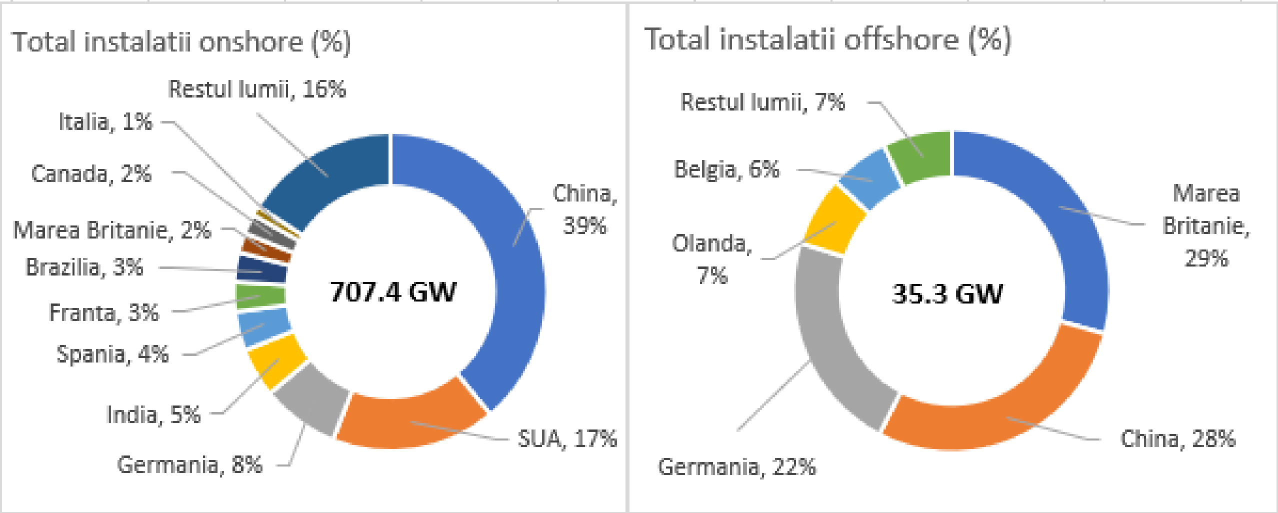

Fig. 1.1 Installed capacity in wind energy worldwide in 2020 [5]

Lower costs from larger wind turbines, innovations in installation and reduced investor risk will boost deployment as follows: by 2030, IRENA expects the average price of an installed kW of onshore wind to continue to fall by 25% from 2018 levels, while the price of offshore wind will fall by 55% from 2018 [6]. But accelerated growth in wind and renewables is needed that can limit global warming to "well below" 2°C, as set out in the Paris Agreement [7].

Over the next 10 years, international institutions are calling for a profound transformation of the system. Total annual global investment in clean energy and active system infrastructure must increase from $380 billion in 2020 to $1.6 trillion by 2030, according to the International Energy Agency (IEA) [8].

1.2. WIND ENERGY USE IN ROMANIA

According to the project "Romania's Energy Strategy 2020-2030, with a view to 2050" by the Ministry of Economy, Energy and Business Environment [9], in 2017, the main primary energy resources in Romania were 34291.4 thousand toe, of which 21305.5 thousand toe from domestic production and the rest from imports (toe - tonnes of oil equivalent).

In terms of electricity production, Romania has a diversified mix, largely based on domestic resources. Wind energy accounts for 15.4% of the total, i.e. an installed capacity of about 3 GW (Fig. 1.2).

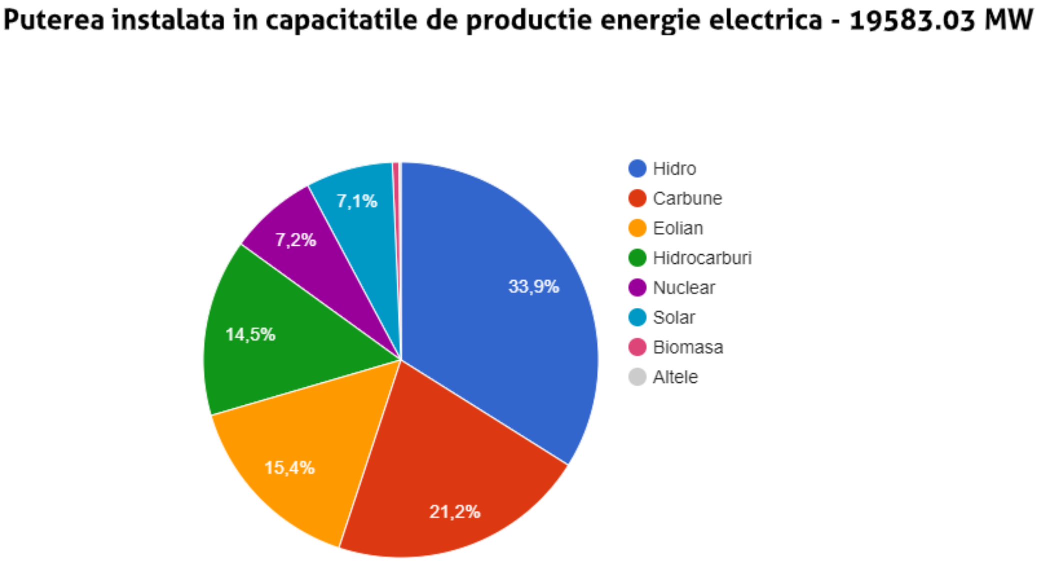

Fig.1.2. Installed power in Romania in percentages - situation as of August 2021 [10].

According to a special report by the European Court of Auditors in 2019, the cost of generating electricity from renewable sources has become comparable to that of fossil fuels, with the cost of generating electricity from wind power plants being several years in the range of the cost of generating electricity from fossil fuels. This represents the cost per MWh of construction and deployment over an estimated financial lifetime [11].

Tab.1.1. Comparative costs 2010 vs 2020 [12].

	Total installation cost (USD/kW)			Total equalised cost of electricity (USD/kWh)		
	2010	2020	Change (percentage)	2010	2020	Change (percentage)
Biomass	2619	2543	-3%	0.076	0.076	0%
Geothermal	2620	4468	71%	0.049	0.071	45%
Hydroenergy	1269	1870	47%	0.038	0.044	18%
Solar	4731	883	-81%	0.381	0.057	-85%
Wind onshore	1971	1355	-31%	0.089	0.039	-56%
Wind offshore	4706	3185	-32%	0.162	0.084	-48%

CHAPTER 2

DESCRIPTION OF A WIND POWER GENERATION SYSTEM - BLOCK DIAGRAMS AND COMPONENTS

Electricity can be generated in several ways. In almost every case, a fuel is used to turn a turbine, which drives a generator, which powers the electricity grid. The same is true for wind-generated electricity (wind power): wind is the 'fuel' that drives the turbine, which drives the generator, which produces the electricity. Unlike conventional fossil fuel power plants where this fuel is burned to drive the turbines, wind power plants use wind, a free and clean 'fuel', and the process is greenhouse gas-free.

2.1. CLASSIFICATION OF WIND TURBINES

The evolution of modern wind turbines is a story of engineering and scientific skills, coupled with a strong entrepreneurial spirit. Over the last 20 to 25 years, turbines have grown in size and power by up to 100 times, from 25 kW power and blade diameters of a few metres, to (2 to 3) MW power and blade diameters of 60 to 100 metres. The largest onshore turbine built to date is Enercon's E - 126, a 7.58 MW turbine with a tower height of 135 m and a rotor diameter of 127 m [13]. For offshore applications the powers are even higher, reaching (14 - 15) MW and diameters of up to 222 m - Vestas V236 or Siemens Gamesa SG 14 - 222 DD models.

Wind turbines can be classified according to several criteria.

1. Depending on the electrical power generated, turbines can be low power, below 100 kW, or high power, above 100 kW.

2. By location: onshore or offshore.

3. Depending on the direction of axis orientation: horizontal or vertical axis.

4. By the number of blades: there are single-blade, two-blade, three-blade or even multiple-blade turbines. The most efficient and most widely used are those with three blades.

In addition to the already classic wind turbine models, other models have been built over the years that have not been very successful. New designs and technologies are still being developed to capture wind energy and convert it into electricity. One such model is the 'Vortex Bladeless' which is a bladeless wind turbine that operates on vibrations induced by resonant air currents. It harnesses wind energy from a vorticity phenomenon called "Vortex Shedding", also known as "Kármán Vortices". Basically, the bladeless technology consists of a cylinder fixed vertically with an elastic rod. The cylinder oscillates on a wind range, which then generates electricity through an alternator system [14]. Fig.2.1 shows this model.

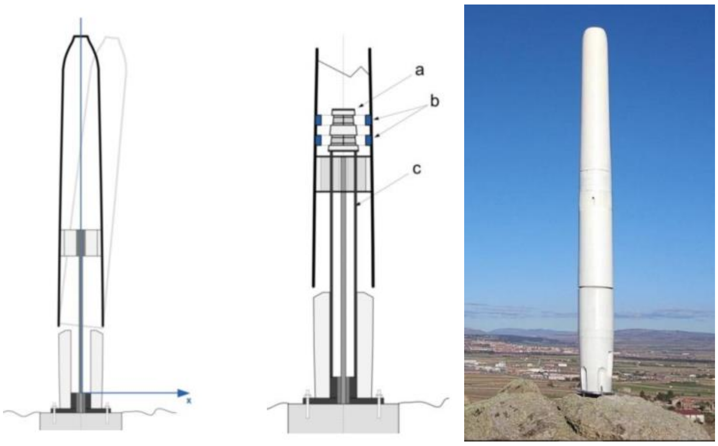

Fig.2.1. ‘Vortex Bladeless' turbine model and main components: a. Stator fixed part; b. Alternator moving part; c. Stator support.

One possible application for this turbine design is to install them on motorways and expressways, replacing the traffic dividers. In this way, air currents generated by speeding cars can be harnessed and converted into electricity by these turbines.

2.2. HORIZONTAL AXIS TURBINE COMPONENTS

Wind turbine technology has developed rapidly over the last 20 years, but the principle of operation has remained largely unchanged. The mechanical systems that make up the turbines have also evolved, with two main systems now in use (Fig. 2.2):

- a system in which the rotational motion of the turbine is transmitted to the generator via a gearbox (speed multiplier);

- gearless system, with direct drive on the generator shaft.

