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Theoretical and experimental research regarding the dynamic behavior of the mechanical system relation to electrical system of the synchronous machine in wind turbine applications

SUMMARY

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CONTENTS

SUMMARY

Prezenta teză de doctorat urmărește să stabilească noi soluții pentru sincronizarea generatorului sincron cu rețeaua de alimentare trifazată, în cazul turbinelor eoliene, care în anumite situații pot fi afectate de variații crescătoare sau descrescătoare ale turației, pot fi supuse unor șocuri la arbore sau se pot accelera excesiv. Prin studierea caracteristicilor motorului sincron, s-a demonstrat importanța curentului și a tensiunii de excitație în controlul acestora. Pornind de la o abordare aprofundată a cercetării mașinii sincrone ca generator, s-au dezvoltat metode eficiente și economice de sincronizare a generatorului cu rețeaua trifazată prin variabilitatea curentului de excitație. Autorul a efectuat testări ale mașinii sincrone pe standuri dedicate, montajul, schemele și modalitățile de optimizare fiind o contribuție personală în domeniu. Acestea au permis simularea șocurilor mecanice la arborele generatorului. Finalitatea lucrării constă în configurarea și construcția unui sistem electric și mecanic care printr-o rezistență suplimentară automată introdusă în circuitul rotoric, poate fi comandat, astfel încât automatul de sincronizare utilizat să poată comanda sistemul electromecanic, păstrând valorile tensiunii în rețeaua națională, compensând șocurile mecanice de la arborele turbinei eoliene .

Theoretical and experimental research regarding the dynamic behavior of the mechanical system in relation to electrical system of the synchronous machine in wind turbine applications

ABSTRACT

This PhD thesis wants to find new ways to synchronize the synchronous generator of wind turbines with the triphasic power grid, which in some cases can be affected by increasing or decreasing speed, shocks to the shaft, or excessive acceleration. By studying the features of the synchronous motor, the importance of current and excitation voltage in its ability to be controlled has been proven. Starting from a thorough approach in researching the synchronous machine as a generator, efficient and economically viable methods of synchronizing the generator with the triphasic grid through the variability of the excitation current have been developed. The author made testing of the synchronous machine on dedicated stands, the montage, the schemes, and the optimization methods being a personal contribution to the domain. These have allowed the simulation of mechanical shocks to the generator shaft. The finality of this work consists of the configuration and construction of an electrical and mechanical system that can be controlled through an additional resistor that is automatically introduced in the rotary circuit so that the automatic synchronization system being deployed can control the electromechanical system while staying at the values of the national grid voltage by compensating for the mechanical shocks coming from the shaft of the wind turbine.

INTRODUCTION

The current trends of the technical-economic development of computerization and the creation of new sources of renewable energy, of energy conservation, lead to the ever-increasing need to study them, to find new solutions, so that they replace in a short period of time other conventional methods of electricity production.

The most important renewable energy technologies responsible for this growth are wind power and solar power. Although, in terms of volume, wind power still lags behind hydropower, the annual volume of electricity produced from wind power increased by 414% between 2005 and 2017, reaching 1000 GW in 2020.

The design, construction and implementation of wind turbines have evolved over time, people looking for new and new construction solutions, with the aim of making it more economical, at the same time producing energy with more efficiency. Different design topologies have been studied, related to the dimensions of the turbines, the size and number of blades, the ability to orient them in the direction of the wind, as well as aspects related to their topology/density on the surface (the tendency is to reduce the distance among them).

Due to the wind speed, which is often not constant over time, problems arise related to variability, finding design solutions at the level of the gearbox, the speed regulator, but also at the electrical level so that the wind turbine and implicitly the synchronous generator of it supply energy at nominal parameters to the three-phase supply network.

Thus, in the field of research, it has become a necessity to find optimal solutions both from a construction and functional point of view, as well as to obtain a constant energy yield. Hence the need to develop a system as economical as possible to preserve the voltage, frequency, sequence of phases and synchronism provided by the synchronous generator of the wind turbine so that regardless of the shaft variations, its disconnection from the grid does not occur.

Content of the thesis

The thesis is structured in 5 chapters, in which theoretical and experimental problems related to wind energy, to the synchronous machine, as well as to the conception and development of this mechanism of the studied mechanical-electrical system are addressed.

The first chapter, entitled *State-of-the art in the field of wind turbines and synchronous machine*, summarizes theoretical aspects regarding the current state of development of wind systems, describes wind turbines and how to connect them to the power grid. It deals with efficiency issues, implementation in grid-connected applications as well as with current research in the field of wind turbine shaft mechanical damping.

The synchronous machine, as a component part of the wind turbine, is described under theoretical aspects regarding its construction, its differences in relation to other rotating electric machines, as well as its role in industry where it can be used as a generator or as a motor.

We started from the definition of the synchronous machine, references were made about its role in industrial applications, the role of the rotor and the stator in the operation was described, presenting two models of synchronous machines, depending on the construction variant - with a rotor core with apparent poles or with drowned poles.

Currently, all power wind turbines as well as hydroelectric turbines have synchronous generators, in order to produce three-phase electricity in the grid. They have a very important feature that sets them apart from other electric machines; they have a constant speed, regardless of the operating mode (stabilized) and independent of the load value (within considered normal limits).

The synchronous motor has a wide applicability due to its robustness, it develops a high torque at an acceptable overall size, and due to its air gap, which can be increased compared to other electric machines, it makes it resistant over time. In the study of the synchronous motor, the operating equations were described, its most important characteristics were highlighted, from which it emerged that the excitation voltage and current play an important role in its start-up and control. Theoretical notions about synchronous motor starting highlight their heavier starting, operational problems that have been solved nowadays by using frequency inverters and automation systems.

The synchronous generator is treated separately in this thesis, where the role of staggered wound windings, at a phasor angle of 120 degrees, was exemplified, as well as the role of the excitation winding, which supplied with a direct current system, provides three-phase parameters in the three-phase supply network, at a nominal grid frequency. The variability of the synchronous generator is closely related to its control by controlling the excitation voltage and current, a fact that led to the study of this aspect in the following chapters.

The second chapter, entitled *Research on the synchronous machine used as a motor*, presents several experimental researches and case studies, which highlight the role and influence of the excitation current in the control of the synchronous motor.

In the first part of this chapter, with the help of an experimental stand, mechanical and electrical characteristics were measured for different values of the excitation current, at different motor torques at the shaft. In the scientific articles published, the need for excitation current variability in synchronous motor control has also been highlighted.

The research continues with the generation of torque curves, which highlight the fact that the synchronous machine maintains its constant speed with respect to the load on the shaft within normal limits. Different torque characteristics were generated at different excitation current values. Studies have shown that the synchronous machine maintains constant speeds at variable and imposed torques.

In the end, different load curves were created and applied to the machine shaft. They simulate possible wind gusts from the shaft of a wind turbine, increasing both the motor torque value and the time interval in which an anomaly remains on the turbine blades.

Following the conclusions of the experimental determinations, we moved to the next level, namely to studies related to research on the synchronous generator.

The third chapter, entitled *Research on the synchronous machine used as a generator* continues the previous study through original contributions related to the construction of a mechanical and electrical system that allowed the research of the synchronous machine in generator mode.

Thus, different stands are presented, which allow the emergence of mechanical and electrical characteristics of the synchronous generator. They highlight parameters that must be changed for the subsequent control of the system presented. The influence of the excitation current on the shaft of the synchronous generator is used for manual and automatic synchronization schemes that are the subject of the scientific research.

In chapter four, entitled *Original contributions on the design and development of the stand for synchronizing the generator to the grid*, I presented research on the choice of a correct manual and automatic synchronization scheme, so that the expenses be minimal, feasible and efficient. The final assembly presented in this work in figure 4.17. is an original contribution by which we studied the automatic control of the excitation current in what concerns speed oscillations of the synchronous generator. The assembly contains an automatic synchronizer that stabilizes the output voltage of the generator around 400 V at speed variations up to a minimum value of 1367 rpm and a maximum value of 1650 rpm, under the conditions of a nominal speed of 1500 of rpm, this being a nominal parameter of the synchronous generator studied. Due to an automatically controlled additional resistance assembled in series with the excitation rotor winding, the system allows the automatic control of this resistance, at variable or sudden speeds, while maintaining the output voltage of the generator. The resulting charts highlighted the importance of the current and implicitly of the excitation resistance in the stability of the wind system.

In the fifth chapter, the final conclusions, original contributions, dissemination of results as well as future research directions are formulated.

1. State-of-the art in the field of wind turbines and synchronous machine

1.1. General considerations for wind energy

Recent studies show that the production of electricity from renewable sources has reached 38% of the world production afferent to 2021. Of the total electricity generated from renewable sources, 10% was produced by wind and photovoltaic systems. The most advanced country in Europe that has implemented electricity production systems from renewable sources is Denmark, the percentage achieved being 50%.

In the Special Report no. 08 of 2019 issued by the European Commission, it is stated that for the implementation of the systems for the production of electricity from wind and solar energy, significant actions are needed to achieve the objectives assumed by the EU [1].

Increasing the percentage of electricity obtained from renewable sources aims to reduce greenhouse gas emissions by 40% by 2030 and by at least 80% by 2050, these gases mostly coming from the use of conventional fuels for the production of electricity and thermal energy. Moreover, this energy is available at no cost without involving other aspects such as importation, taxes, variable prices, as it happens in with fossil fuels.

Romania developed an integrated national plan in the field of energy and climate change regulated by DECISION no. 1.076 of October 4, 2021 published in the Official Journal no. 963 of October 8, 2021 [3].

Our country's targets for 2030 are to reduce emissions from ETS sectors by 43.9% compared to the level recorded in 2005, with 2% emissions from non-ETS sectors compared to the level recorded in 2005. Other targets are related to the increase by 30.7% of the percentage of energy from renewable sources in the total gross consumption and the reduction by 40.4% of the final energy consumption compared to the PRIMES 2007 projection [4].

The wind turbine manufacturing industry has ramped up production amid increased demand from power producers and more. An important aspect for research and system optimization is the command and control strategies of high-power turbines (wind farms) that feed energy directly into the grid. The main goal pursued is to reduce the total costs of electricity production. One way to achieve this is by reducing the mechanical components and adjusting the blade pitch in order to obtain the maximum energy that can be produced by the turbine [5].

Due to the production cost, the electricity produced from wind sources reached the lowest price compared to the other sources, at one point being 4 euro cents/kWh. The power installed in Europe in 2005 was 50 GW representing a percentage of 1.3% of the total power installed on the globe). The proposed deployment of wind power by 2020 was estimated to have reached a power of 400 GW (8% of the total installed power on the globe) [5].

Wind turbines have long been studied in order to function optimally, the goal being the production of electricity at the lowest possible price. Thus, designing the turbine blades, designing the angle of incidence on the blades, the wind speed, were aspects researched in detail [6].

From the studies carried out, it was concluded that an average nominal wind speed can be 12-15 m/s. This wind potential is also found in the Black Sea area[7]. Thus, the primary machine, the turbine, must be able to provide an electrical power as close as possible to the rated power of the generator [5].

If the wind speed increases very much, the wind turbine, through the protection systems, will stop so as not to be destroyed. Wind turbines operating at high wind speeds are equipped with control and protection systems.

Wind turbines that operate at constant speed have in their structure induction generators with squirrel cage rotor and in this case no turbine control strategies are necessary for their operation.

Wind turbines built for variable wind speeds have a dual control strategy. One is for the generator, and the second for the turbine rotor, the control system being common.

The electric machines used are permanent magnet synchronous machines with field winding or wound rotor asynchronous machines. In the case of wind systems designed for variable speeds, the electromechanical system is more complex than those designed for constant speed. The problems given by wind variation have led researchers to find solutions to the challenges that have arisen. The control modes of wind systems designed for variable wind speeds are pitch control, stall control and active stall control [5].

Wind turbines in any configuration (horizontal or vertical), transform the energy given by the wind into mechanical energy, which is later transmitted to an electric generator and is transformed into electrical energy. The electrical energy obtained is directly dependent on the primary energy supplied by the wind, the surface of the blades and the air density. [8].

The main maintenance problem for wind systems, despite their availability, is mechanical transmission, which causes higher costs and longer outages. The other components break down less often and do not cause such high maintenance costs [9].