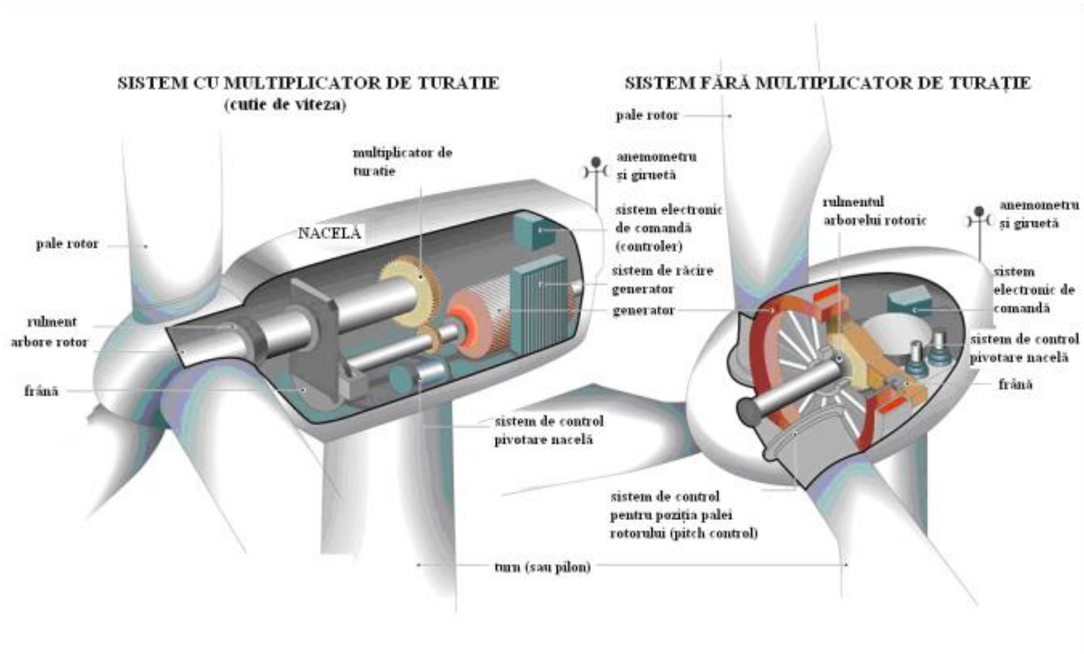

Fig.2.2. Wind turbine drive system with or without gearbox (speed multiplier) [15]

The horizontal axis wind turbine can be divided into 4 main subassemblies: foundation, tower or pylon, nacelle and rotor. The nacelle, considered as the machine room for the wind turbine, is composed of several pieces of equipment, such as: the electric generator, the speed multiplier (if applicable), the main shaft (to which the rotor is also connected), the braking device, the cooling and pivoting systems, the electronic command and control equipment. The nacelle is constructed in such a way that it can rotate on the steel tower to allow the rotor to be oriented perpendicular to the wind direction, a movement achieved by an automatic control system connected directly to the impeller on the nacelle.

The percentage costs of a 1.5 MW wind power system built by Enercon in Germany are as follows [16]:

- Electric generator 16,31 % ;
- Speed multiplier 10,29 % 16,16 ;
- Construction materials (foundation, tower, propeller, other construction elements) 54,61 %;
- Power electronics 4,15 ;
- Transport of components and physical realisation of the system construction 13,45 % ;
- Maintenance 1,19 % .

2.3. ELECTRIC GENERATORS USED IN WIND POWER PLANTS

The electric generator is the equipment used to convert mechanical energy (shaft rotation) into electrical energy. There are currently several models of wind turbines using different electromechanical conversion systems. Broadly speaking, two types of electrical generators are used: synchronous and asynchronous.

Synchronous generators are the main sources of electricity generation used in conventional power plants and wind farms. They generally have an excitation (magnetic system) made up of permanent magnets or rotor coils fed in direct current through an assembly of brushes and slip rings.

Asynchronous generators are increasingly found in wind turbines, as they have several advantages over synchronous ones, such as: lower production cost, better reliability, simple maintenance and the ability to vary speeds within set limits. One of the major disadvantages of asynchronous generators is that they require reactive power, which implies additional costs with capacitor banks or penalties for the consumption of reactive power from the grid to which it is connected [17].

CHAPTER 3

RELIABILITY, PROTECTION AND MAINTENANCE OF WIND POWER GENERATION SYSTEMS

3.1. RELIABILITY

Reliability is one of the most important attributes of a piece of equipment or system, which must be taken into account in its design and construction. In wind power generation systems, one of the main drawbacks that prevented the implementation of these solutions in the past was the high production price and low reliability.

The qualitative approach to reliability can be described by a number of indicators, such as the ability of the equipment not to fail, the lifetime of the equipment and the ability to be restored to service through repair. Qualitative reliability analysis helps to identify weaknesses and potential faults that may occur. Closely related to the term reliability are other terms such as durability, deterioration, failure and maintenance.

3.2. FAILURE OF WIND SYSTEMS

The interruption or alteration of the ability of a system or element to perform its intended function or to work within acceptable parameters is called a failure. In reliability theory, failure is a fundamental event and represents the deviation of system characteristics from acceptable operating conditions.

Failure modes are one of the essential pieces of information needed to assess and improve the reliability of a system. The failure mode is the effect or phenomenon due to which the failure occurred (e.g. a short circuit). In an wind turbine we have several components in which failures can occur. The main components are:

- Structural components: tower, blades and nacelle;
- Mechanical components: gears, bearings, shafts, couplings, etc.;
- Electrical components: generator, transformer, drive motors, automation, etc.

According to literature data, the average failure rates of the main subsystems of a (2-3) MW wind turbine are shown in Fig. 3.1, where it can be seen that only three of the subsystems (electrical, converters and control) cause more than half (55%) of the total failures of a wind turbine [19], [20], [21].

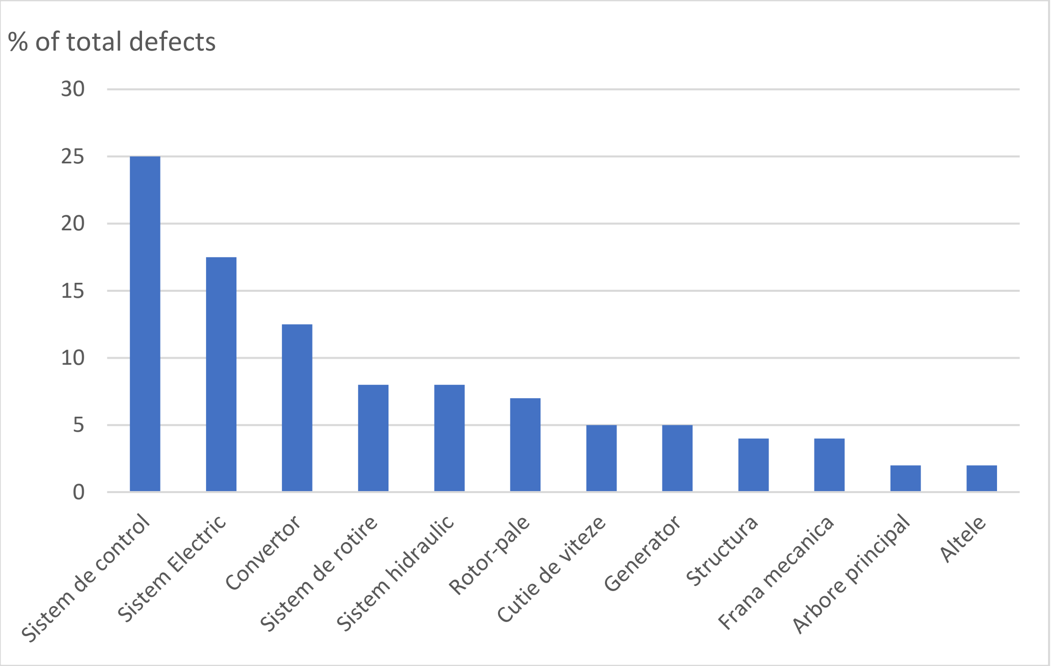

Fig. 3.1. Fault distribution per subsystem of a wind turbine

3.2.1. Failure modes of the main components of a wind system

a) Blade defects

These generally occur due to changes in the roughness of the surface of the blades. This phenomenon can occur due to manufacturing defects, the influence of pollution, ice deposition on the blade surface or impact with flying animals. Roughness defects cause an imbalance of the rotating masses resulting in additional centrifugal forces being transmitted to the tower and nacelle.

b) Faults in the drive system

Drive system failures in general are typical failures that most commonly occur in the form of shaft cracks or mass imbalances. Some of the causes of these defects are: manufacturing defects, transport or assembly defects, torque overloads, faulty design, bending due to asymmetrical rotor forces.

c) Rolling bearing defects

Rolling bearing failures can be caused by overload, overheating, friction damage or corrosion. These faults can be monitored and prevented by vibration sensors. The information received from these sensors can be analysed in terms of vibration time distribution (static algorithms), vibration time domain analysis algorithms or vibration frequency analysis algorithms [18].

d) Gearbox defects (speed multiplier)

As with rollers, vibration sensors can also be used on the gearbox to detect mechanical faults. Temperature monitoring sensors, grease oil monitoring sensors and accelerometers can also be used to monitor rotational speeds.

e) Generator faults

The characteristic parameters of the environment (temperature, humidity, altitude) that determine stator insulation wear as well as thermal, electrical and mechanical stresses are closely related to the failure of rotating machinery. The main cause of insulation and stator winding failure is overheating. Most manufacturers have taken steps to improve the reliability of rotating machines by installing temperature sensors at various critical points, as well as sensors that measure voltage, current and magnetic flux in the end regions of the coils.

The most common ways for generators to fail can be in the factory through assembly accidents, overheating of the winding, poor insulation, etc. or in exposure through excessive heating, wear or foreign bodies entering the machine.

3.2.2. Protection of wind systems

One of the most important components of a wind turbine is the systems for monitoring the condition and operating parameters of the component equipment. These systems include electrical or optical sensors. Without sensors, wind turbines would undoubtedly be less safe, more costly to operate, unable to accurately predict and resolve impending failures, or could have a lifespan shorter than the twenty-five years they are expected to operate.

Wind turbines are complex and have a large number of components, many of which can be monitored by sensors, such as position, temperature, pressure, level, accelerometers or sensors of oiling fluid properties.

Due to the unique construction design of wind turbines, these tall structures are prone to damage due to climatic conditions. Wind turbines can rise to heights of over 200 metres and are generally located on high ground in open country, making them vulnerable to lightning strikes. The most exposed components are the nacelle and blades, which are made of composite materials capable of withstanding a direct lightning strike, but the surge can propagate into the electrical equipment inside the nacelle and through the transformer into the power grid.

The lightning and atmospheric surge protection system for the wind turbine consists of two main systems: an external lightning protection system (e.g. surge arrester) and surge protection equipment to protect electrical and electronic equipment. The most popular arrester designs are metal oxide arresters (MOA) without sparking gaps and silicon carbide arresters with priming sparking gaps and variable shunt resistors (VRA) [22], [23].

One of the most important and expensive pieces of equipment in a wind turbine assembly is the transformer. High-voltage power lines for the remote transmission of electricity produced in wind power plants are subject to very high stresses in the event of lightning strikes in their vicinity, due to the overvoltages generated by these lightning strikes. These surges are very high and can reach values (8 - 12) times higher than the nominal values of the transformer winding voltages [24].

There is research in the literature on various methods of reducing the effect of overvoltage on the transformer, either by modifying certain construction parameters or by adding additional protective elements such as guard rings or protective screens [25], [26], [27].

3.3. MENTENANȚA SISTEMELOR EOLIENE

According to the European standard EN 13306:2001 - Maintenance Terminology [28], maintenance is defined as the totality of all management, administrative and technical actions intended to maintain and restore an equipment or system to a condition in which it can perform the function for which it was built and installed, throughout its lifetime as defined by the manufacturer.

Expenditures that may occur in the life cycle of an equipment are: design, manufacturing, transport, installation and commissioning, operation, maintenance and/or repair.

In operation, the reliability and cost-effectiveness of wind energy systems is determined by the type of maintenance strategy applied. These can be divided into three categories:

- corrective maintenance;
- preventive maintenance;
- predictive maintenance;

Corrective maintenance can be described as the action of intervening on a piece of equipment or assembly after a failure has occurred (e.g. repairing or replacing faulty equipment). This maintenance strategy involves complete repair and replacement of problems that have arisen at an early stage.

In the past, production costs were the main focus. Nowadays, methods are being sought to reduce maintenance costs, but by going with the concept of only intervening on the equipment or assembly when it has failed, we cannot control the occurrence of faults or improve maintenance costs much.

The concept of **preventive maintenance** is based on preventive action carried out at well-defined intervals, recommended by the manufacturer of the equipment or resulting from operating experience, with the aim of preventing equipment failure or reducing the likelihood of the development of faults over time. This concept can be interpreted as a maintenance programme aimed at eliminating or preventing corrective or reactive actions.

However, it is not the best option in terms of actual cost, as some equipment will not remain in service until the end of its possible life. To improve cost, one can move from time-based maintenance to predictive, measurement-based maintenance.

At the heart of the **predictive maintenance** concept is the use of dedicated measuring devices and sensors to monitor the condition of equipment in real time. This type of maintenance is also called condition-based maintenance. Continuous monitoring of various equipment, diagnosing and interpreting these measurements aims to detect a condition, which over time can become a fault. By identifying these conditions and taking concrete remedial action, the likelihood of a fault occurring is drastically reduced.

CHAPTER 4
STUDY OF THE WIND POTENTIAL OF A LOCATION AND METHODOLOGY FOR ACQUIRING AND PROCESSING WIND DATA

Wind is one of the meteorological phenomena with complex problems in terms of mapping spatial distribution both because it is a vector quantity characterized by two main magnitudes, namely speed and direction, and because local conditions have a strong influence on it (e.g. terrain configuration, roughness, obstacles, etc.).

4.1. SITE SELECTION CONSIDERATIONS

Several criteria should be taken into account when choosing the location of a wind turbine. In addition to the existence of a wind energy potential, a number of other important criteria should be studied, such as:

- Reduction of environmental impact;
- The existence of electricity transmission networks for the electricity generated by the wind farm;
- Existence of a potential skilled workforce in the area for the construction and operation of the wind farm;
- Existence of appropriate road infrastructure.

There are also a number of physical pollutants that need to be taken into account in wind farm projects: noise, visual impact, shading and electromagnetic fields.

4.2. STUDY OF THE WIND POTENTIAL OF THE CHOSEN SITE

This PhD thesis will study the location of a wind farm in Romania, Galati county, Smârdan commune, near Mihail Kogălniceanu village. The turbines will be located on a series of agricultural lands near the village and the county road 251. The geographical coordinates of the location are: 45º 30' 24" north latitude and 27º 53' 42" east longitude.

4.2.1. Importance of wind resource

For any wind farm developer, the general wind maps available in the literature or in various studies are not useful enough for site selection and economic justification of financing. This requires local measurements of wind potential (wind speed and direction) in order to calculate and simulate the most accurate data at the desired location.

The electricity production of a wind farm can be estimated by making a local wind atlas using data obtained from meteorological stations near the location, but in general these data are cumulated with a new set obtained by installing a measuring tower in the desired area.

4.2.2. Methods and equipment for measuring wind data

Accurate measurements of the wind potential of a location are of particular importance in order to best estimate the electricity production of a wind farm, as this parameter is a defining parameter between a feasible and an infeasible project.

On measuring towers, several anemometers are generally mounted at different heights, e.g. 40, 50 and 60 metres and a minimum of two weathervanes. In addition to these, temperature sensors are installed in areas prone to cold weather conditions. All measured data is recorded and stored in a data concentrator. Some systems are even equipped with an internet connection modem for real-time data transmission to a server or the cloud.

In addition to anemometer and weathervanes measuring towers, there are other solutions for ground-based monitoring without the need for a tall tower. Two examples of such devices are:

- SODAR ("SOnic Detection And Ranging"): this device is based on the emission and reception of sound waves, on the basis of which it measures wind speed by Doppler effect;

- LIDAR ("Light Detection And Ranging"): this device works similarly to Sodar, on the same principle, except that it emits and receives light from a laser.

These types of devices are relatively new to the field, but have already shown their value in terms of measurement accuracy and ease of installation. Their biggest advantage is that they do not require a measuring tower, they measure up to 200 metres high, but at the same time they are more expensive solutions.

4.3. WIND DATA PROCESSING

Over time, the multi-year repetitive nature of the wind has been observed, making measurements over a 12-month period relevant for multi-year estimation of the wind potential at a location. In this thesis, measurements recorded over a 12-month period were considered with an anemometer tower mounted at 40, 50 and 60 meters height. For the processing of the measured data the use of the Windographer software was considered.

Once loaded into the analysis program, the measurements are processed automatically and different standardized and/or customizable graphs are generated, which are relevant in the analysis of wind potential. One of these is the so-called "wind rose" diagram, which represents the frequency distribution of wind occurrence from different directions. In Fig. 4.1 shows this diagram.

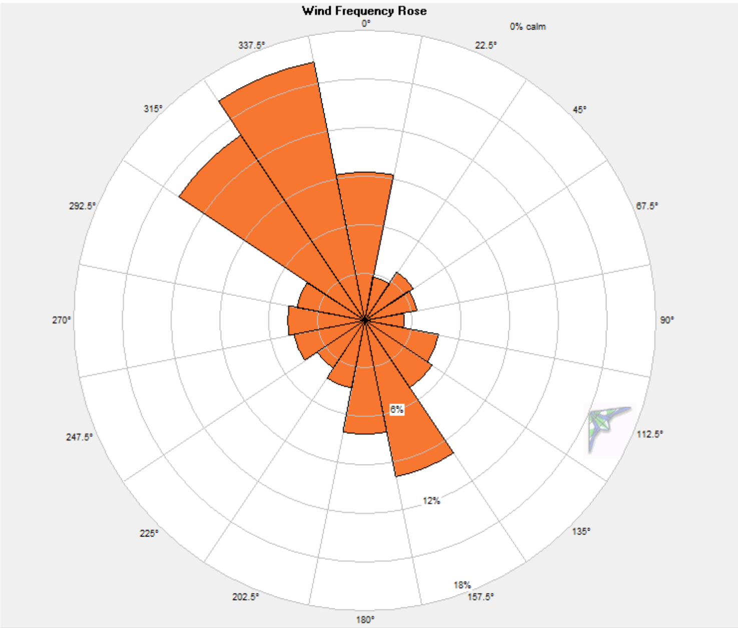

Fig. 4.1. Wind rose - the frequency of occurrence of wind from a given direction

In addition to the important data presented in the wind rose, another very important parameter for calculating the energy production of a wind farm should be analysed, namely the frequency of occurrence of wind speeds. This describes the length of time, as a percentage of the total period during which measurements were made, that the wind speed fell within a fixed range of values.

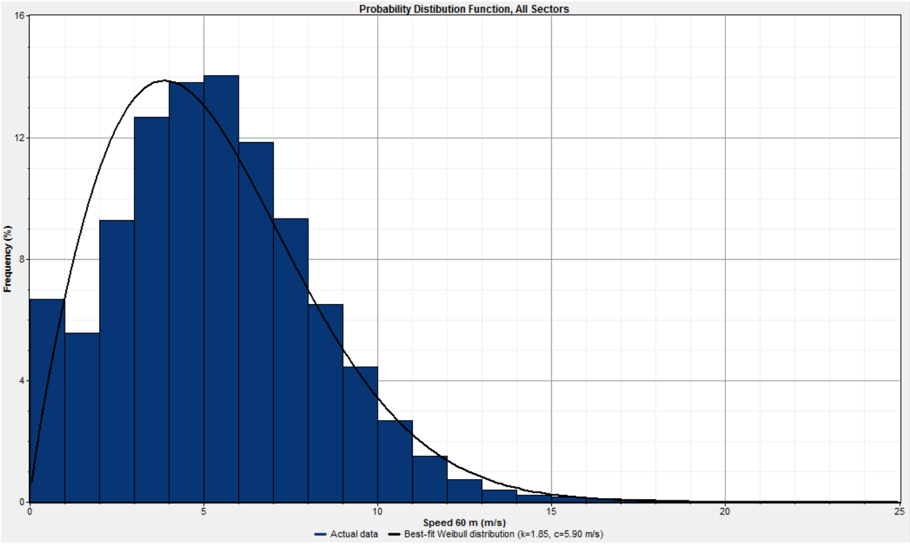

Fig. 4.2. Frequency of occurrence of wind speeds - Weibull distribution

As an example, we can see from the graph shown in Fig.4.2 that in 14% of a year (measurement period) the wind speed was in the range (5 - 6) m/s.

In Tab. 4.1. the most important values measured or calculated from the measurement data are summarized.

Tab.4.1. Summary of important values

Variable	Speed at 60m	Speed at 50m	Speed at 40m
Average wind speed (m/s)	5.27	4.876	4.795
Minimum wind speed (m/s)	0.4	0.3	0.4
Maximum wind speed (m/s)	23	22.4	22.1
k - Weibull shape parameter	1.852	1.748	1.859
Average power density (W/m^2)	174	144	133
Average annual recoverable energy (kWh/m^2 /year)	1,524	1,263	1,166
Number of data recorded	52,560	52,560	52,560
Number of lost data	0	0	0
Number of hours of maximum wind values	23	23	22

At a site with the turbines 100 metres above the ground, the average wind speed would be about 5.8 m/s. In general, wind turbines can only be considered if the average wind speed is above 5 m/s with a high frequency of occurrence of wind speeds above 4 m/s. We thus consider that the location given in this paper, according to the wind measurements, is feasible for further study of the choice of turbines and their actual location in the field, thus we will be able to calculate the installed and generated power of the wind farm. This step is also important in determining the techno-economic conditions for installing a wind farm in the studied location. The study of the location and choice of turbines is carried out using the WAsP design software, presented in the next chapter.

Remarks: Some of the results obtained in this chapter are based on a documentation carried out based on data obtained by consulting accessible websites such as [29], [30], [31], [32] as well as accessing the bibliographical references indicated at the end. Among these, the websites of the National Meteorological Administration and Meteoblue from which some of the data used throughout Chapter 4 were extracted were also of great help.

CHAPTER 5
WIND FARM OPTIMISATION - MODELLING AND SELECTION OF THE IDEAL SITE AND TURBINE MODEL USING DEDICATED SOFTWARE SOLUTIONS

When designing and optimising a wind farm, either using software solutions or classical methods, a number of losses must be taken into account which can be estimated or calculated by various methods. These losses can be significant in value and can make the difference between a feasible or infeasible project. When the wind passes by a turbine, the energy and speed following it is lower. *Proximity losses* refer to the influence of turbines on each other due to this effect.