The speed difference that occurs between the rotor and the generator can be increased with the help of speed boosters. In everyday practice it has been proven that these RPM amplifiers actually have a shorter lifespan than the one given by the manufacturers. The faults that occur are located at the level of the planetary gear bearings of the intermediate shaft, at the bearings of the high-speed shaft, which are otherwise the most stressed elements in motion. From the analysis of the data collected from the energy producers, it was concluded that most failures are not caused by the mechanisms involved in the fatigue of the rolling contacts (latent and superficial type according to ISO 15243), which can be estimated by prediction methods. Most failures occur due to cracks that cannot be analyzed in this way [9], [10]. Incidentally, besides the defects in bearings on the mechanical side, there are also defects in axles, couplings, gears, gearboxes, nacelle, tower, blades or electric generator defects [10].

Wind systems have evolved in terms of performance over time, and while wind turbines operated at wind speeds between 3.8 m/s and 22 m/s with an average operating time of 1600 hours/year, we now have systems which operate 3000 hours/year at wind speeds between 2.2 m/s and 33.3 m/s, the technological evolution being obvious thanks to the variable pitch concept.

The reliability of onshore wind systems (EMO) has increased over time, a fact that is due both to the standardization related to the functionality of these systems and to the economic requirements that impose this [9], [19]. Studies show that from an average failure frequency of between 1 and 3 turbines per year of operation, it was proposed a frequency of less than 1 per year.

Increasing reliability has many elements, namely: the manufacturing technology of wind systems, the technology of operation of wind systems, the materials from which they are made, the operating conditions of the systems. In what concerns reliability, one can make predictions, these influence production capacity along with available wind conditions. Also, logistical access to the facility, location, infrastructure costs and type of maintenance are also important [21].

Manufacturers made different types of EMO turbines, but we do not have data on their reliability. On the other hand, being a non-linear system that does not depend on time, the wind turbine has variable stochastic inputs that have a rather large weight on reliability [9].
The design of wind systems over time has addressed several technical and economic aspects in order to meet high technical conditions at acceptable prices and to have high efficiency.
The changes that appeared in the wind turbines occurred in almost all components, with several variants being tested. The concepts tested concerned the type of rotation (vertical and horizontal), positioning of the turbine rotor, control strategies, other types of basic components such as braking systems or types of blades, types of generators [22].
In order to have a basis for design, some components have been standardized (for eg. three-bladed, horizontal-axis, variable-speed turbine, etc.) [9].
On the other hand, through the continuous development of wind systems, progress has been made in their use in a wide range of wind speeds, but new problems have arisen in terms of reliability.

1.2. Design aspects of wind turbines

Wind turbines are systems that have the ability to transform the kinetic energy given by the wind into mechanical energy. This is transformed by means of the generator into electrical energy, which is then delivered to the electricity supply grid after standardized synchronism and quality conditions are met.
The electric generator takes the mechanical energy from the blades to the shaft and transforms it into electrical energy. This energy can be stored in batteries or delivered to the public power grid.
Over time, their construction has concerned several aspects related to dimensions, materials, positioning, mechanical systems, electrical power, so that today we can talk about wind turbines included in a wide range of electrical power, respectively from 25kW to 7 MW for turbines located on land (the E-126 model from Enercon) and for turbines located at sea, the current models reach electric powers between 14-15 MW (for eg. models Vestas 236 and Siemens Gamesa SG 14-222 DD) [28].

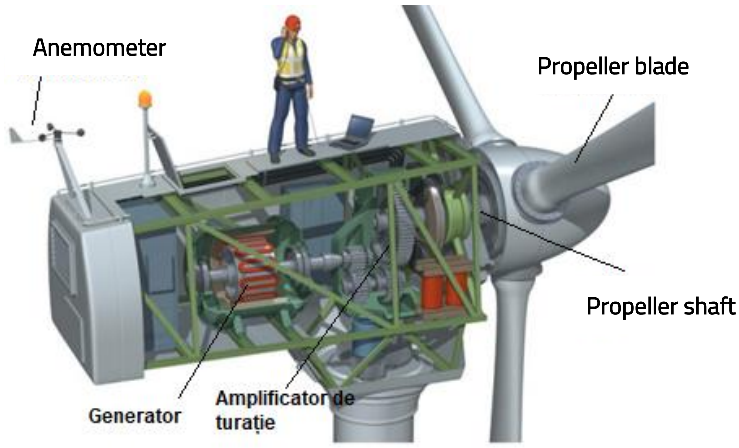


Fig.1.5. Wind turbine [29]

A simple classic wind turbine consists of three important parts: the rotor with the related blades (they capture the wind energy and transmit it to the rotor), the speed booster (for large turbines), the generator and the brake. Horizontal axis turbines additionally require an orientation system depending on the wind direction [8]. In Figure 1.5. the turbine components are shown.

1.2.3. Standardization of wind system components

The creation of a mandatory technical legislative framework, to which researchers also contributed, was both a challenge and a necessity. Continuous product improvement and product quality assurance is a condition of existence on the market for wind system manufacturers.
Dynamic aspects in the standardization of wind systems include: the design of systems for monitoring and measuring wind potentials, design of blades, design of support towers, design of power transmission systems, design of generators, supporting the introduction of new designs that bring high productivity.
In designing wind systems over the last few years, dedicated standards have been developed. For example, the IEC 61400 group of standards was adopted by our country under the name SR EN IEC 61400. For example, the 2019 SR EN 61400 -1 standard addresses "essential design requirements to ensure the structural integrity of wind turbines. Its purpose is to provide an adequate level of protection against damage caused by all hazards over the planned lifetime. The document covers all wind turbine subsystems such as: control and protection functions, internal electrical systems, mechanical systems and support structures. This document applies to wind turbines of all sizes. For small wind turbines, IEC 61400-2 may apply. IEC 61400-3-1 provides additional requirements for offshore wind turbine installations". This group of standards can be harmonized with the dedicated IEC and ISO Standards [23].

1.2.4. Reliability of wind systems

Reliability is a characteristic that aims at two concepts, namely, one qualitative (if it exists) and the second quantitative (how much it exists), both of which being correlated when analysing them with other aspects that influence them (indicators, parameters, conditions, etc.) [41] .
The qualitative aspect of reliability refers to the ability of a product (seen as an element, set of elements or system) to fulfil its intended use, in a determined period of time, given the specified conditions of use.
In the quantitative concept of reliability, elements of performance are introduced and it is seen as a probability of correct operation in a given period of time, under conditions well specified by the manufacturer.
In what concerns the study of the reliability of wind turbines, numerous researches have been done in different countries on their main components, but also on the regulation techniques as well as the environmental conditions in which they operate [19], [20]. Thus, the studies show concerns about improving performance, but the types of analyses and the data obtained were difficult to compare. In [50], indicators such as capacity factor, time availability, technical availability, energy availability, average downtime were analyzed. Collecting data from different users using these indicators have helped wind turbine manufacturers to improve their manufacturing technology and operational performance. Moreover, the current concerns for improving the reliability of turbines show that some of the problems have been removed and that in this context the reliability indicators pursued are also different [51]. In other studies, comparisons of the reliability of onshore and offshore systems are made on the main components and the results show that one of the important common causes that produce other major failures are bolted fastening systems that act on high forces [50].

1.2.6. Connecting wind turbines to the grid

Due to variations in the primary energy source, wind power generation systems raise quality issues (harmonics, frequency drop) when connected to the grid. For this reason, studies were made to reduce these problems. Thus, Sava et al. [52] address the main challenges of connecting wind energy conversion systems (SCEEs) to the grid. Wind power plants with a capacity greater than 10MW must comply with the conditions imposed by the grid operator, which are similar to classic power plants. The network operator, through the RED technical code and Order no. 51/03.04.2009 ANRE for the approval of the technical norm "Technical conditions for connection to electrical grids of public interest for wind power plants", supplemented by ORDER no. 29 of May 17, 2013 and Order no. 208 of December 14, 2018, based on which regulations were established regarding operation in stable operating conditions and operation in dynamic conditions caused by network disturbances [45], [54].

In normal operation, duration is unlimited without active or reactive power reduction, frequency limits are within 50 Hz ±10%. The voltages delivered to the network cannot vary by more than ± 4% from the nominal value in the case of high and medium voltage networks and by ±5% of the nominal value in the case of low voltage networks. Another condition of connection to the network is given by the fulfilment of keeping the power factor at the following values by appropriate adjustments, namely minimum 0.95 inductive power factor and minimum 0.95 capacitive power factor. Also, the value of the regulated voltage must be at least 95% of the reactive power in 30s.

In the event of disturbances from the power grid, the wind farm must operate continuously at variable frequencies in the 47.5-52 Hz range to avoid even greater problems such as a drop in active power from the grid in the event of a plant disconnection. For this reason, wind power plants must be equipped with automatic active power control systems that take into account the frequency value, moreover, they will remain in operation when voltage variations and voltage gaps occur.

Wind power plants are controlled and monitored by SCADA systems. At powers greater than 5MW, the data is transmitted continuously to the network operator. An interface compatible with the SCADA system is used for data transmission and monitoring of network parameters. The monitored electrical quantities are minimum and maximum allowed values of frequency, electrical voltage, active power and reactive power. The position of the switching equipment at the demarcation point is also transmitted, the frequency depending on the power, the direction of the wind and its speed, the temperature of the environment and the atmospheric pressure are monitored.

In another study carried out by Nirosha in [55] the consequences arising from power supply problems in the case of wind systems are presented. These are: abnormal voltage values, increases or decreases, voltage gaps, short-term interruptions, long-term voltage variations, flicker, harmonics.

Considering the compliance with the technical connection norms, the reliability of wind systems remains a sensitive subject with quite a few issues still to be solved. Standardization, a good design, optimal maintenance, can reduce the problems that are caused, from a technical and legislative point of view, by the operation of wind power plants in national systems [56].

1.2.10. Mechanical systems for regulating the speed of the generator shaft

In order to increase the efficiency of variable speed wind turbines, systems have been developed over time that aim to correct the fluctuation of mechanical power that is due to variable wind speed. Thus, some systems include power electronics which in turn perform rectification and conversion leading to additional losses and have expensive control software leading to additional costs, while component semiconductor devices cause power quality problems to the grid [66]. Other technical solutions for power variation compensation propose eliminating the power converter and tying the generator directly to the grid [66] or using variable speed drive trains that include motors and hydraulic pumps that can be controlled. V-belt drives with two spring pulleys could be used for low power wind turbines. This mechanism adjusts the gear ratio corresponding to the torque applied to the drive pulley. If the springs are properly designed between the torque and the transmission ratio, a characteristic relationship is obtained that provides the necessary conditions for a good system operation.
Another proposed solution is to use a hybrid transmission that has two stages of planetary transmission which consists in the fact that the speed of the gear of the second stage is controlled by means of three synchronous machines, to allow the speed of the rotor to remain variable and the speed of the synchronous generator to remain constant.
The solution suggested by Zao et al. in [66] is the use of a variable speed drive train system, which proposes power sharing using a planetary transmission that is electrically controlled and two pairs of regulating gears. The transmission consists of three shafts, one at the input side which is connected to the turbine rotor and two at the output which are connected to the servomotor and the generator, as in figure 1.14.

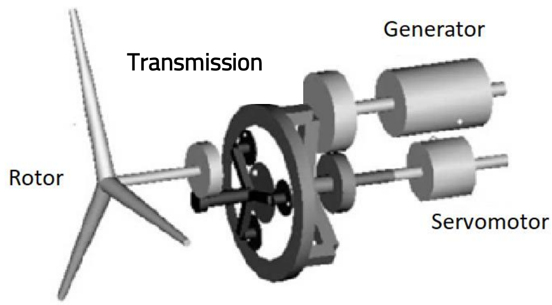


Fig.1.14. Power split device [66]

The authors analyze the efficiency of the system using two configurations for the transmission system showing that the system brings significant improvements to the overall efficiency and that grid connection issues are lessened.
In other fundamental researches [67] [68] speed boosters for wind and hydropower systems with direct current motors and counter-rotating electric generator are studied both with speed boosters in different configurations and without speed booster systems. The models made take into account the operating point characterized in stationary mode by external kinematic and static parameters. The analysis of these systems presents the advantage and disadvantage of each configuration. With respect to the general maintenance related to the overall costs of the wind systems, the speed booster brings important

additional costs. Therefore, finding solutions that optimally respond to the technical-economic challenges remains still to be solved.

1.2.11. Design of wind turbine with synchronous generator

The model analyzed in [70] has the role of simulating the dynamic behaviour of a 1.5 MW wind power plant. The model was simulated in Matlab / Simulink. The parts that make up the turbine-generator assembly shown in figure 1.15 are: the wind simulator, the turbine, the synchronous generator and a power inverter [70].