5.1. WASP SOFTWARE OVERVIEW

WAsP is a specialised software for wind resource assessment, site assessment and calculation of the total energy yield of wind farms. This software can be used for any location, regardless of the type of terrain. WAsP is an abbreviation for "Wind Atlas Analysis and Application Program" and is developed and distributed by the Wind Energy Department of the Technical University of Denmark (formerly Risø National Laboratory). The main applications in which it can be used are [33].

- Calculating the efficiency of a turbine or wind farm;
- Placing the wind farm in the field;
- Wind potential calculation for site assessment and wind resource mapping.

5.1.1. Topographic map and wind forecast

Specialised calculation programs for wind farms are relatively simple to use and require a range of input data: wind measurements, topographical map of the terrain, characteristics of the wind turbine used and its location in the terrain. [36]. After establishing the location and taking wind measurements, the next step is to produce the vector terrain map in a format supported by the software used. Map making can be done in several ways, from several sources.

The Shuttle Radar Topography Mission (SRTM) was an international mission coordinated by NASA in 2000 to map the entire Earth by radar and create the most complete topographic database. All these records are freely available online from various sources in a format that must be further processed in software such as GlobalMapper[34] to obtain the digital topographic map in the format supported by design software. The process is fairly quick and involves minimal cost, as SRTM data is free. However, the topographic maps produced with SRTM data are not very accurate and may affect subsequent wind farm simulations. [35]

At this stage, it was considered that the map made from SRTM data was sufficiently accurate. The resulting map was loaded into WAsP, where the measurement tower was placed in the spatial location where it was installed and in the field (Fig. 5.1). The coordinates shown in Fig. 5.3 (X-Y) are in Stereo70.

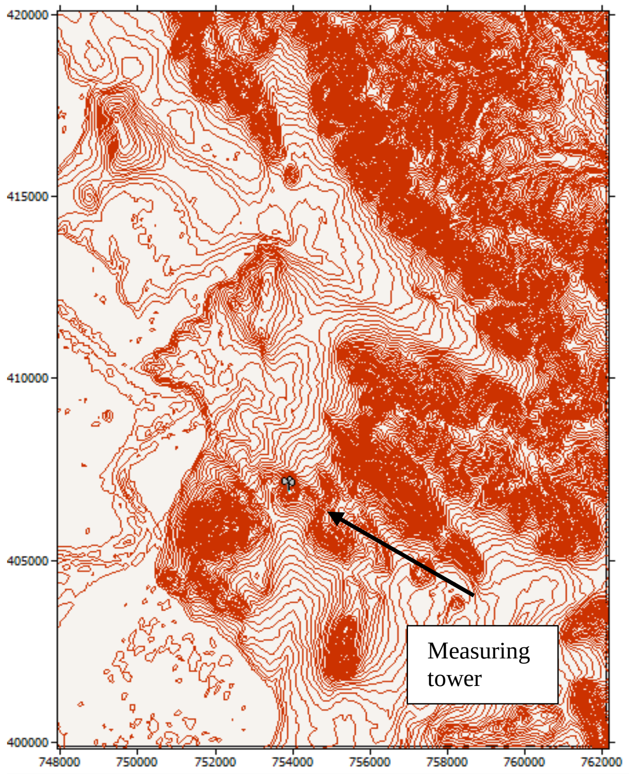

Fig. 5.1. Topographic map and measuring tower - WAsP work window

The next step is to forecast the wind regime at the location studied, which involves analysing all the records.

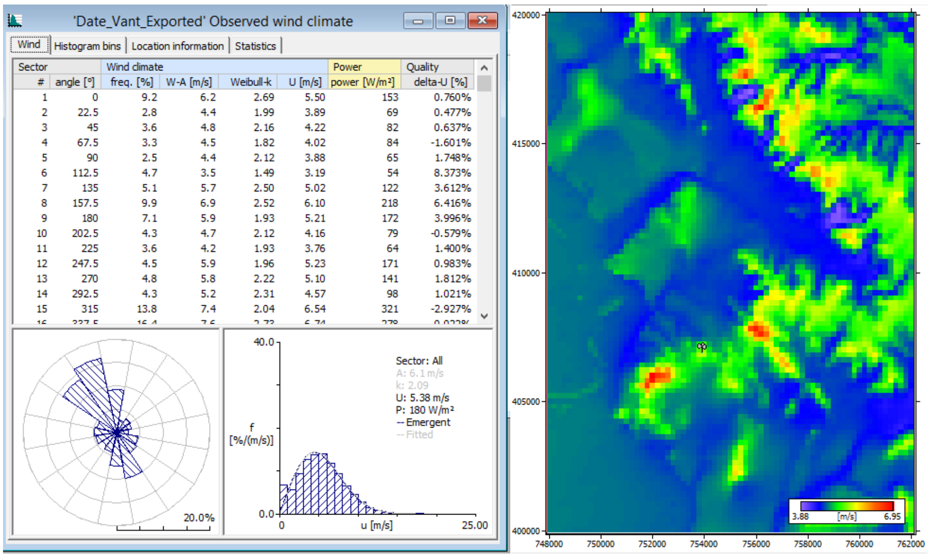

Fig. 5.2. Wind data loaded and processed in the program - wind regime forecast (right)

The wind regime forecast is performed automatically by the program following the input of the topographic map and the wind data measured by the tower located according to Fig. 5.1 and Fig. 5.2. When using this function, we can select the number of points where the calculation will be performed. The higher the number of points, the better the wind map shown in Fig. 5.2 (right) will be defined. Depending on the processing performance of the computer used and the number of points chosen, the forecast can take several days to produce.

5.2. OPTIMISING THE LOCATION OF TURBINES IN THE FIELD

After uploading all the data mentioned above, there are two more steps: choosing the turbine model we want and placing them in the field. With a number of models already loaded in WAsP available we can choose from these, or if another model is needed, we can create it by entering the operating characteristics. In the example in this paper a turbine from the database, a Vestas V90 model of 1.8 MW power, with a rotor shaft height of 100 metres, was used. After choosing the wind turbine model, the last step is to place them in the field, according to the restrictions imposed by the area (villages, roads, power lines, irrigation canals, etc.).

Other aspects must also be taken into account when placing the wind farm, which will determine its output. For example, in order to locate turbines in areas with favourable wind conditions, a local wind map can be generated and displayed in the software using the information entered so far (Fig. 5.2). Thus, we can choose to locate the turbines, if we have no other restrictions, in the areas with the best wind speeds. Another aspect to be taken into account is that the turbines should be located as far as possible in the form of a grid with turbine spacings of 7-9 rotor diameters (D = 90 metres) in the prevailing wind direction and 5-7 diameters in the direction perpendicular to it [37]. This recommendation will help to improve turbine performance by reducing proximity losses.

5.2.1. Simulation of the wind farm data in a first variant of the layout

In accordance with the restrictions and recommendations mentioned, a first layout variant of 10 turbines was developed.

Once the turbines were placed on the map, the program was run to calculate a whole series of characteristic parameters for the evaluation of the wind farm under study. (Tab.5.1 - initial location)

From these values it can be deduced that the total proximity losses on the wind farm are 6.84%. This total value as well as the individual turbine values are above the recommended value of maximum 5% proximity loss (except turbines 6, 8, 9 and 10 which have losses less than 5%).

In order to manually optimise this site, the following steps will be followed:

1. Relocate the turbines with proximity losses greater than 5% and the turbines with the lowest generated power, taking into account the instalation recommendations and the data obtained in the first simulation;
2. Recalculate and if the turbines' proximity losses have decreased below 5% and the generated power has increased, then we can consider that site as optimal;
3. If the proximity losses of the turbines have not decreased below 5% or the generated powers are low, then we try to reposition one or more turbines, depending on the case, until we reach the situation shown in point 2.

There are also software applications dedicated to the automatic arrangement of turbines in the field (e.g. WindPro), but these are expensive and the results obtained are not very accurate, which makes it necessary for the user to intervene at the end for small adjustments.

5.2.2. Simulation of wind farm data after site optimisation

Analysing the simulated data for the first layout and following the recommendations above, a second layout was performed. After placing the turbines on the map, the program was run to recalculate the characteristic parameters for the wind farm assessment. This final layout may involve repositioning the turbines and simulating the parameters several times until the values considered optimal are reached. In this case, turbine 6 remained in place, turbines 1, 2, 4, 5, 7 and 8 were only slightly adjusted and turbines 3, 9 and 10 were repositioned on the map. Tab.5.1 shows the most important values compared for the two locations.

Tab. 5.1. Differences in values for the two locations

Nr. turbina	Initial location			Optimized location			Percentage difference		
	Brut AEP	**Net AEP**	**Proximity losses**	**Brut AEP**	**Net AEP**	**Proximity losses**	**Brut AEP**	**Net AEP**	**Proximity losses ***
	[GWh]	[GWh]	[%]	[GWh]	[GWh]	[%]	[%]	[%]	[%]
Turbine 001	6.559	6.137	6.43	6.368	6.137	3.62	-3.00	0.00	-77.62
Turbine 002	5.898	5.229	11.34	6.440	6.251	2.94	8.42	16.35	-285.71
Turbine 003	4.16	3.849	7.47	5.932	5.824	1.81	29.87	33.91	-312.71
Turbine 004	6.098	5.621	7.81	6.187	6.125	1	1.44	8.23	-681.00
Turbine 005	5.667	4.829	14.8	5.920	5.802	1.99	4.27	16.77	-643.72
Turbine 006	6.021	5.95	1.18	6.021	5.956	1.08	0.00	0.10	-9.26
Turbine 007	3.179	2.957	6.98	5.953	5.744	3.5	46.60	48.52	-99.43
Turbine 008	6.261	6.05	3.36	6.244	6.067	2.83	-0.27	0.28	-18.73
Turbine 009	1.81	1.731	4.36	5.624	5.507	2.08	67.82	68.57	-109.62
Turbine 010	5.433	5.236	3.62	5.784	5.654	2.24	6.07	7.39	-61.61
Total wind farm	**51.08**	**47.59**	**6.84**	**60.47**	**59.1**	**2.32**	**15.53**	**19.43**	**-194.83**

***)** For example, for turbine 001, the percentage difference in proximity losses was calculated as follows: $\frac{3,62-6,43}{3,62}\cdot 100=-77,62\%$

It can be seen that the net annual energy in some cases has increased by up to 68.57% (turbine 9) and the proximity losses have decreased by about 7 times. (turbines 4 and 5). Thus, over the whole wind farm studied, proximity losses decreased by 194.83% and the annual net energy generated increased by 19.43% to a value of 59.1 GWh/year.

5.3. CHOICE OF TURBINE MODEL FOR THE GIVEN SITE

The purpose of this case study is to demonstrate how important the proper choice of turbine model is, so that simply replacing a wind turbine with another turbine model can produce major changes in the efficiency of the wind farm, under certain conditions making the difference between a feasible and an infeasible project.

The previously calculated optimal location has been taken into account and simulations for three turbine models have been re-run:

- Vestas V90 1.8 MW;
- Vestas V90 2 MW;
- Vestas V90 3 MW.

5.3.1. Configuration I - Vestas V90 turbine 1,8 MW

Tab. 5.1 shows the simulation results for this turbine model. (optimized location)

5.3.2. Configuration II - Vestas V90 2 MW turbine

Tab.5.2 shows the values resulting from the optimised simulation for this 2 MW turbine model.

Tab. 5.2. List of the resulting parameters for the optimal installation variant - Vestas V90 2 MW

Turbine no.	Location Stereo70	Location height	Turbine height	Brut AEP	Proximity losses	Average wind speed	Power density
	[m]	[m]	[m]	[GWh]	[%]	[m/s]	[W/m²]
Turbine 001	(751946.7,405853.3)	298	100	6.658	3.58	8	410
Turbine 002	(752085.8,405986.1)	309	100	6.740	2.92	8	419
Turbine 003	(751818.7,405657.3)	266	100	6.185	1.78	7.7	369
Turbine 004	(755927.4,407806.6)	376	100	6.449	1	7.8	373
Turbine 005	(756265.1,407674.2)	383	100	6.154	2.05	7.6	344
Turbine 006	(755594.8,417654.4)	410	100	6.226	1.11	7.7	354
Turbine 007	(756249.8,416501.3)	408	100	6.206	3.55	7.7	367
Turbine 008	(756110.1,416379.8)	406	100	6.524	2.86	7.9	396
Turbine 009	(756470.2,416888.7)	455	100	5.834	2.13	7.5	324
Turbine 010	(752452.4,406024.1)	267	100	6.021	2.28	7.5	345

Parameter	Minimum	Average	Maximum	Total wind farm
Net AEP [GWh]	5.71	6.157	6.543	61.565
Brut AEP [GWh]	5.834	6.304	6.74	63.039

It can be seen that by changing the turbine model from 1.8MW to 2MW, the annual net energy generated by the entire wind farm increased from 59.07GWh/year to 61.565GWh/year, which represents an increase of 2.5GWh/year or 4.224%. At the same time, by changing the turbine design and size while keeping the same location, the proximity losses change, with the average value for the whole wind farm increasing to 2.34% from 2.32%.

5.3.3. Configuration III - Vestas V90 3 MW turbine

Tab.5.3 shows the values obtained from the simulation for this 3MW turbine model.

Tab. 5.3. List of the resulting parameters for the optimal installation variant - Vestas V90 3 MW

Turbine no.	Location Stereo70	Location height	Turbine height	Brut AEP	Proximity losses	Average wind speed	Power density
	[m]	[m]	[m]	[GWh]	[%]	[m/s]	[W/m²]
Turbine 001	(751946.7,405853.3)	298	100	7.658	3.5	8	410
Turbine 002	(752085.8,405986.1)	309	100	7.775	2.89	8	419
Turbine 003	(751818.7,405657.3)	266	100	7.42	1.71	7.7	369
Turbine 004	(755927.4,407806.6)	376	100	7.319	1.03	7.8	373
Turbine 005	(756265.1,407674.2)	383	100	6.912	2.35	7.6	344
Turbine 006	(755594.8,417654.4)	410	100	7.069	1.27	7.7	354
Turbine 007	(756249.8,416501.3)	408	100	7.058	3.79	7.7	367
Turbine 008	(756110.1,416379.8)	406	100	7.482	3.05	7.9	396
Turbine 009	(756470.2,416888.7)	455	100	6.507	2.37	7.5	324
Turbine 010	(752452.4,406024.1)	267	100	6.803	2.45	7.5	345

Parameter	Minimum	Average	Maximum	Total wind farm
Net AEP [GWh]	6.352	6.987	7.55	69.866
Brut AEP [GWh]	6.507	7.162	7.775	71.623

It can be seen that by changing the turbine model from 1.8 MW to 3 MW, the annual net energy generated by the entire wind farm increased from 59.07GWh/year to 69.866GWh/year, which represents an increase of 10.8GWh/year or 18.277%. At the same time, by changing the turbine design and size while keeping the same location, the proximity losses change, with the average value over the whole wind farm increasing to 2.45% from 2.32%.

5.3.3. Availability coefficient and economic parameters

For the comparison of the three turbine versions we can look at several parameters: the annual net energy generated by the whole wind farm, the availability coefficient, the cost of the wind farm and the payback period.

Tab.5.4 shows all the availability coefficients calculated for each turbine and for the whole wind farm for the three turbine designs studied.

Tab.5.4. List of availability coefficients

Turbine No.	V90 1.8MW	V90 2MW	V90 3MW	V90 1.8MW	V90 2MW	V90 3MW	V90 1.8MW	V90 2MW	V90 3MW	V90 1.8MW	V90 2MW	V90 3MW
	Net AEP			Average annual power			Availability Coefficient			Availability		
	[GWh]			[kW]						hours/year		
Turbine 001	6.137	6.42	7.39	700.57	732.88	843.61	0.39	0.37	0.28	3409.4	3210.0	2463.3
Turbine 002	6.251	6.543	7.55	713.58	746.92	861.87	0.40	0.37	0.29	3472.8	3271.5	2516.7
Turbine 003	5.824	6.075	6.922	664.84	693.49	790.18	0.37	0.35	0.26	3235.6	3037.5	2307.3
Turbine 004	6.125	6.385	7.243	699.20	728.88	826.83	0.39	0.36	0.28	3402.8	3192.5	2414.3
Turbine 005	5.802	6.028	6.749	662.33	688.13	770.43	0.37	0.34	0.26	3223.3	3014.0	2249.7
Turbine 006	5.956	6.197	6.979	679.91	707.42	796.69	0.38	0.35	0.27	3308.9	3098.5	2326.3
Turbine 007	5.744	5.986	6.791	655.71	683.33	775.23	0.36	0.34	0.26	3191.1	2993.0	2263.7
Turbine 008	6.067	6.338	7.254	692.58	723.52	828.08	0.38	0.36	0.28	3370.6	3169.0	2418.0
Turbine 009	5.507	5.71	6.352	628.65	651.83	725.11	0.35	0.33	0.24	3059.4	2855.0	2117.3
Turbine 010	5.654	5.884	6.636	645.43	671.69	757.53	0.36	0.34	0.25	3141.1	2942.0	2212.0
Total wind farm	**59.067**	**61.566**	**69.866**	**6742.81**	**7028.08**	**7975.57**	**0.37**	**0.35**	**0.27**	**3281.5**	**3078.3**	**2328.9**

From this calculated data, we can see that the availability of the 3 MW turbine is about 27% of the year, which is a low value. The recommendation is that this availability coefficient should be above 0.35. The values calculated in Tab.5.4 only took into account the simulated net energies in WAsP and did not take into account downtimes due to malfunctions, maintenance or grid unavailability. Obviously the actual values in the table will be lower in these cases.

The cost of installing a wind farm, according to the data in Tab.1, is 1355 $/kW for on-shore wind installations. According to [38], for the "Centralized Market for Renewable Electricity Supported by Green Certificates", the weighted average price of electricity in 2021 was 287.44 lei/MWh, and green certificates had a weighted average price of 142.22 lei/MWh, so we can say that for 1MWh delivered to the grid we get about 97$. Thus, with these parameters we can calculate the cost of the wind farm in the three variants, the annual amount recovered through the sale of electricity (annual benefit), the payback period (ROI - return of investment) and the estimated profit after 20 years which is the estimated lifetime of the wind farm.

The values expressed in the previous paragraph in lei can be converted into $ (dollars), taking into account the exchange rate used: 1$ = 4.429 lei.

Tab. 5.5. Economic parameters

Turbine model	Installed power	Wind farm price	Net AEP	Annual benefit	ROI	Profit
	kW	million $	GWh	million $	years	million $
V90 1.8MW	18000	24.39	59.067	5.73	4.26	90.20
V90 2 MW	20000	27.1	61.566	5.97	4.54	92.34
V90 3 MW	30000	40.65	69.866	6.78	6.00	94.89

The values in Tab.5.5 only take into account the values of generated and traded energy, without taking into account downtime, repair/maintenance costs, etc. For a complete analysis all costs should be taken into account over the lifetime of the wind farm. In this study, the values in Tab.5.5 were considered relevant enough to choose a turbine model.

Thus, taking into account the annual net energy generated by the whole wind farm, the availability coefficient, the cost of the wind farm, the payback period (ROI) and the profit after the lifetime of the turbines, we can exclude the 3MW turbine variant due to the following elements:

- It has very low availability coefficient;
- ROI higher by 18-21 months compared to 2 MW and 1.8 MW turbines respectively;
- The price of the wind farm is much higher, almost double compared to the other variants;
- Profit after the lifetime of the turbines is very close to the other two variants;

The 1.8 MW and 2 MW turbine variants remain valid, all calculated parameters are close, we can say that either of the two variants are feasible.

CHAPTER 6
EXPERIMENTS ON THE MODEL OF A LABORATORY WIND SYSTEM

In recent times, the consumption and cost of coal and oil for power generation has increased and with it the pollution from these traditional methods of generating electricity. The power generation market has recently turned its attention to alternative methods of generating electricity.

In Bucharest, installing a wind turbine is not economical because the wind potential of the area is low for a year. For this reason, a laboratory model of a real wind turbine system has been used instead of a real one, replacing the generator's drive propeller with a system consisting of three components: a variable frequency converter, an asynchronous motor and a mechanical speed divider.

6.1. DESCRIPTION OF THE LABORATORY WIND SYSTEM

Fig.6.1. shows the block diagram of the wind system used for the experiments. This laboratory model shown is functional and is located in the Electrical Machines Laboratory of the Faculty of Electrical Engineering, Polytechnic University of Bucharest.

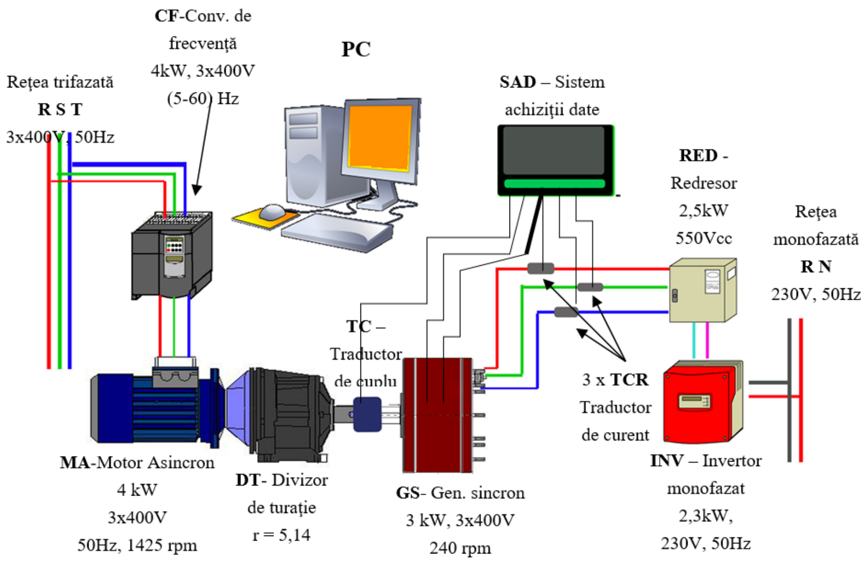

Fig. 6.1. General scheme of the experimental wind system model

In addition to the elements shown in Fig. 6.1, the paper also shows some elements specific to the laboratory model: voltage, speed, temperature, current transducers and a data acquisition board with USB communication port.