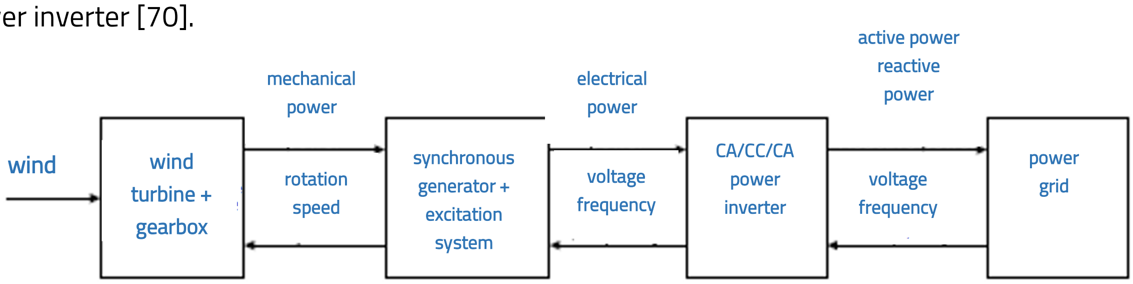


Fig.1.15. General structure of a wind turbine assembly with generator [70]

The wind turbine converts the kinetic energy of the wind flow simulator into mechanical energy. By means of a gearbox the turbine shaft rotates the generator rotor.

1.3. The synchronous machine

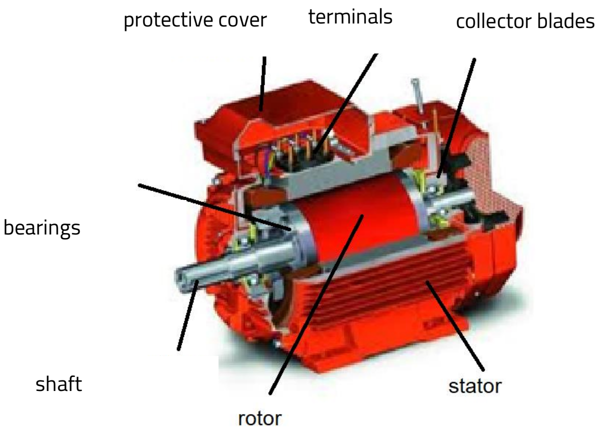


Fig.1.17. Main elements of the synchronous machine [71]

1.3.1. Generalities and definitions

The synchronous machine, by definition, is an alternating current machine. Its speed is constant, regardless of the operating mode (which is stabilized) and independent of the consumer's value (within normal limits). *The synchronous speed of the synchronous machine is related to the frequency of the alternating current network to which the machine is connected* [73].

In the synchronous machine, the speed of rotation of the rotor is in constant relation to the frequency of the electrical network to which it is connected, the inductive magnetic field being produced by the system of pole pairs of the excitation winding which is fed by direct current [74].

Thus, two operating modes of the synchronous machine are distinguished: the motor mode and the generator mode.
The basic mode for the operation of the synchronous machine is that of the electric generator, just as the motor mode is the basic mode for the asynchronous machine. The synchronous generator represents the economic basis of electricity production in current power plants. In their operation as a generator, synchronous machines reach high rated powers because the largest rotating electric machines built to date [77].

1.3.3. Types of excitation systems

- *with the exciter machine*, it is actually a direct current generator. It can be separately excited or shunt (self-excited). It can be connected to the same shaft of the synchronous generator (figure 1.21.a.). The method has its advantages which consist in the fact that the resulting constant excitation voltage does not depend on the network voltage. Problems occur at low speeds, with hydrogen generators that have larger dimensions of the excitations, as well as at high speeds, in the case of turbo-generators where limitations may occur due to commutation (sparking at the brushes). These characteristics limit the power of DC exciters. at approximately 500 kW;

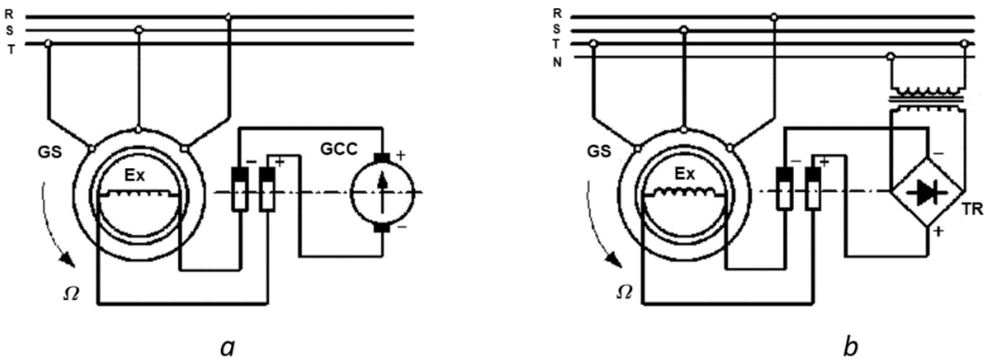


Fig.1.21. Types of excitation systems [77]

- *with static excitation* (figure 1.21.b), it is in fact a rectifier bridge that rectifies an AC stator phase, the rotor in this case being fed from the rectifier through the sliding brushes. In this way, the disadvantage of using electric machines that have inertia of moving masses as well as wear and tear over time is eliminated. Static excitation systems are efficient, simple, safe to operate and with minimal maintenance.
- *with brushless exciter machines* (figure 1.22.). In this case, the synchronous generator is inverted. The inductor of the GS main generator and the armature (rotor) of the synchronous generator of excitation GS_e are assembled "next", on the common rotor being mounted on two disks the diodes that make up the rotating rectifier. The connections of the rectifier with the excitation coil become fixed, thus renouncing to the brush system [77].

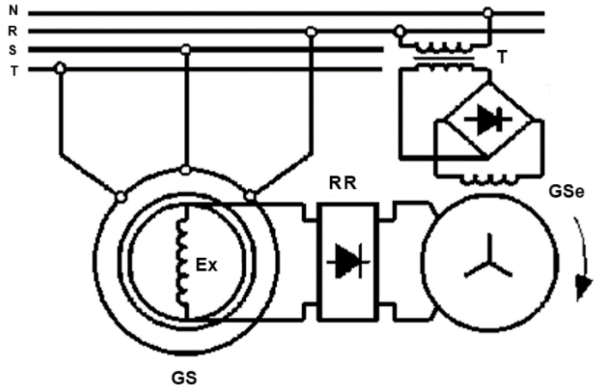


Fig.1.22. Synchronous system with brushless exciter machine [77]

1.3.8. Synchronous generator

The three-phase synchronous generator has convenient characteristics for the production of alternating current electricity representing the only solution generally accepted by the designers of power plants and power systems.

The production of electricity can be achieved by means of turbo generators, hydrogen generators, respectively wind turbines.

Turbo generators are driven by steam turbines, gas turbines or diesel engines and operate at high speeds, n_0=(1500-3000) rpm. They have a small number of poles, the rotor ones being drowned poles (the rotor is a cylindrical monoblock, equipped with rotor notches), that is, a constant air gap is ensured, and the shaft is horizontal.

Hydro generators have a hydraulic turbine as their primary machine, the speed in this case is of the order of hundreds of revolutions per minute, and the number of poles is higher. They have protruding rotor poles and the air gap is no longer constant along the inner circumference of the stator. The shaft is usually vertical. [77]

The wind turbine is a machine that converts the kinetic energy of the wind into mechanical energy. If the mechanical energy is subsequently converted into electricity, then the machine is called a wind generator, wind turbine or wind energy converter [78].

The three-phase alternating current synchronous generator is an electric machine, which converts mechanical energy into three-phase alternating current electrical energy.

It has the same similar construction as the single-phase alternating current generator, except that it has three coils wound on the stator, with similar parameters, spatially offset from each other by 120°.

The terminal box of a synchronous machine generally has eight terminals, of which: six for the stator windings and two for the excitation rotor winding.

The three stator windings are isolated both from each other and from the stator of the machine where they are located, we call them phases and generally have the ends of the coils marked as follows:

– the beginning ends of the phases with U1, V1, W1 or A, B, C;

– the ends of the phases are marked with U2, V2, W2 or X, Y, Z.

The construction of a three-phase synchronous generator is represented by a cross-section of the electric machine, which section is represented in figure 1.35.

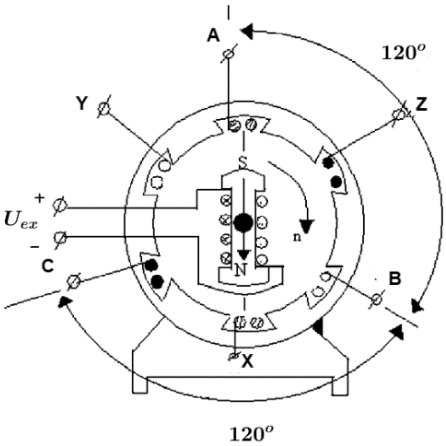


Fig.1.35. Cross section through the three-phase synchronous generator [79]

In figure 1.35., the hatched conductors represent phase A, the white ones represent phase B, and the black ones represent phase C. The coils of the stator windings are placed in such a way that starting from the beginning of the winding of phase A and up to the beginning of the winding of phase B, be a 120° phase lag, leading identically between the beginning of the phase B winding and the beginning of the phase C winding.

Taking into account these constructional peculiarities, it results that the operation of the synchronous generator, compared to the a.c. single-phase, differs in that at the output three voltages are obtained out of phase with each other by an angle at 120°, of alternating current.

1.4. Conclusions and objectives

Current legislation provides new regulations on reducing the use of fossil fuels. In this context, the European Union has developed directives related to the increase of electricity production from renewable sources and established precise objectives. Each country, taking into account the European legislative packages, has developed its own energy strategy. In the context of the crisis caused by the war in Ukraine, some targets have been modified especially due to the increase in the prices of both fuel and methane gas and electricity.

This situation with major economic implications causes governments to look for solutions in a much shorter time. On the other hand, the commission's report highlights the vulnerabilities that appear due to national legislation and its own initial recommendations. The report shows that the share of renewable energies relative to availability can be greatly improved in implementation and that this could be accelerated through legislative adjustments and the use of public and private funds. Regarding Romania's targets, the percentage of 30% allocated to the increase in electricity production from renewable sources is a bold one but not impossible to achieve in the conditions in which hydrographic and solar profiles are fluctuating and depend on weather conditions. Globally, the production of wind turbines of all capacities and types has increased due to the growing demand from consumers. In parallel with the implementation and connection of the new consumers to the network, aspects related to quality, reliability, safety in operation, connection to the network, energy storage, etc., were regulated through standardization and regulations. The concerns of researchers and manufacturers have mainly focused on increasing the energy density on the surface. This leads to concerns related to the improvement of the elements involved in the capture of wind energy, the improvement of the sub-assemblies involved in the transmission of motion and rotational speed to the shaft, the improvement of the blade control systems, the optimized design of the wind turbine-generator assembly, the improvement of the support towers, the increase in the reliability of the components of the wind systems, the design of the connection systems to the national grid, and of the storage systems.

All these aspects lead to new limits, new challenges, new problems to be solved that have to be faced. It is estimated that in the future, with the introduction of an increased number of renewable electricity producers into the network, quality issues will arise that must be carefully managed so that the safe supply of all consumers is not affected.

In order to highlight the characteristics of the synchronous machine, the synchronous machine with its characteristics has been dealt with, detailing the synchronous motor with its characteristics and the synchronous generator where their most important aspects have been highlighted.

In today's power generation applications, synchronous generators are used in all wind systems as well as hydroelectric power plants.

It starts from the consideration that the synchronous machine is an alternating current machine whose speed is constant, regardless of the operating mode (stabilized) and regardless of the load value (within normal limits). *The speed is that of synchronism and is rigorously linked to the frequency f of the alternating current network to which the machine is connected* [73].

The synchronous machine is characterized by the fact that the speed of rotation *n* of the rotor is found in constant relation to the frequency of the network to which it is connected, and the inductive magnetic field is produced by a system of pole pairs whose excitation winding is supplied with direct current [75]. It can operate in generator mode or motor mode.

The construction types of synchronous machines, with apparent poles or sunken poles, were highlighted, as well as the differences among them. Their characteristics were exemplified.

The peculiarity of this machine is related to the fact that the stator winding has three coils that can be supplied with a three-phase system of voltages if the synchronous machine operates in motor mode or can discharge three-phase voltages in the network if it operates as a generator. In both situations, the rotor winding must be supplied from a direct current source with a voltage called excitation voltage. Depending on how this voltage is supplied, there are connection variants that differentiate the assembly of the synchronous machine.