6.2. WIND SYSTEM MODEL OPERATION AND NORMAL OPERATION TESTS

The wind system operates stably for any frequency in the range (5 ... 60) Hz, unless there are very rapid variations in the values of this frequency. If rapid variations in wind speed occur (tornadoes, strong gusts) these are equivalent to the very rapid variation of the frequency of the frequency converter, characterised for the laboratory model by a sudden rotation of the frequency control knob leading to the occurrence of current shocks in the generator circuit, shocks which lead to the automatic disconnection of the model from the single-phase network to which it is connected (the green light on the system panel goes out and the red light on the same panel comes on). The operating mode of the model provides a single-phase sinusoidal alternating voltage output. The energy produced by the system is fed into the grid.

6.2.1. Assembly diagram made in the laboratory

In normal operation, the wind model runs continuously, unless controls are used to simulate fault conditions. In Fig. 6.2. shows the installation scheme for the measurements.

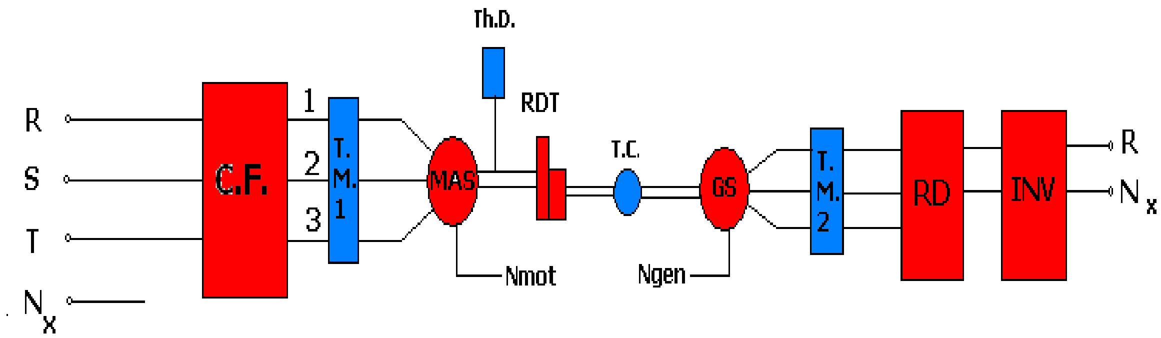

Fig. 6.2. Arrangement drawing for normal operation tests

6.2.2. Results of normal operation tests

Wind model tests performed in normal operation were carried out by varying the frequency of the frequency converter in the range (15 - 50) Hz.

In Tab. 6.1 shows the measured and calculated data resulting from the tests. The notations in this table are as follows: P1 is the power at the output of the converter; P2 is the power at the output of the generator; Pr is the power delivered to the grid; I1 is the current absorbed by the asynchronous motor; I2 is the current of the synchronous generator; U1 is the voltage applied to the motor; U2 is the voltage of the synchronous generator; f1 is the frequency at the output of the converter; n1 is the speed of the asynchronous motor; cosφ1 is the power factor of the asynchronous motor; Ur is the grid voltage to which the system power is delivered.

Tab.6.1. Measured and calculated values

Nr.	U_1	f_1	I_1	$\cos\varphi_1$	n_1	U_2	I_2	$\cos\varphi_2$	U_r	P_1	P_2	P_r
	V	Hz	A		rpm	V	A		V	W	W	W
1	112.6	15	1.8	0,134	427	180	0.00	-	382	47.1	0	0
2	140.1	20	2.1	0,200	573	244	0.00	-	382	102	0	0
3	175.2	25	3.3	0,428	708	284	0.61	0,866	381	429	260	255
4	215.6	30	4.7	0,533	845	320	1.19	0,970	382	937	640	579
5	261.6	35	6.3	0.603	982	352	1.9	0,967	382	1722	1120	1013
6	306.6	40	7.5	0,631	1127	380	2.54	0,957	383	2514	1600	1467
7	352.4	45	8.2	0,647	1270	404	3.12	0,989	382	3240	2160	1936
8	361.3	46	8.3	0,653	1296	408	3.22	0,984	382	3390	2240	2013
9	370.0	47	8.4	0,657	1325	416	3.32	0,970	382	3540	2320	2096

10	385.2	48	8.5	0,648	1353	420	3.41	0,967	381	3675	2400	2178
11	388.8	49	8.7	0,646	1382	424	3.5	0,980	381	3786	2520	2247
12	389.1	50	9.1	0,642	1409	428	3.54	0,975	381	3942	2560	2297

6.2.3. Characteristics of the wind model in normal operation

Using the data presented in Tab. 6.1 some characteristics of the wind system for the normal operating regime can be determined. These characteristics are efficiency characteristics, power factor characteristics, mechanical characteristics and other characteristics specific to the normal operating regime.

a. Efficiency characteristics

The active energy losses in the mechanical couplings used in the assembly scheme are neglected and are very low. The asynchronous motor, the speed reducer and the synchronous generator are the main elements of the wind model where the highest active energy losses occur. At low frequencies of 15Hz and 20Hz the synchronous generator cannot be connected to the grid because its voltage is reduced below the grid voltage. For these two frequencies the laboratory model does not inject electrical power into the grid. The system comes into operation after the asynchronous motor supply voltage frequency rises above 25Hz. If the efficiencies are calculated with the data in Tab. 6.1, for all frequencies in the range (25...50)Hz, the values of $\eta_m \cdot \eta_{red} \cdot \eta_g$. These values are in the range (0.606 ... 0.680). These values are relatively low due to power losses in the synchronous generator, the speed reducer and especially the asynchronous motor because the latter operates in the saturated area of its magnetic circuit.

b. Power factor characteristics

Using the values in Tab. 6.1 the power factor characteristics for the asynchronous motor cosφ1 = f(f1) and for the synchronous generator cosφ2 = f(f1) can be determined. These characteristics are shown in Fig. 6.3.

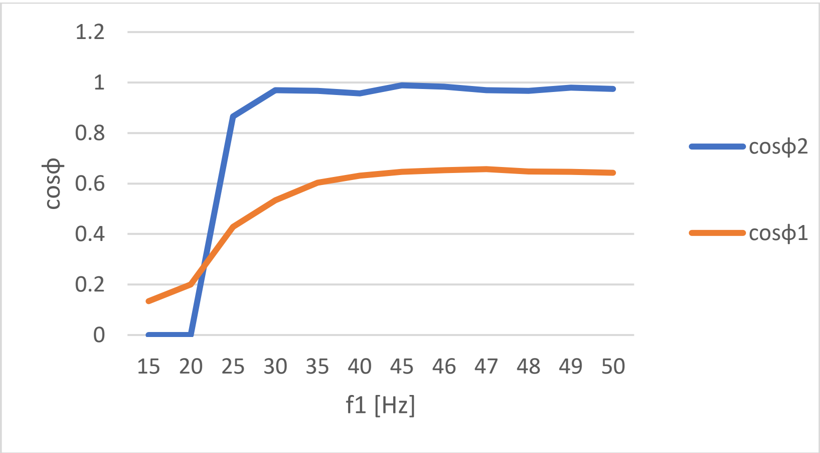

Fig. 6.3. Power factor characteristics for asynchronous motor and synchronous generator

c. Mechanical characteristics of the asynchronous motor

The asynchronous motor operates, for certain frequencies, in saturated mode. This also has an influence on the mechanical characteristic of the motor, defined at variable frequency. The mechanical characteristic is not classically defined by considering the frequency and voltage of the motor constant, but is defined by considering the ratio U1/f1 = constant, i.e. considering the maximum magnetic flux in the magnetic circuit of the asynchronous motor constant. In Tab. 6.2 numerical values of the mechanical characteristic of the asynchronous motor defined at constant magnetic flux are given. The mechanical characteristic is shown in Fig. 6.4. It can be seen that for frequencies in the range (25 ... 50) Hz, the mechanical characteristic is approximately a straight line.

Tab.6.2. Mechanical characteristic of asynchronous motor at constant magnetic flux

M [Nm]	*M*	1,05	1,70	5,78	10,55	16,74	21,3	25,7	26,71
f_1 [Hz]	f_1	15	20	25	30	35	40	45	50

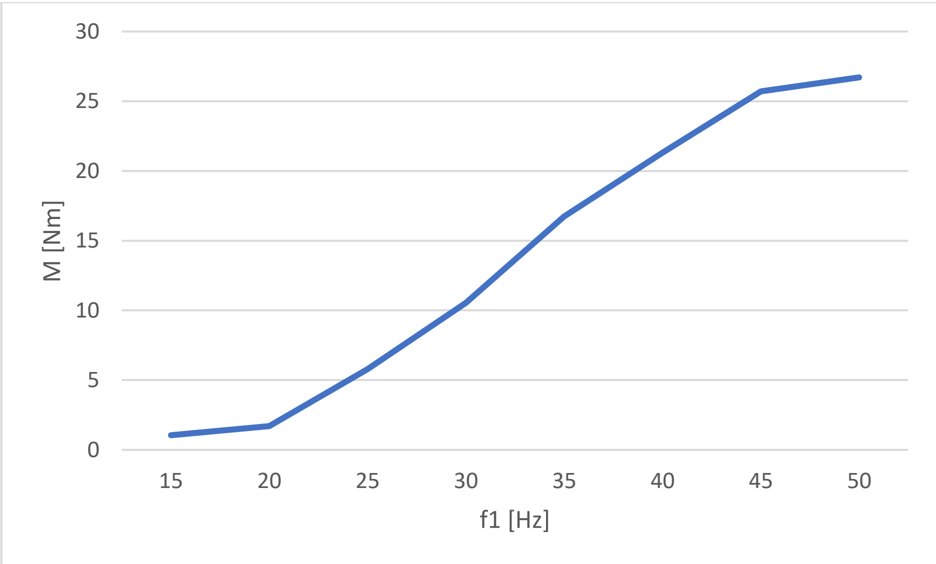

Fig. 6.4. Mechanical characteristic of asynchronous motor defined at constant maximum flux

d. Idling characteristic of the synchronous generator

The synchronous generator has rotor excitation by permanent magnets. In Tab. 6.3 shows the numerical values of the idling characteristic.

Tab.6.3. Idling characteristic of the synchronous generator

U [V]	0	40	100	160	220	280	340	400	460
n [rot/min]	0	20,7	51,9	83	113	145	178	210	236

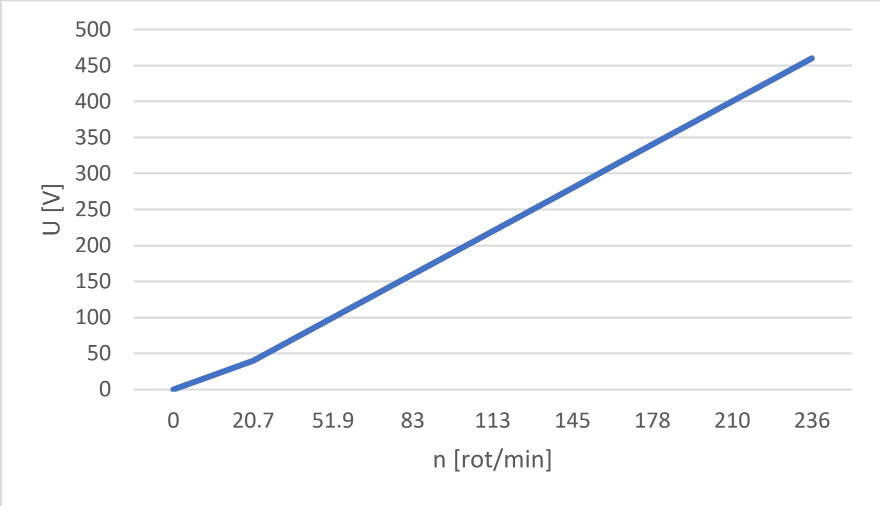

Fig. 6.5. Idling characteristic of the synchronous generator

The idling characteristic is shown in Fig. 6.5. It can be seen that this characteristic is approximately a straight line. This means that the synchronous generator is working very well, its magnetic circuit saturation is low.

e. Instantaneous variation of synchronous generator currents iA, iB and iC

Since the three-phase winding of the synchronous generator is connected in the star, the instantaneous sum of the currents on the 3 phases is zero at any point in time.

The three-phase system of synchronous generator currents iA, iB and iC have non-sinusoidal instantaneous values containing higher order harmonics the higher the lower their frequency. It is found that as the generator speed increases, the harmonic spectrum for the iA, iB, iC currents flowing through the synchronous generator also changes. In this way, one of the advantages of the rectifier-inverter unit between the synchronous generator and the grid into which it delivers electricity has been highlighted. In other words, it eliminates the higher-order harmonics that would enter the grid to which the synchronous generator is connected.

f. Current variation in the inverter intermediate circuit

The direct current in the intermediate circuit between the rectifier and the single-phase inverter contains pulsations whose magnitude depends on the frequency of the synchronous generator voltage. For example, at 25 Hz, the pulses represent about 40% of the average size of the DC current which is approximately 0.7A. For a frequency of 47.5 Hz the pulses represent about 12% of the average value of this current, which is approximately 4.1A. Therefore, as the wind speed, and therefore the speed of the model, increases, the value of the DC current in the intermediate circuit between the rectifier and the single-phase inverter increases and at the same time the relative size of its current pulses decreases.

6.3. WIND MODEL TESTS IN LIMIT REGIMES

The laboratory model must also be able to model certain special operating regimes of the wind system such as: sudden increases in wind speed variation, and therefore asynchronous motor speed, which would occur during strong storms in the area where the wind turbine is located.

In Fig. 6.6 shows the variation in time of the active torque of the generator when it is automatically disconnected from the grid in case of a strong increase in wind speed.

If, when the generator is disconnected from the grid due to over or under-rotation, its speed returns to a value for which the generator can be connected to the grid then the control system of the laboratory model does this automatically and couples the generator to the grid as shown, for example, in Fig. 6.7.

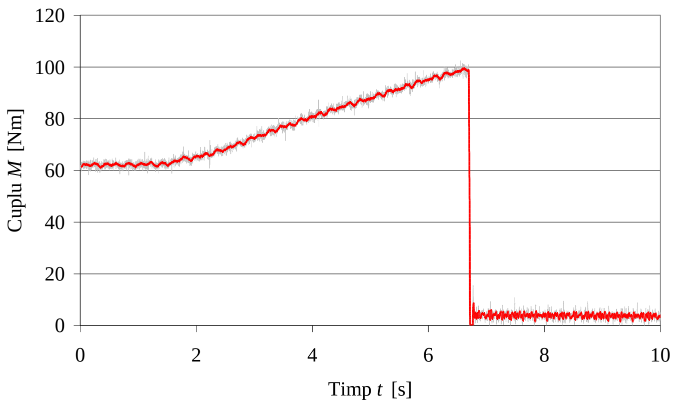

Fig. 6.6. Generator disconnection due to generator overload

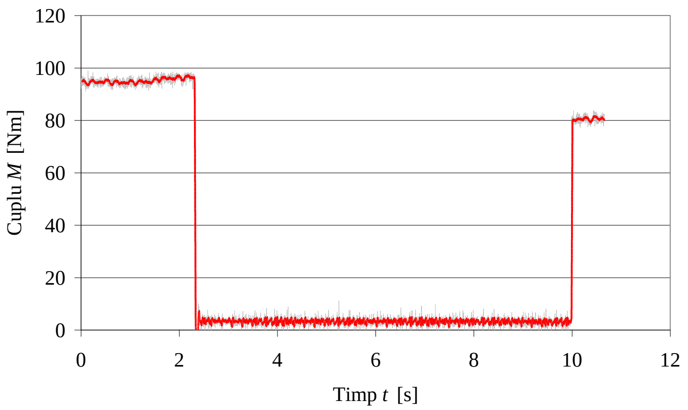

Fig. 6.7. Generator disconnection and reconnection produced during dynamic operation.

The realization of the laboratory model of the wind system and its tests lead us to some important conclusions such as:

- Highlighting the trend for modern wind systems to be built without a speed multiplier, i.e. the mechanical shaft of the synchronous generator is mechanically coupled directly to the wind turbine shaft;
- The generator of the laboratory model can be synchronous with permanent magnets, which brings certain constructive, functional and operational advantages;

- The voltage of the synchronous generator has a variable frequency and is firstly rectified, then inverted to the grid frequency and finally filtered so as not to introduce distorting power into the grid and thus protect it;
- The lower the wind speed of the wind system model, the more the higher harmonic content of the instantaneous voltage and current curves of the synchronous generator increases;
- Wind system protections at under- or over-running are automatically achieved by the system.

CHAPTER 7
CONCLUSIONS, ORIGINAL CONTRIBUTIONS AND PERSPECTIVES FOR FURTHER RESEARCH

7.1. CONCLUSIONS

This PhD thesis deals with the fundamentals of wind power generation systems. It studies the main technical and technological elements that are directly related to medium and large wind power plants.

The introduction analyses the installed worldwide power from renewable energy sources and outlines trends for the near future development of these plants. It also specifies some elements concerning the aim of the PhD thesis and finally thanks the Faculty of Electrical Engineering in which the PhD thesis was developed and the committee that evaluated the thesis throughout the PhD thesis.

Chapter 1 of the thesis presents the general elements of wind energy. Globally, wind energy production is developing at an accelerated pace thanks to the supportive international policy of the world's most developed countries. Over the next 10 years, international institutions are calling for a profound transformation of the energy system. Estimates of the growth in installed wind power show that by 2030 wind power sources will increase by about 3 times. During this period, total investment in wind will also increase by more than 5 times, according to the International Energy Agency. In terms of wind resources, Romania is at the eastern end of the circulation of currents generated in the North Atlantic basin and the atmospheric circulation generated in the Russian Plain and Black Sea area. From the annual mean wind speed map presented in the paper, it appears that the circulation of air currents is of sufficient intensity to be exploited only at high altitudes on the Carpathian ridges and in the Black Sea area.

Chapter 2 provides a general description of the main elements of a wind energy system. To begin with, wind turbines are classified according to several criteria: installed power, location, type of turbine (horizontal and vertical axis). The components of a horizontal axis turbine are then described, with an emphasis on the faults that can occur in different parts of the turbine. The connection diagrams of wind power plants to electrical grids used for asynchronous generators with a short-circuited rotor or wound rotor, respectively for synchronous generators with classical direct current excitation, or with permanent magnets, are also analysed. It is shown that a particular role is played by harmonic filters connected between the electrical generator and the mains, either directly or via a power transformer.

Chapter 3 of the paper deals with the reliability, protection and maintenance of wind power generation systems. It describes the general elements that characterise reliability and the quality indicators for expressing it. The study of reliability can be described by some specific elements such as: establishment of optimal values of reliability indicators, collection and processing of data related to product reliability, study of faults occurring in operation (cause of fault occurrence, development over time of fault, methods of combating fault occurrence). In some cases the cost of fixing a fault may exceed the cost of new equipment. Protection of wind systems is another issue addressed. It is shown that the most commonly used control systems are electrical, magnetic, mechanical, electronic and control systems. At the end of the chapter, the maintenance services in wind energy systems and their objectives are discussed: preventing failures, increasing the availability of the wind energy system, extending the lifetime of the equipment, reducing the number and duration of unplanned outages. The types of maintenance analysed are corrective maintenance, preventive maintenance and predictive maintenance.

Chapter 4 investigates the study of wind potential at a location and the methodology for processing wind data. For the layout of a wind system, the wind potential of the area, the impact of the system on the surrounding environment, the existence of power grids in the area and the existence of a favourable road structure should be analysed. An analysis of local physical factors that may influence wind potential such as: type of terrain in the location of the turbines, presence of surface and height differences, obstacles such as forests, buildings or other constructions. It is shown that accurate measurements of the wind potential at a location are of particular importance in order to best estimate the electricity production of the wind farm. In order to achieve these requirements, several basic elements are of particular importance, such as: the tower for measuring important parameters for the wind system, specialised equipment (tiltmeters, anemometers and ground monitoring devices: SODAR ("SOnic Detection And Ranging") and LIDAR ("LIght Detection And Ranging"). For the chosen location, the thesis analyses several important parameters such as: wind speed, Weibull distribution, average wind speed curves as a function of height above ground level over a year and the evolution of ambient temperatures over the same period.

Chapter 5 deals with the optimisation of a wind farm in terms of modelling and choosing the ideal site for three high-power wind turbine models. In this case, a specialised software called WAsP is used, with the help of which an optimal spatial distribution of wind turbines for a given location can be achieved. It uses the topographic map of the location and the wind regime forecast. The optimization process was done manually because the calculation time for an automatic optimization is very long. The following steps were followed to perform this process: an initial location is chosen at first, taking into account the simulated local wind map and some location recommendations, thus obtaining a first variant. The turbines for which the proximity losses are higher than 5% or have low values of generated energy are retained and their location is changed, after which the calculations are repeated until it is found that the proximity losses have dropped below 5% for all turbines in the park and the generated energy is at a value as good as possible. In addition to the local wind map and the numerical data calculated in the program, other functions were used, provided by the software used to achieve a faster and more accurate optimisation. In the paper, after optimizing the location of 1.8 MW Vestas turbines, the parameters of different turbine models, 2 MW and 3 MW, are simulated for the same optimal location, comparing both electrical and economic parameters of the three variants.

Chapter 6 experiments are carried out on a laboratory model of a wind turbine system, its operation under normal operating conditions as well as under abnormal fault or overload conditions. The system is located in the Electrical Machines Laboratory of the Faculty of Electrical Engineering of PUB. The system is a special one that models the turbine drive propeller using a variable frequency converter, a three-phase asynchronous motor and a speed reducer, since the laboratory model refers to a wind system that has the synchronous generator driven directly by the turbine. The experimental model therefore eliminates the speed multiplier between the turbine and the generator shaft, which is increasingly used worldwide. The main characteristics of the wind system under normal operating conditions (electrical characteristics and mechanical characteristics) are determined experimentally, and the harmonic content at the output of the synchronous generator is analysed as a function of the system speed.