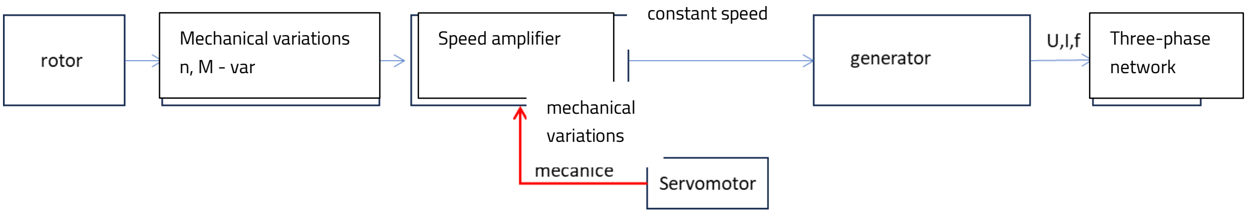
The operating equations of the synchronous machine highlight the variability of the excitation current and voltage that is used in starting, controlling and monitoring this electrical machine.

The most important aspect of the synchronous motor is related to the fact that it is used in widespread applications, generally in industry, in situations where we need high torques at low speeds. If not long ago there were problems related to starting them, recent applications with frequency inverters and automation systems solve these aspects.

The synchronous generator is treated as the operating mode of the synchronous machine. Their mechanical and electrical characteristics highlight the role of excitation current in the control of this machine. The design of the synchronous generator shows the role of the stator winding with their coils phase-shifted by 120 degrees.

Finally, it is highlighted that, in order to control the variability of the mechanical parameters of the synchronous machine, its characteristics must be controlled and compensated in the regulation of the excitation current and voltage. That is why it was considered, that for a research in the proposed field, it is important to study these characteristics both in motor mode and in generator mode.

From the research carried out, presented in chapter 1.2.10, the study of variability at the rotor shaft is taken over by a mechanical transmission driven by a servomotor. It brings the mechanical system to the proper synchronizing speed of the generator. Its block diagram is presented in figure 1.40.



The proposed research, also stated in the objectives of the doctoral thesis, replaces the mechanical control system with an electrically controlled control system, by compensating the variations from the shaft with the help of a variable load resistance assembled in the rotor circuit, which allows the electronic control of the preservation of the parameters in the three-phase network, within certain variable limits of the generator speed. Thus, the block diagram of the system shown in figure 1.40, illustrated in figure 1.14 can be replaced by the system shown in figure 1.41., requiring lower costs, higher reliability and high precision.

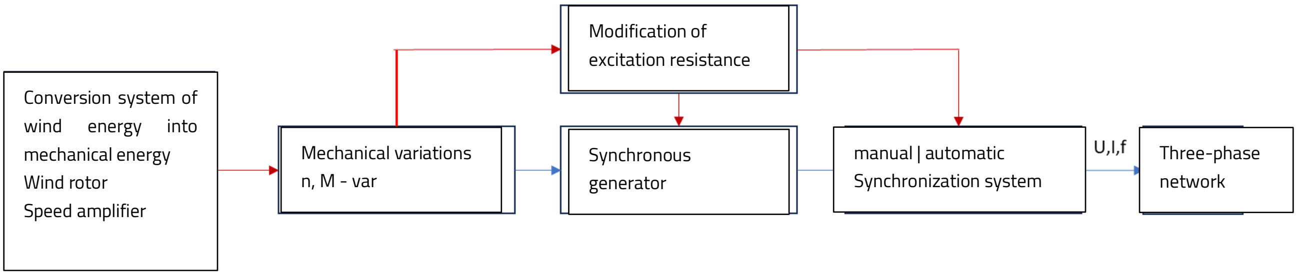


Fig.1.41. System block diagram of the system proposed for research

Objective of the doctoral thesis

The study of the electrical and mechanical parameters of the synchronous generator in order to support the nominal values provided in the national energy system, depending on the variation of the mechanical parameters of the wind rotor shaft.

Following the wording of the general objective of the doctoral thesis, the following specific objectives were formulated:

O1. Assemblies and methods for the study of the synchronous motor in order to identify solutions that can control and stabilize the speed according to the motor torque

O2. Assemblies and methods for the study of the synchronous generator in order to identify solutions that can control and stabilize electrical parameters according to accidental variations from the wind turbine shaft

O3. The substantiation of the synchronization procedure and the development of a stand used for the automatic regulation of the voltage charged by the synchronous generator in the case of the variation of the wind rotor speed

2. Research on the synchronous machine used as a motor

2.1. Introduction

The operating characteristic of the synchronous motor is defined by the equality between the rotating magnetic field and the rotational speed of the machine rotor. The speed of rotation, in stationary operating mode, depends on the frequency of the supply voltage of the alternating current network, on the number of poles of the respective rotating magnetic field of the excitation winding.

A characteristic element of the synchronous machine is the direct current supply to the excitation winding. Due to this fact the synchronous machine can operate at unity power factor. [82]

The main disadvantage of the synchronous motor consists in the fact that it develops electromagnetic torque only at the synchronism speed and in addition presents a rigid mechanical characteristic until the resisting torque reaches the maximum value of the electromagnetic torque, at which point the motor goes out of synchronism [82].

The mechanical characteristic is influenced by the electrical parameters of the synchronous machine. The excitation voltage and current of the synchronous machine changes the triggering value of the synchronous machine output. The rated current increases slightly with changes in the resistive torque until out of synchronism. The thesis presents experimental determinations for the nominal excitation current of the synchronous motor: $n= f(M_r)$, $I= f(M_r)$, $P_2= f(M_r)$, $\eta=f(M_r)$

The synchronous motor, due to its rigid mechanical characteristic, is currently used more and more in the actuation of working machines and mechatronic systems. The synchronous motor presents, compared to the other electric motors, the following advantages: the rotation speed does not depend on the load, the motor maintains its rotation speed constant; high power factor; high yield.

Among the main disadvantages of the synchronous motor can be cited: oscillations that can occur with sudden variations in load on the shaft, more complicated construction due to the exciter, higher cost price. In what concerns low-power drives, the starting schemes are more complex in the case of speed changes imposed by the technological process. Synchronous motors are currently preferred especially for driving work machines that require high power and constant working speed.

Since the speed of the synchronous motor does not vary with the load on its shaft, its mechanical characteristic is linear, and the slope of the characteristic defined by the derivative of the angular velocity in relation to the derivative of the moment is zero, figure 2.1.

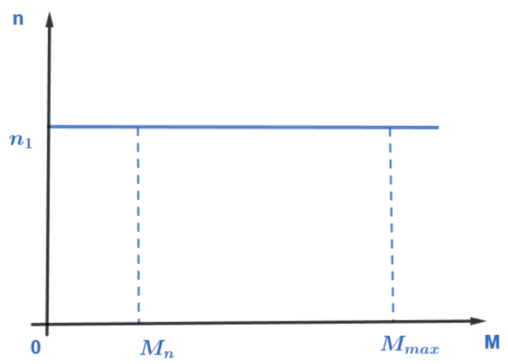


Fig.2.1. Mechanical characteristic of synchronous machine [86]

If a certain load torque value is exceeded, the motor goes out of synchronism and stops, although theoretically the torque value can be quite high . [86]

2.2. Experimental determinations on the mechanical and electrical characteristics of the synchronous motor

Choosing the type and power of an electric motor, its rational use, the possibility of speed adjustment, etc., requires studying the mechanical and electrical characteristics of the motor. Each motor type possesses several types of characteristics.

The stand in figure 2.3 is used to plot the mechanical and electrical characteristics of the motors. The basic electrical diagram is shown in figure 2.2. The stand has the following functional blocks in its structure:

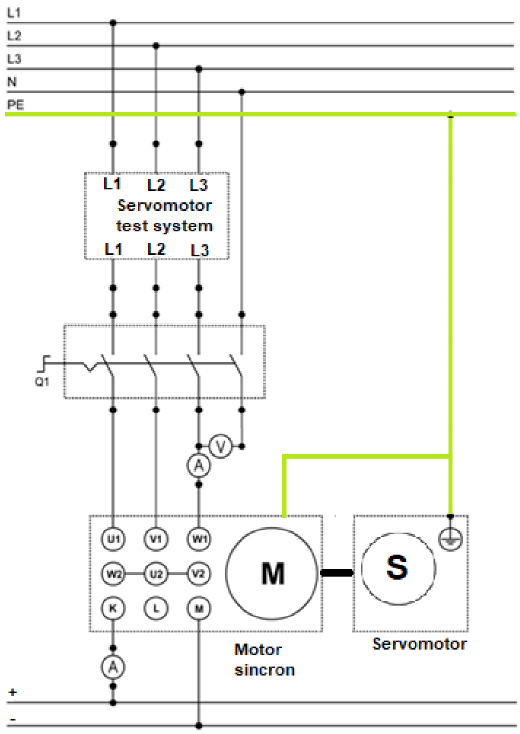


Fig.2.2. Basic diagram for establishing synchronous motor characteristics

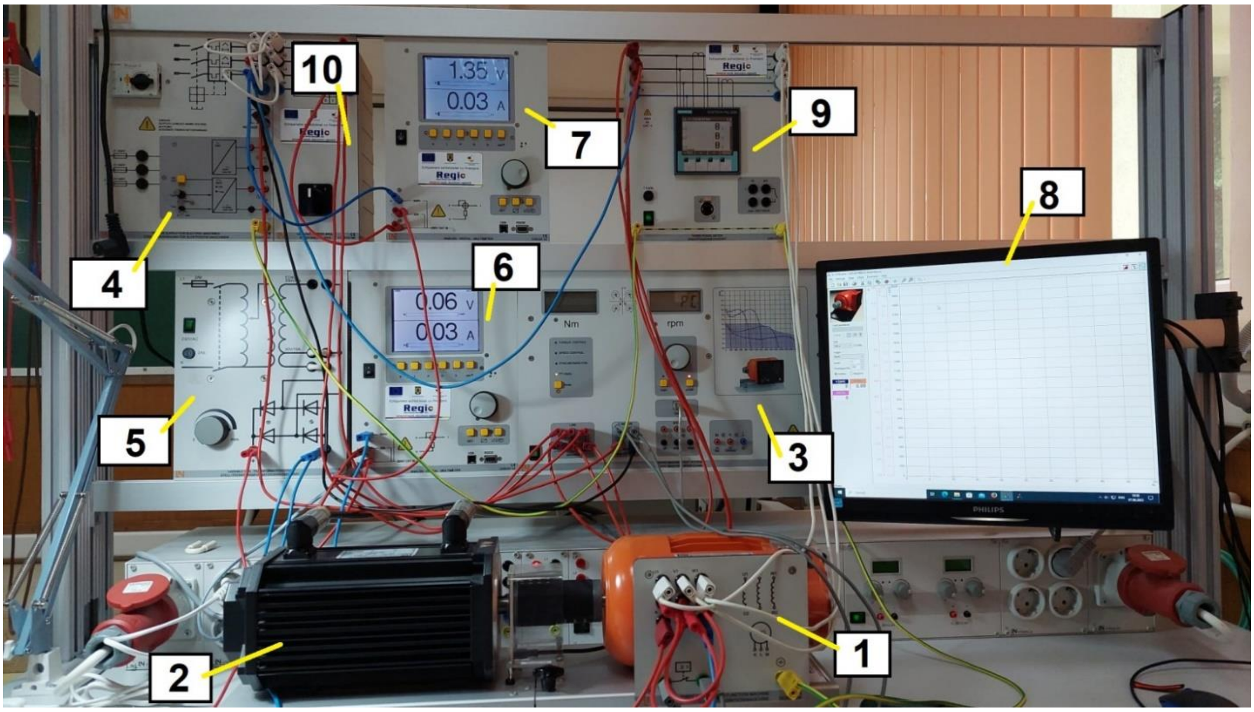


Fig.2.3. Stand for establishing the characteristics of electric machines

1- Synchronous machine;
2- Brake servomotor;
3- Servomotor controller;
4- Universal power supply with thermal protection for direct current and three-phase alternating current;
5- Autotransformer - for generating voltage and excitation current;
6- Analogue/digital multimeter, voltmeter, ammeter – for measuring current and excitation voltage;
7- Analogue/digital multimeter, voltmeter, ammeter – for measuring current and voltage in the stator winding;
8- ActiveServo software;
9- Digital multimeter for measuring three-phase parameters
10- Three-pole general switch with 2 positions.

The universal power supply (4) provides a three-phase alternating voltage of 400V to the stator winding of the synchronous machine, connected in star connection. The analogue/digital multimeter (6) measures the DC values of the excitation current and voltage variably delivered by the autotransformer (5) on the rotor winding of the synchronous machine (1). The controller (3) communicates with the servomotor (2) via the dedicated ActiveServo software (8). The synchronous machine is connected to the network through the main switch (10), after which voltage and excitation current are generated on the rotor winding. The voltage and current of the entire system are monitored by the analogue/digital multimeter (7). [80]

2.3. Establishing parameters to determine the characteristics of the synchronous motor

The servomotor used to determine the experimental values is part of a complete test system consisting of: digital controller, a servomotor with brake and a dedicated software: ActiveServo. The system allows electric motors to be braked at predefined torque points, nominal values to be displayed in time charts, and generators to be synchronized manually and automatically.

The servomotor of the stand allows the simulation of different resistance moments for the synchronous motor through the controller. The controller transmits the command quantity to the synchronous motor after comparing the reference quantities with those transmitted by the moment sensor within the servomotor-synchronous motor mechanical transmission. The reference values are imposed by the test programme, complying with the purpose for which the determination of the various operating characteristics of the synchronous motor takes place. The servomotor through the mechanism, mechanically coupled to the shaft, executes the test programme established by the imposed command quantities.
The servo motor has the following characteristics from a construction and functional point of view: [81]

- speed adjustment within very wide limits;
- the generated mechanical characteristics are linear;
- high starting torque;
- high overload capacity;
- reduced electromechanical time constant;
- protection against autostart;
- small gauge and specific weight, etc.;
- absence of autostart, etc.

The brake servomotor is a resolver-type self-cooling asynchronous motor. It has thermal monitoring and, in conjunction with the controller, constitutes a monitoring and braking system that does not require calibration. The technical parameters of the servomotor are:

- Max. speed: 4000rpm;
- Max. torque: 10Nm;

Temperature monitoring: continuous temperature sensor (KTY);
Resolver resolution: 65536 pulses/revolution.
The controller within the actuation and control system has the role of generating the resistant moments imposed on the studied characteristic. The controller has the following technical characteristics:

- Dynamic and static operation in the four quadrants;
- 10 selectable operating modes / car models;
- Integrated galvanic isolated amplifier system for voltage and current measurement;
- Displays values of speed and torque;
- Monitor with four quadrants;
- USB interface;
- Thermal monitoring of the electric car;
- Testing the presence of a protective cover on the shaft;
- Connection voltage: 320 ... 528V, 45 ... 65Hz;
- Maximum output power: 3kVA.

ActiveServo software is a programme for monitoring and recording the characteristics of electric machines to determine static and dynamic operating points. Simulates seven different loads (flywheel, pump, calender, lift drive, compressor, rotational speeds, configurable time-dependent load) for which parameters can be configured individually.

2.4. Determination of the mechanical and electrical characteristics of the synchronous motor

For the experimental determinations, carried out in order to study the characteristics, a synchronous motor with the following characteristics was used: Pn=0.27kW, In=1.5A, f=50Hz, n=1500rot/min, Ue_{rr}=20Vcc; Ie_{rr}=4A. The excitation source generated a step voltage from 0-20 Vdc at imposed excitation current values of 0.5A, 1A, 1.5A, 2A, 2.5A, 3A. The motor was braked in 30 steps of torque values.
For example, the representation of the data obtained after the application of an excitation current of Ie_{rr}=3A was chosen.

2.4.6. Determination of the mechanical and electrical characteristics of the synchronous motor for Ie_{rr}=3A

Following the determinations made, the following characteristics were obtained for Ie_{rr}=3A:
n=f(M), represented in figure 2.39, Table 2.36.
I=f(M), represented in figure 2.40, Table 2.37.
P1=f(M), represented in figure 2.41, Table 2.38.
P2=f(M), represented in figure 2.42, Table 2.39.
cos φ =f(M), represented in figure 2.43, Table 2.40.
η=f(M), represented in figure 2.44, Table 2.41.

Characteristic n=f(M)

Table 2.36. Results obtained n=f(M) for Ie_{rr}=3A

n [rpm]	1507	1507	1506	1502	1501	1499	1498	1495	1498	1496	1497	1495
M [Nm]	0	0,09	0,18	0,27	0,37	0,46	0,55	0,65	0,74	0,83	0,93	1,02
n [rpm]	1492	1494	1499	1492	1498	1493	1495	1487	504	503	501	499
M [Nm]	1,11	1,21	1,3	1,39	1,48	1,58	1,67	1,76	0,48	0,2	0,13	-0,27

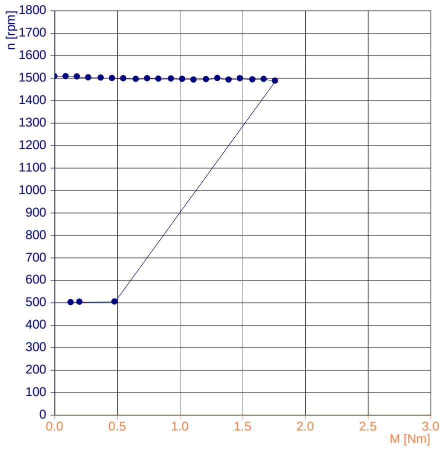


Fig.2.39. Representation of characteristic n=f(M) for Ie_{rr}=3A [87]

From the previous chart it can be seen that the engine speed is kept constant until the value of 1.76 Nm, after which it decreases and goes out of synchronism at the value of 0.48Nm.

Characteristic I=f(M)

Table 2.37. Results obtained I=f(M) for Ie_{rr}=3A

I [A]	0,11	0,12	0,13	0,15	0,16	0,17	0,19	0,21	0,23	0,26	0,28	0,30
M [Nm]	0	0,09	0,18	0,27	0,37	0,46	0,55	0,65	0,74	0,83	0,93	1,02
I [A]	0,33	0,36	0,38	0,41	0,44	0,47	0,50	0,53	0,20	0,13	0,13	0,04
M [Nm]	1,11	1,21	1,3	1,39	1,48	1,58	1,67	1,76	0,48	0,2	0,13	-0,27

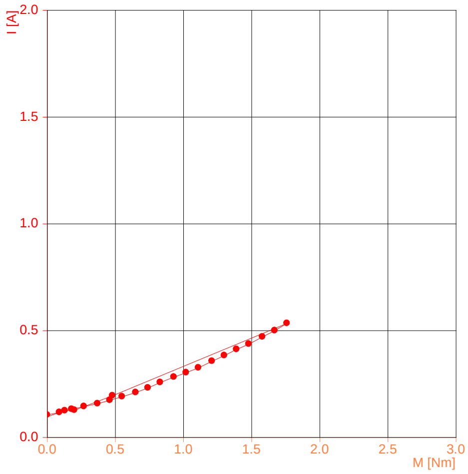


Fig.2.40. Representation of characteristic I=f(M) for Ie_{rr}=3A [87]

The analysis of the presented chart led to the conclusion that the intensity of the electric current in the rotor winding increases according to the increase in torque from the value of 0.11A to the value of 0.53A at 1.76 Nm, after which the motor goes out of synchronism.

Characteristic P_1=f(M)

Table 2.38. Results obtained **P_1=f(M)** for Ie_{rr}=3A

P_1 [W]	22,41	41,06	58,55	73,11	85,87	100,87	116,18	131,81	147,81	166,67	185,15	200,15
M [Nm]	0	0,09	0,18	0,27	0,37	0,46	0,55	0,65	0,74	0,83	0,93	1,02
P_1 [W]	216,06	238,45	257,26	277,13	293,81	316,70	336,14	360,56	107,40	33,43	36,17	2,23
M [Nm]	1,11	1,21	1,3	1,39	1,48	1,58	1,67	1,76	0,48	0,2	0,13	-0,27

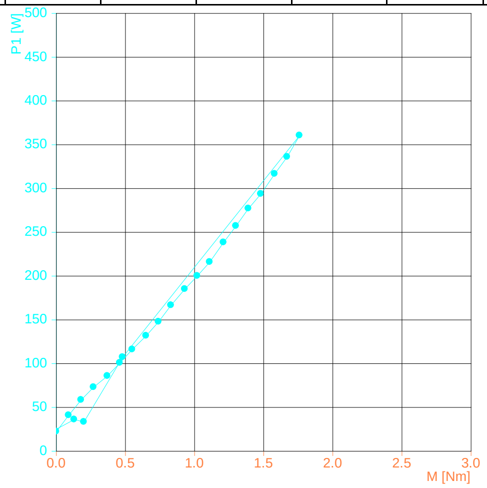


Fig.2.41. Representation of characteristic P_1=f(M) for Ie_{rr}=3A [87]

From the analysis of the obtained results, the following conclusion can be drawn: the active power increases depending on the torque values from 22.41W in nominal speed up to the value of 360.56W, after which the motor goes out of synchronism.

Characteristic P_2=f(M)

Table 2.39. Results obtained **P_2=f(M)** for Ie_{rr}=3A

P_2 [W]	0,00	14,20	28,39	42,47	58,16	72,21	86,28	101,76	116,08	130,03	145,79	159,69
M [Nm]	0	0,09	0,18	0,27	0,37	0,46	0,55	0,65	0,74	0,83	0,93	1,02
P_2 [W]	173,43	189,31	204,07	217,18	232,17	247,03	261,45	274,06	25,33	10,53	6,82	-14,11
M [Nm]	1,11	1,21	1,3	1,39	1,48	1,58	1,67	1,76	0,48	0,2	0,13	-0,27

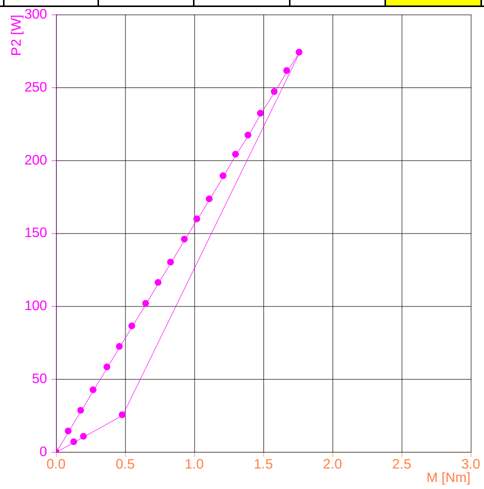


Fig.2.42. Representation of characteristic P_2=f(M) for Ie_{rr}=3A [87]

From the chart presented in figure 2.42. it is observed that the mechanical power at the shaft increases proportionally with the increase of the motor torque from the value 0 to the value of 274.06W for the torque of 1.76Nm, after which it goes out of synchronism

Characteristic cos φ=f(M)

Table 2.40. Results obtained **cos φ =f(M)** for Ie_{rr}=3A

cos φ	0,30	0,50	0,63	0,72	0,77	0,83	0,87	0,90	0,91	0,93	0,94	0,95
M [Nm]	0	0,09	0,18	0,27	0,37	0,46	0,55	0,65	0,74	0,83	0,93	1,02
cos φ	0,95	0,96	0,96	0,96	0,96	0,96	0,96	0,96	0,78	0,37	0,41	0,08
M [Nm]	1,11	1,21	1,3	1,39	1,48	1,58	1,67	1,76	0,48	0,2	0,13	-0,27

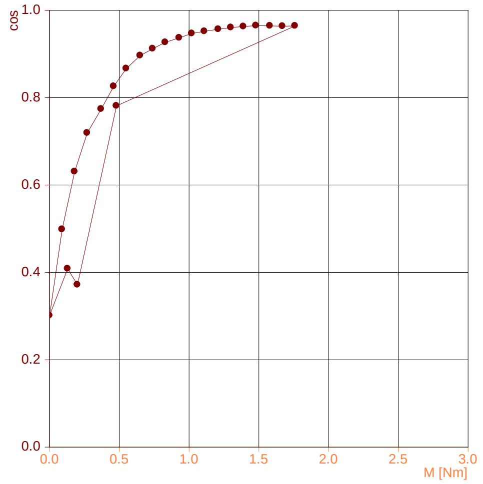


Fig.2.43. Representation of characteristic cos φ=f(M) for Ie_{rr}=3A [87]

Analyzing figure 2.43, it can be seen that the cosine of the phase shift angle between voltage and current has an increasing value up to the value of 0.96 for a torque of 1.76Nm, after which it decreases until the out of synchronism.