7.2. ORIGINAL CONTRIBUTIONS

This PhD thesis makes many original contributions to the field of wind power generation systems. Among these contributions the most important ones can be mentioned:

- Presentation of the current status of wind energy production and use worldwide and in Romania and its development trends in the coming years;

- A well-documented summary of the main processes and general schemes for wind energy systems currently in use, analysing their advantages and disadvantages;
- Comparative analysis between two wind systems with and without speed multiplier and comparison of the results between the two situations in terms of total investment cost and technological operating conditions;
- Conduct an in-depth study of the wind potential of a given location and a methodology for acquiring and processing topographic data and data on wind speed and temperatures of the location for a calendar year, with a description of the equipment needed to carry out this study.
- Optimisation of the location of wind turbines in a given location so that proximity losses are reduced below 5%, using appropriate software, depending on the topography of the terrain, for three models of high power Vestas wind turbines;
- A unified presentation of the issues of reliability, maintenance and protection of wind systems, analysis of the main types of failures of the main elements of these systems and ways to remedy these failures so that these systems operate safely;
- Experimentation with a laboratory model of a wind system operating under normal and abnormal conditions, determination of the operating characteristics under such conditions with explanation of how to measure the electrical and mechanical characteristics for the particular case of the laboratory model.

7.3. PROSPECTS FOR FURTHER RESEARCH

Future prospects for further research in this PhD thesis are multiple. The most important may be the following:

- Optimisation of wind farms for other types of wind turbines of very high power up to 10MW per unit, turbines manufactured by various manufacturers using specialised, state-of-the-art software;
- Writing special chapters and publishing them in the form of books and scientific papers on wind power generation systems;
- Obtaining practical information on wind power systems and collaborating with various commercial companies in this field to carry out specific projects in this important area.

REFERENCES

[1] Interational Energy Agency - IEA, "*World Energy Outlook 2021*", 2021

[2] Agenția pentru Dezvoltare Regională Centru, „*Analiza potentialului energetic eolian la nivelul regiunii centru in perspectiva dezvoltarii economice durabile*,”, Alba Iulia, 2010

[3] Directiva 2009/28/CE a Parlamentului European și a Consiliului, "*Jurnalul Oficial al Uniunii Europene L140/16*", 23 aprilie 2009. Accesat: iulie 2021, Link: https://eur-lex.europa.eu/legal-content/RO/TXT/HTML/?uri=CELEX:32009L0028&from=EN

[4] Comisia Europeana, "*Energie curata pentru toti europenii*," 2019, Accesat: iulie 2021, Link: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

[5] Global Wind Energy Council (GWEC), "*Global Wind Report 2021*", Brussels, Belgia, 2021.

[6] International Renewable Energy Agency*, "Global Renewables Outlook: Energy transformation 2050*", Abu Dhabi: IRENA, 2020.

[7] Convenției-cadru a Organizației Națiunilor Unite privind schimbările climatice (UNFCCC - acronim în limba engleză), "*ACORDUL DE LA PARIS*," Jurnalul Oficial al Uniunii Europene L282/4, 2016.

[8] International Energy Agency, "*World Energy Outlook 2020*," IEA, 2020.

[9] Ministerul Economiei, Energiei şi Mediului de Afaceri, "*Strategia energetică a României 2020-2030, cu perspectiva anului 2050*," Bucuresti, 2020.

[10] ANRE, "*Puterea instalată în capacităţile de producţie de energie electrică*,", Accesat:03 08 2021. Link: https://www.anre.ro/ro/energie-electrica/rapoarte/puterea-instalata-in-capacitatiile-de-productie-energie-electrica.

[11] Curtea de Conturi Europeană, "*Raport special nr. 08: Energia eoliană și solară pentru producerea de energie electrică: sunt necesare acțiuni semnificative pentru atingerea obiectivelor asumate de UE*," 2019.

[12] Agenţia Internaţională de Energie Regenerabilă (IRENA), "*Reneweble Power Generation Costs in 2020*," IRENA, Abu Dhabi, 2021.

[13] ENERCON, "*Model E-126," Enercon, 2021*. [Online]. Available: https://www.enercon.de/en/products/ep-8/e-126/. [Accessed 12 August 2021].

[14] Villarreal D. J. Y. "*VIV resonant wind generators*", Vortex Bladeless S.L., 2018.

[15] Jäger T., E. Lanz E., Seligmann C., Glöser S., Som O., Espinoza L. T., Zanker C. "*Sectoral Energy Report: The Machine Building Industry for Wind Power*", Energy Systems Analysis Agency, 2012.

[16] Ria Fathiyah, Ryan Mellott, Mahendra Panagoda, Melissa Lane, "*Windmill Design Optimization through Component Costing*", IEEE Seminar: London, UK, 2000 – Citeseer, [Online]: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.437.906&rep=rep1&type=pdf (Acces at 16.02.2022).

[17] Badea A. Necula H., (coordonatori), Cenusa V., Ciobanu M. C. Dinca C., Ghita C., Ionescu C., Kisch D. O., Marculescu C., Morega A., Popa B., Porumb R., Safta Carmen, Tristiu I., "*Surse regenerabile de energie"*, Bucuresti, Editura Agir, 2013.

[18] **Viişoreanu A. M.**, Răchiţeanu Alina, "*Reliability and Maintenance of Wind Power Systems*", in FOREN – FORumul ENergiei, Bucureşti, 2020, EMERG, Volume VI, Issue 3/2020, ISSN 2668-7003, ISSN-L 2457-5011, DOI: 10.337410/EMERG, The EMERG publication is BDI indexed in EBSCO and Copernicus International.

[19] Tazi N., Châtelet E., Bouzidi Y., "*Using a Hybrid Cost-FMEA Analysis for Wind Turbine Reliability Analysis*," Energies 2017, Nr. 10, 276.

[20] Arabian-Hoseynabadi H., Oraee H., Tavner P., "*Failure modes and effects analysis (FMEA) for wind turbines*," Int. J. Electr. Power Energy Syst. 2010, 32, 7, 817–824.

[21] Shafiee M., Dinmohammadi F., "*An FMEA-based risk assessment approach for wind turbine systems: A comparative study of onshore and offshore*," Energies 2014, No.7, pg. 619–642.

[22] Răchiţeanu Alina, **Viişoreanu A. M.**, "*Surge Arrester for Protection Against overvoltage of high voltage networks*", EMERG, vol. VI, no. 3/2020, ISSN 2668-7003, ISSN-L 2457-5011, DOI: 10.337410/EMERG, The EMERG publication is BDI indexed in EBSCO and Copernicus International.

[23] Răchiţeanu Alina, **Viişoreanu A. M.**, "*Overvoltage Protection of Transformers and High Voltage Networks by Surge Arrester*", EMERG, vol. VI, no. 2/2020, ISSN 2668-7003, ISSN-L 2457-5011, DOI: 10.337410/EMERG, The EMERG publication is BDI indexed in EBSCO and Copernicus International.

[24] Deaconu I. D., Chirilă A. I., Năvrăpescu V., Răchiţeanu Alina, **Viişoreanu A. M**., Ghiţă C., Sărăcin Cristina Gabriela", *Lightning Impulse Voltage Modeling for Transformer Windings Testing*," în Advanced Topics in Electrical Engineering - ATEE, Bucuresti, Romania, 2019, DOI: 10.1109/ATEE.2019.8724942, Conferintă ISI.

[25] Deaconu I. D., Chirilă A. I., Năvrăpescu V., Ghiţă C., Răchiţeanu Alina, **Viişoreanu A. M.**, "*Influenta variatiei parametrilor schemei echivalente a transformatorului electric, asupra propagarii undelor de supratensiune atmosferica de-a lungul infasurarilor*", in International Conference and Exposition on **E**lectrical and **P**ower **E**ngineering **-** EPE, Iasi, 2020, DOI: 10.1109/EPE50722.2020.9305584, Conferintă ISI.

[26] Răchiţeanu Alina, **Viişoreanu A. M.**, "*Propagarea undelor de supratensiune în transformatoare prevăzute cu inel de gardă*", Simpozionul de Masini Electrice - SME '21, Ediţia a XVII-a, Bucuresti, 2021, ISSN / ISSN-L: 1843-5912, Journal.iem.pub.ro/apme/, https://www.doi.org/10.36801/apme.2021.1.5.

[27] Deaconu I. D., Chirilă A. I., Ghiţă C., Năvrăpescu V., Răchiţeanu Alina, **Viişoreanu A. M.**, Popescu S. V., Gheorghiu C. I., Sărăcin Cristina, "*Determination of the Electric Capacitance of the Overvoltage Protective Shield of an Electric Transformer*", The 12th International Symposium on **A**dvanced **T**opics in **E**lectrical **E**ngineering - ATEE, 2021, DOI: 10.1109/ATEE52255.2021.9425086 , Conferintă ISI.

[28] EN 13306: 2001, "*Maintenance Terminology*"

[29] "*Cod de proiectare, Evaluarea acţiunii vântului asupra construcţiilor, Indicativ CR 1-1-4/2012*" https://www.academia.edu/36896352/CR_1_1_4_2012_Normativ_vant_pdf(Accesat martie 2022)

[30] "*Parc eolian, instalare turn monitorizare si control, racordare la sistemul energetic national, reabilitare cale de acces si construire statie de transformare (20kV – 110kV), judetul Tulcea, comuna Casimcea"* https://www.eib.org/attachments/pipeline/20110247_eia_ro.pdf, (Accesat martie 2022)

[31] Administraţia Naţională de meteorologie, "*Caracterizare climatologică multianuală 1961-2021*", https://www.meteoromania.ro/clim/caracterizare-multianuala/cc_03_1961-2021.html, (Accesat martie 2022)

[32] Meteoblue, Istoric şi climat, Arhiva meteo, https://www.meteoblue.com/ro/vreme/historyclimate/ weatherarchive/mihail-kog%0c4%83lniceanu_rom%c3%a2nia_673377?fcstlength=1y&year= 2021& month=3 (Accesat martie 2022)

[33] WAsP - Wind Atlas Analysis and Application Program, www.wasp.dk/, Accesat: august, 2019

[34] Blue Marble Geographics, Global Mapper software, link: https://www.bluemarblegeo.com/global-mapper/; Accesat: august, 2019

[35] Earth Resources Observation and Science (EROS) Center, "*USGS EROS Archive - Digital Elevation - Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global*", Iulie 2018, link: https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1; Accesat: august 2019

[36] **Viişoreanu A.-M.**, Răchiţeanu Alina, "*Evaluarea potenţialului eolian dintr-o locaţie şi amplasarea turbinelor*", SME '21 Ediţia a XVII-a, 2021, ISSN / ISSN-L: 1843-5912, Journal.iem.pub.ro/apme/, https://www.doi.org/10.36801/apme.2021.1.10.

[37] T. Khan, J. Taweekun, T. Theppaya, "*Determination of feasible sites for wind farm using WAsP in Uttaradit, Thailand*", International Conference on Engineering and Technology (ICET 2021)

[38] Opcom, "*Raport anual de sinteză a rezultatelor funcţionării pieţelor centralizate operate de Opcom – 2021",* link: https://www.opcom.ro/opcom/ uploads/doc/rapoarte/Anual/ RS_2021_RO.pdf, Accesat: ianuarie 2022.