Characteristic η=f(M)

Table 2.41. Results obtained **η=f(M)** for Ie_{rr}=3A

***η* [%]**	0,00	34,59	48,48	58,09	67,73	71,58	74,26	77,20	78,54	78,02	78,74	79,78
M [Nm]	0	0,09	0,18	0,27	0,37	0,46	0,55	0,65	0,74	0,83	0,93	1,02
***η* [%]**	80,27	79,39	79,32	78,37	79,02	78,00	77,78	76,01	23,59	31,52	18,85	0,00
M [Nm]	1,11	1,21	1,3	1,39	1,48	1,58	1,67	1,76	0,48	0,2	0,13	-0,27

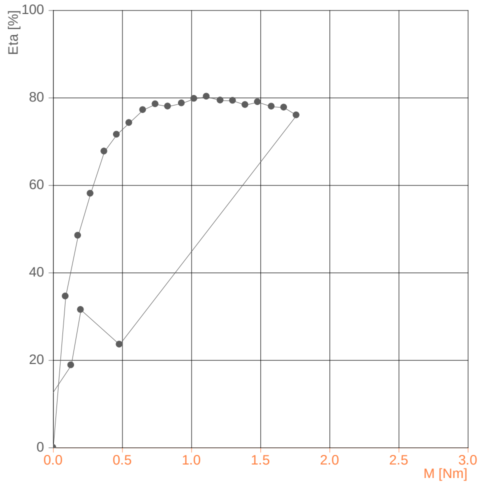


Fig.2.44. Representation of characteristic η=f(M) for Ie_{rr}=3A [87]

In figure 2.44. it is observed how the efficiency increases in the first steps from the value 0 to 79.39 % after which it remains relatively constant and decreases due to the exit from synchronism.

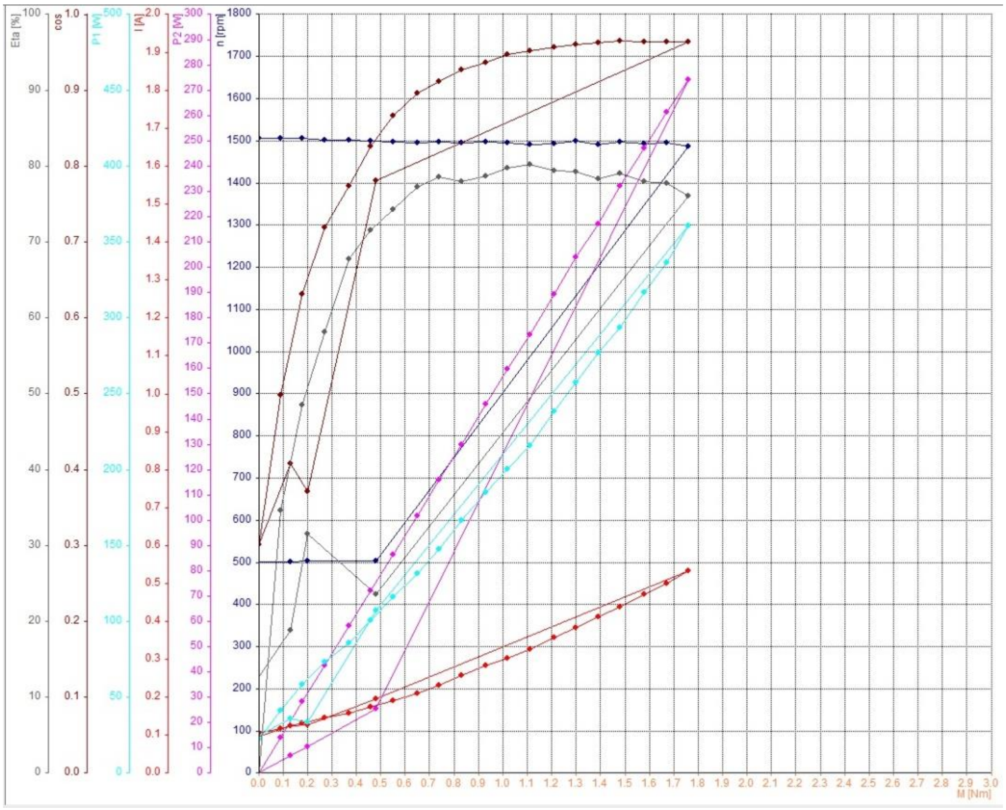


Fig.2.45. Representation of characteristics for Ie_{rr}=3A [87]

Changing the value of the excitation current to the value of 3A, it is practically observed that the synchronous machine maintains its synchronism speed at a successive loading of the moment, up to 1.76 Nm when it destabilizes and goes out of synchronism. It destabilizes up to a speed of 1487 rpm, after which it stops.

The value of the nominal current increases gradually, up to 1.76Nm. A decrease in the value of the nominal current is observed due to the increase in the value of the excitation current. The mechanical power has a linear increase, directly proportional to the increase in torque, up to the value of 1.76Nm when exiting the synchronism. The active power instead increases with the increase of the rated current up to the value of 360.56W after which it stops. Compared to the previous value of the excitation current, due to the decrease in the intensity of the current, the exit from synchronism is made at lower values of the active power.

The yield is influenced by the value of the torque, the curve is relatively linear, it has the maximum value of 79.32% at a torque of 1.3Nm, after which it decreases slightly compared to the increase of the torque. It is practically observed that the synchronous machine maintains its synchronous speed at successive torque loading up to 1.76 Nm when it destabilizes and goes out of synchronism. It destabilizes up to a speed of 1487 rpm, after which it stops. The cosine of the dephasing angle maintains its increasing trend up to the value of 0.96Nm after this value the motor goes out of synchronism.

2.4.7. Analysis of mechanical and electrical characteristics for increasing values of the excitation current

This sub-chapter proposes the charts for mechanical and electrical characteristics for increasing values of the excitation current from 0.5 A to 3 A

Following the determinations made, for Ie_{rr}=0.5A - 3A the characteristics were obtained:

n=f(M), represented in figure 2.46.

I=f(M), represented in figure 2.47.

P_1=f(M), represented in figure 2.48.

P_2=f(M), represented in figure 2.49.

cos φ =f(M), represented in figure 2.50.

η=f(M), represented in figure 2.51.

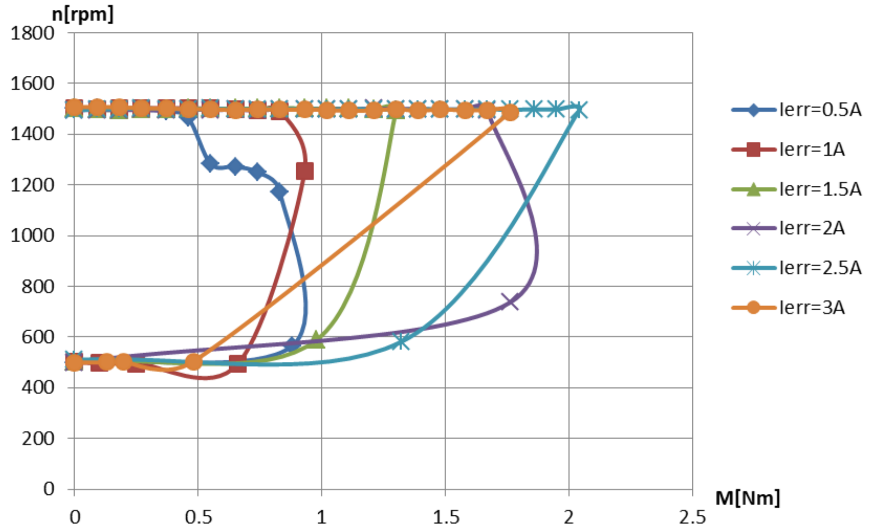


Fig.2.46. Characteristics n=f(M) for increasing values of the excitation current

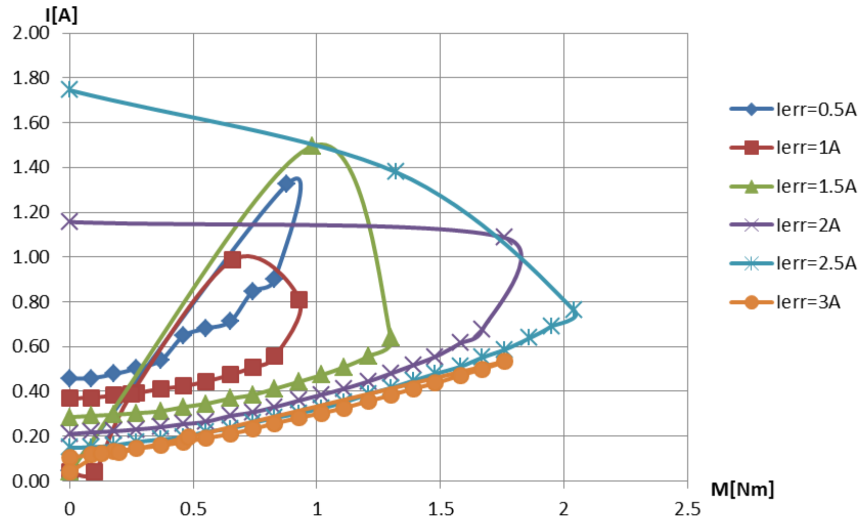


Fig.2.47. Characteristics I=f(M) for increasing values of the excitation current

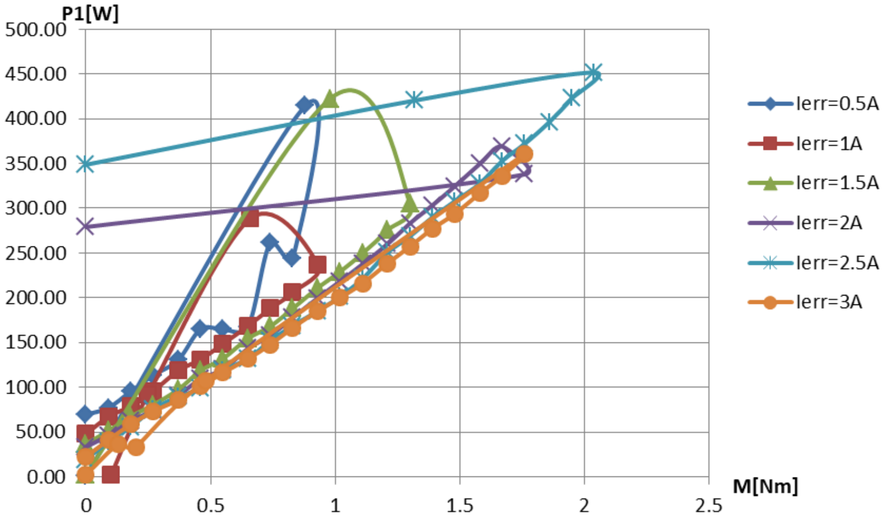


Fig.2.48. Characteristics P_1=f(M) for increasing values of the excitation current

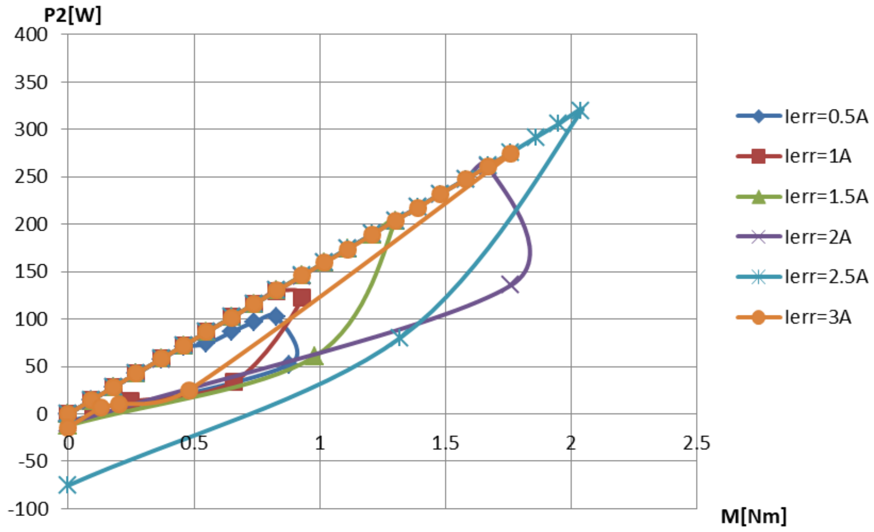


Fig.2.49. Characteristics P_2=f(M) for increasing values of the excitation current

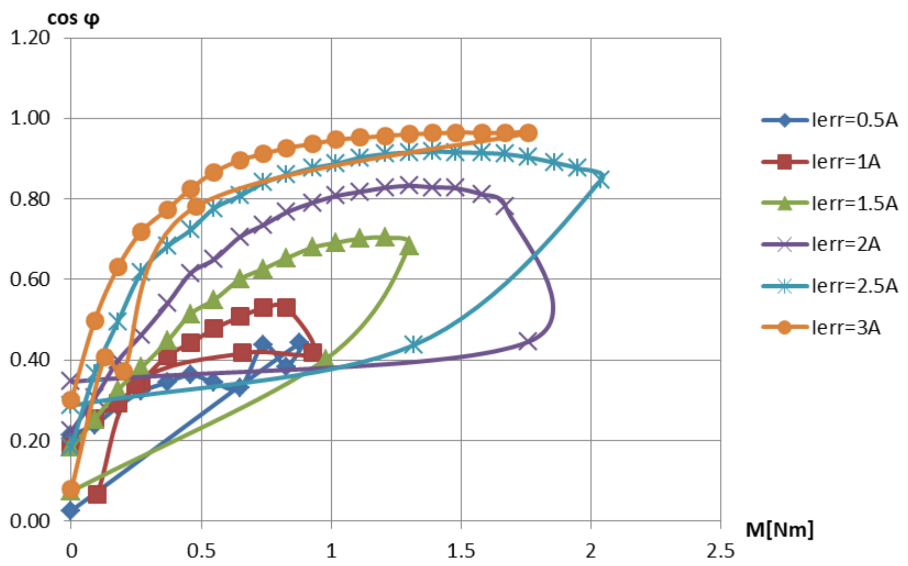


Fig.2.50. Characteristics cos φ =f(M) for increasing values of the excitation current

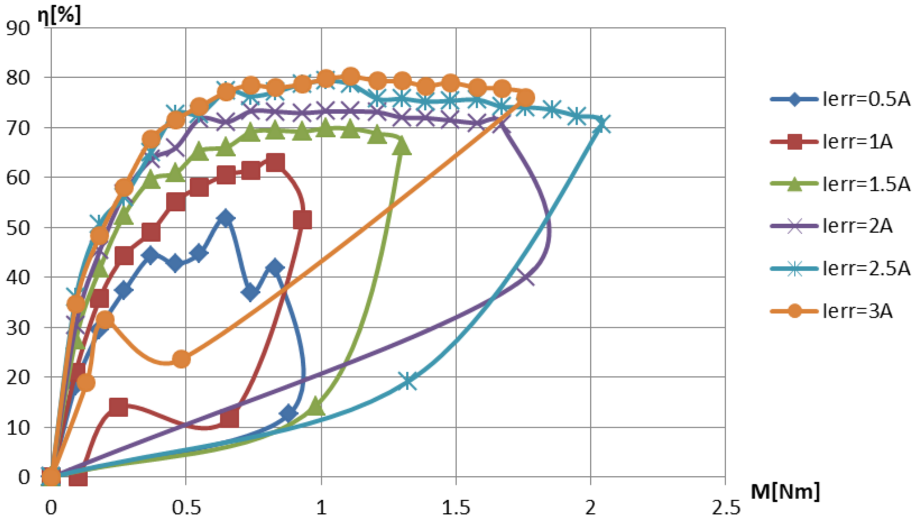


Fig.2.51. Characteristics η=f(M) for increasing values of the excitation current

2.5. Mechanical and electrical characteristics over time for increasing imposed values of motor torque

For the experimental determinations, carried out in order to study the characteristics, a synchronous motor with the following characteristics was used: Pn=0.27kW, In=1.5A, f=50Hz, n=1500rot/min, Ue_{rr}=20Vcc; Ie_{rr} = 4A. The excitation source generated a gradual voltage from 0-20 Vcc at imposed excitation current values of 0.5A, 1A, 1.5A, 2A, 2.5A, 3A. The stand used to determine the characteristics is shown in figure 2.3.

For the studied synchronous motor, the time dependence of the following quantities will be observed

- The intensity of the electric current in the rotor circuit, I[A]
- Motor torque M[Nm]
- Speed n[rpm]

The motor is brought to synchronism speed for 5 values of the excitation current, between 0.5 and 3A with a step of 0.5 A. By programming we imposed the following torque characteristic:

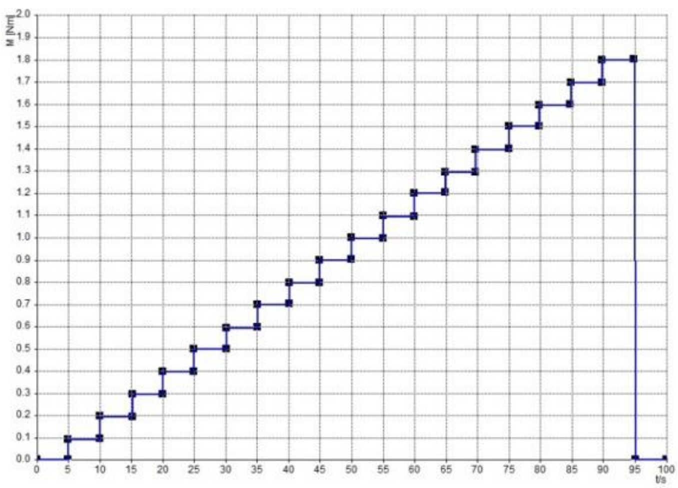


Fig.2.52. Torque diagram

For 100s, the torque diagram was drawn so that for 1 step=0.1Nm, motor braking starts from 5s to 95s. At this value, the motor will be braked with 1.8 Nm.

For example, the graphic representation for a current of 3A was chosen.

2.5.6. Mechanical and electrical characteristics over time for increasing imposed values of motor torque for Ie_{rr}=3A

This stage proposes to raise the mechanical and electrical characteristics dependent on time for increasing imposed values of motor torque for Ie_{rr}=3A. [90]

Table 2.48. Results obtained for increasing imposed values of motor torque at an excitation current of Ie_{rr}=3A

t[s]	n [rpm]	M[Nm]	I [A]
0	1498	0.01	0.09
10	1491	0.19	0.11
20	1493	0.39	0.14
30	1504	0.6	0.18
40	1504	0.81	0.24
50	1502	0.89	0.26
60	1502	1.21	0.35
70	1504	1.38	0.42
80	1501	1.58	0.48
90	1497	1.81	0.54
92	1497	1,8	0,55
94	1498	1,81	0,55

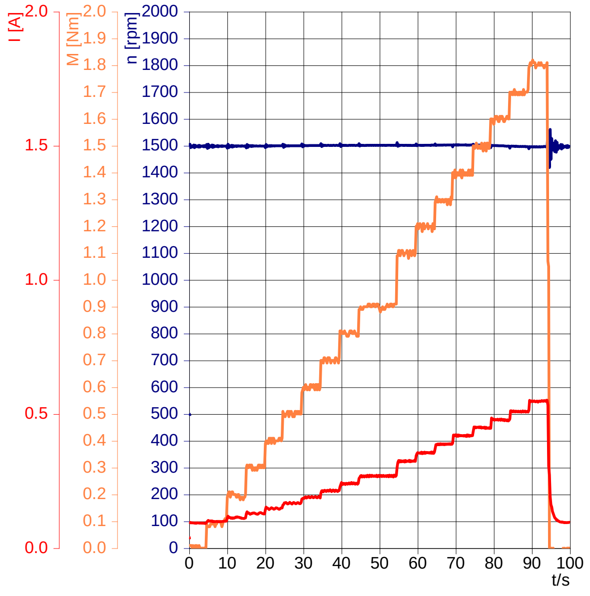


Fig.2.58. Representation of characteristic for Ie_{rr}=3A [90]

From the previous figure it results that the intensity of the electric current increases with the imposed torque curve up to 94s. After this value, because the speed destabilizes, the current value increases unstably up to 0.55A, after which it goes out of synchronism at a motor torque of 1.81Nm.
The speed remains constant until 94s at 1.81 Nm, after which it destabilizes and at the value of 1498 rpm it goes out of sync and the engine stops.

2.6. Mechanical and electrical characteristics over time for variable imposed values of motor torque

For the studied synchronous motor, the time dependence of the following quantities is observed
- Intensity of the electric current in the rotor circuit, I[A]
- Mechanical power at shaft P2[W]
- Motor torque M[Nm]
- Speed n[rpm]

The motor is brought to synchronism speed for 5 values of the excitation current Ie_{rr}, between 0.5 and 3A with a step of 0.5 A. By programming a torque characteristic was imposed at which for 100 the torque diagram was drawn so that for variable values imposed from 0 to the maximum synchronism value, reduced and alternated with mechanical shocks until the return value to the nominal values.
For example, I chose to represent the diagram at a current of 3A.

2.6.6. Mechanical and electrical characteristics over time for variable imposed values of motor torque for Ie_{rr}=3A

[89] This subchapter aims to analyze, plot and represent mechanical and electrical characteristics dependent on time for variable imposed values of the motor torque for excitation current values of Ie_{rr}=3A. [89]

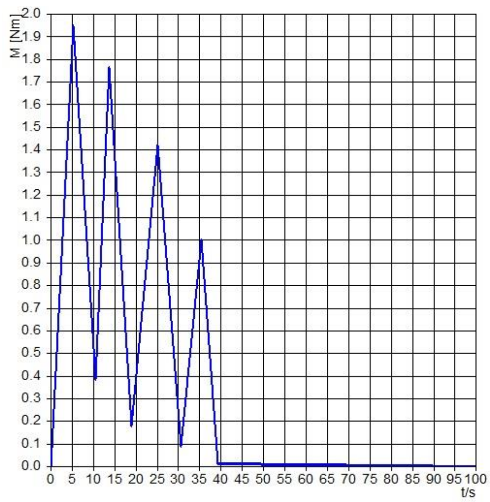


Fig.2.70. Variable imposed torque characteristic for Ie_{rr}=3 A [89]

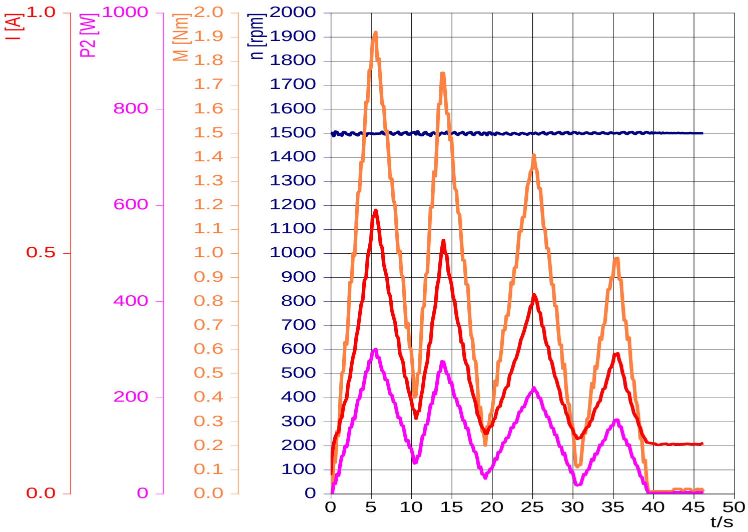


Fig.2.71. Mechanical and electrical characteristics for variations of torques over time at an excitation current of Ie_{rr}=3A [89]

In the torque variation analysis (figure 2.70), the maximum torque value was increased to 1.95Nm, so that it approaches the value of the synchronism output, the other torque variables were also increased, but the studied allure was preserved.
From the chart presented previously in figure 2.71, it can be seen that the speed is kept constant with alternating torque variations, if the increase or decrease of the torque is linearly increasing within 5 s. Also, when the excitation current increases, the speed variations are more flattened. The intensity of the electric current in the stator circuit maintains the imposed torque curve, as does the mechanical power at the motor shaft.

2.7. Mechanical and electrical characteristics of the synchronous motor at different torque variations over time

To represent the mechanical and electrical characteristics of the synchronous motor at different torque variations over time, an excitation current value of 3A was considered so as to verify the behaviour of the synchronous motor at higher values of synchronism output.
By imposing torque variations on the shaft of the synchronous machine, its behaviour in terms of speed was observed, since any wind variation on the shaft leads to speed and torque variations.
Four different torque characteristics are plotted to exemplify these aspects.
In the first part of this study, it was considered that the variations are of short duration, and they take place during 10 s, a jump of linear increasing or decreasing variation takes place for one second. The following torque characteristic resulted, shown in figure 2.72.

2.7.1. Variable imposed torque characteristic for Ie_{rr}=3 A, in 10s

This subchapter aims to analyze, establish and represent mechanical and electrical characteristics over time for variable imposed values of motor torque in 10 seconds, for excitation current values of Ie_{rr}=3A.

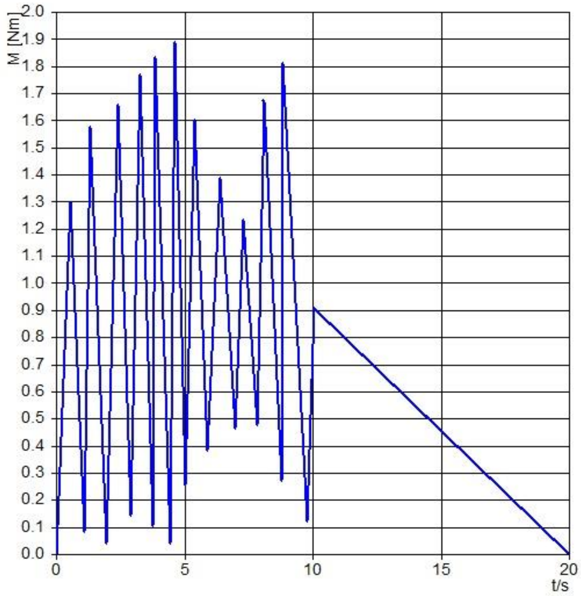


Fig.2.72. Variable imposed torque characteristic for Ie_{rr}=3 A, in 10s [90]

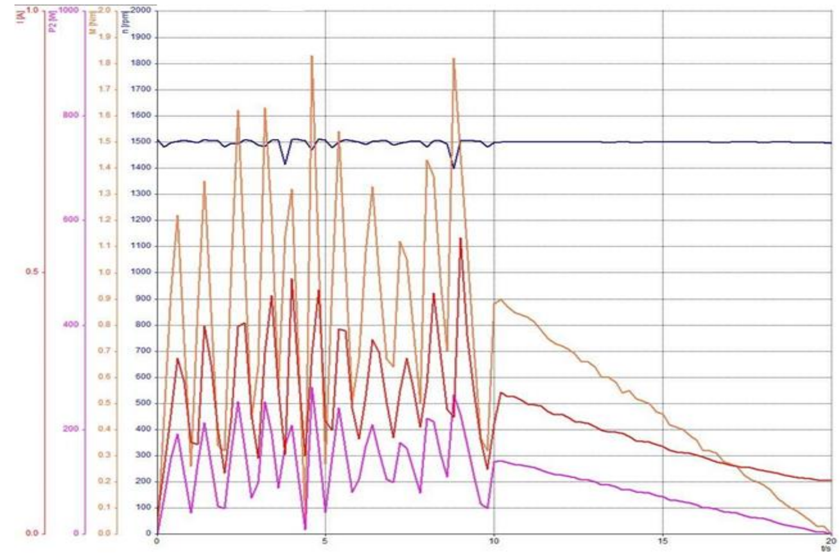


Fig.2.73 Mechanical and electrical characteristics for variable torques over time at an excitation current of Ie_{rr}=3A, in 10s [90]

From the analysis of the chart studied, presented in figure 2.73., it can be seen how the speed has small variations at linearly increasing and decreasing variable torques up to the value of 1.63 Nm. From this value the motor tends to desynchronize, especially at the sudden drop in motor torque. The speed has a variability and drops to 1400 rpm. On variations that return to lower torques, it returns to synchronism speed, but then, the speed variability returns to the sudden increase in torque to 1.8Nm.
That is why it was considered appropriate to study the behaviour of the synchronous motor at the same torque variations, but at a development in 50 s. In the extended thesis, this aspect is presented in chapter 2.7.2.

2.7.3. Imposed torque characteristic at sudden torque variations for Ie_{rr}=3 A, in 50s

Following the previously studied charts, the need to study how the synchronous motor behaves at sudden torque variations arose, because nature can be unpredictable and can accelerate or brake the motor shaft. The following torque characteristic was imposed, which looks like figure 2.76.

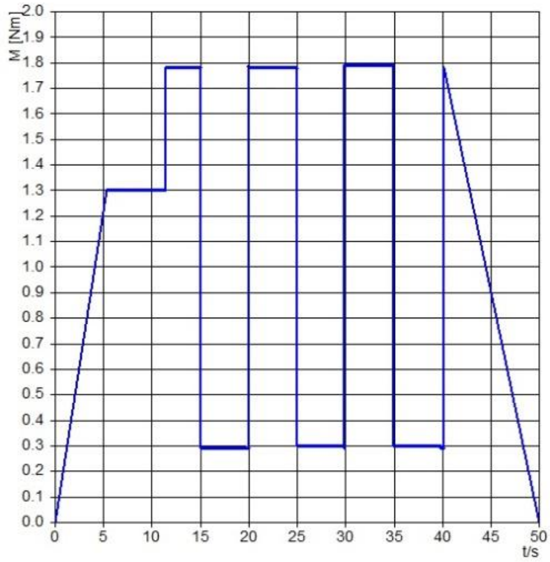


Fig.2.76. Imposed torque characteristic for Ie_{rr}=3 A, in 50s [90]

The motor was considered to start and have a linear increase in torque from 0 to 1.3Nm. It is kept at this value and after 7 s, the torque suddenly increases to 1.8Nm. After 4s it suddenly increases to 1.8Nm and after another 5s it suddenly decreases to 0.3Nm. After this value, the sudden increase and decrease of the torque values are maintained until 40s, after which it decreases linearly from 1.8Nm to 0Nm.

The following results were obtained:

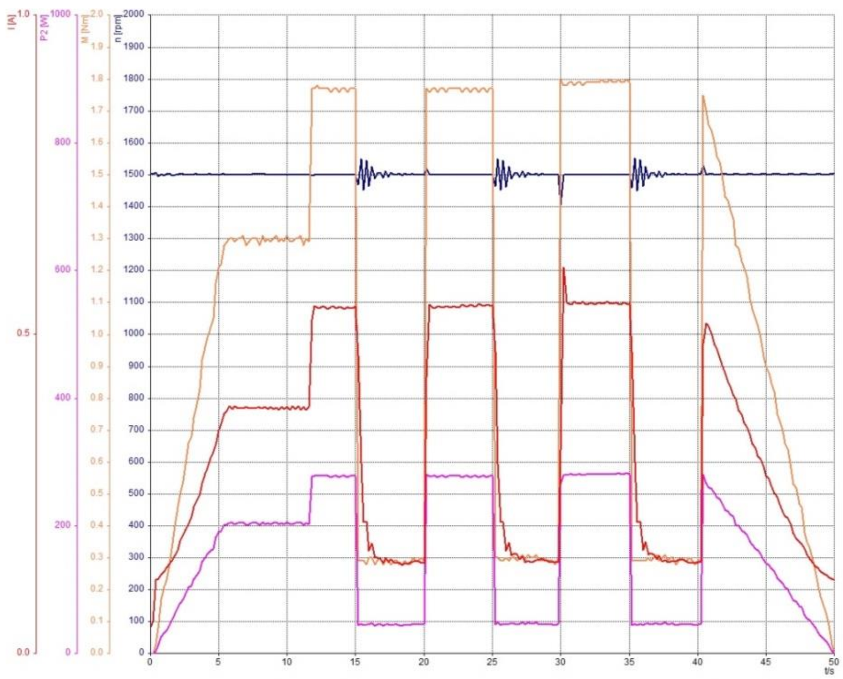


Fig.2.77 Mechanical and electrical characteristics for instantaneous variable torques over time at an excitation current of Ie_{rr}=3A, în 50s [90]

From the analysis of the characteristic presented in figure 2.77, it is observed how the speed is kept constant at the increase value up to 1.8Nm. Instead, there is a variability of the speed at the sudden decrease in torque, which is repeated with each decrease. The intensity of the electric current and the mechanical power keep the status of the torque. In conclusion, the motor desynchronizes slightly on sudden drops in torque, but does not go out of sync.

2.8. Conclusions

To represent the mechanical characteristics of the electrical and mechanical parameters depending on the motor torque, gradual values of the excitation current between 0.5A – 3A with a step of 0.5A were charged on the excitation stator winding.

From the analysis of the characteristics presented in this chapter, the following conclusions can be drawn:

- - From the analysis of the charts n=f(M) it results that the synchronous machine maintains its relatively constant speed of 1500rot/min according to the increasing values of the torque up to values out of synchronism. The value of the synchronism output directly depends on the value of the excitation current. The higher this is, the motor maintains its constant speed at higher torque values. Instead, the maximum value of the excitation current imposed by the rated values of the studied synchronous motor must not be exceeded.
- From the analysis of the charts *I=f(M)* it results that the value of the intensity of the electric current increases according to the increasing value of the mechanical torque at the shaft, but by changing the value of the excitation current in the sense of its increase, the motor absorbs a smaller current from the network. At out-of-synchronism values, the current increases suddenly for a short time after which the motor stops.
- From the analysis of the charts $P_2=f(M)$ it results that the mechanical power increases linearly over time according to the increase of the motor torque. By changing the value of the excitation current, the mechanical power increases at the shaft until it is out of synchronism. The maximum value of the mechanical power is obtained at the maximum value of the excitation current.
- From the analysis of the charts $\eta=f(M)$ it results that the yield has a linear increase up to half of the value of the torque imposed on the shaft, after which it stabilizes, it has a small variation until the exit from synchronism. It is observed that the maximum values of the yield are not obtained at the maximum values of the torque, they are obtained at values prior to them. Depending on the increasing values of the excitation current, the yield value increases, from 51.68% at Ie_{rr}=0.5A to 0.96% at Ie_{rr}=3A.
- From the analysis of the charts $P_1=f(M)$ it results that the active power increases linearly depending on the value of the torque in general up to values of 350W regardless of the value of the excitation current. At lower values of the excitation current, we had a small variability, at higher values the allure was almost linear.
- From the analysis of the charts $\cos \varphi=f(M)$ it results that at low values of the excitation current cos φ has maximum values starting from 0.43 which indicates a high consumption of reactive power. At the

maximum value of 3A cos φ reaches the value of 0.96, the consumption of reactive power being almost zero.

To establish the mechanical and electrical characteristics over time for increasing imposed values of the motor torque value, an imposed torque diagram was used, in which the motor is brought to synchronism speed for 5 values of the excitation current, between 0.5 and 3A with a step of 0.5 A, so that for 100 s the torque diagram was drawn at 1 step =0.1Nm to start the motor braking from 5 s to 95 s, at this value the motor being braked by 1.8 Nm.

For the studied synchronous motor, the time dependence of the following quantities was monitored

- The intensity of the electric current in the rotor circuit, I[A]

- Motor torque M[Nm]

- Speed n[rpm]

Analyzing the value of the current intensity in the rotor circuit, it is observed that it decreases for increasing values of the excitation current. If for Ie_{rr}=0.5A the maximum value of the current when exiting synchronism is 0.98A, for the value of Ie_{rr}=3A the motor exits synchronism at the value of 0.54A.

As in the case of the analysis of the torque characteristics, it is observed from the previous charts that although the torque increases successively, the motor speed is kept constant at the value of 1500rot/min until the out-of-synchronism value. It is observed that at Ie_{rr}=0.5A the motor goes out of synchronism after 45 seconds at 0.89 Nm while at the maximum studied value of Ie_{rr}=3A the motor goes out of synchronism at 95 seconds at the value of 1.81 Nm.

The charts express the fact that for a synchronous motor the value of the excitation current is very important to keep the speed constant according to the value of the torque. The out of synchronism is closely related to the maximum value of the torque but at the same time also to the value of the excitation current.

From the analysis of the chart presented in figure 2.61., for an excitation current of Ie_{rr}=0.5A, it is observed that the motor has constant speed at increasing values of the motor torque, but tends to desynchronize at higher values of the motor torque, but does not go out of synchronism. The speed returns to nominal values when the torque decreases. The intensity of the electrical current in the stator circuit maintains the imposed torque curve, as does the mechanical power at the motor shaft. Increasing the value of the excitation current by 0.5A, it is observed that the speed is kept constant with alternating torque variations, if the increase or decrease of the torque is linearly increasing within 5 s. The intensity of the electric current in the stator circuit keeps the imposed torque curve, as well as the mechanical power at the motor shaft.

For a current of Ie_{rr}=1.5A, the maximum value of the torque was increased to 1.2Nm, so as to approach the value of the synchronism output, the other torque variables were also increased, so as to keep the studied allure.

The speed is kept constant with alternating torque variations, if the torque increase or decrease is linearly increasing within 5s. The intensity of the electrical current in the stator circuit maintains the imposed torque curve, as does the mechanical power at the motor shaft.

From the torque variation analysis, from figure 2.69., it is observed that the maximum value of the torque has increased to 1.75Nm, so that it approaches the value of the synchronism output, the other torque variables have also increased, but the studied allure has been preserved. Also, when the excitation current increases, the speed variations are more flattened. The intensity of the electric current in the stator circuit maintains the imposed torque curve, as does the mechanical power at the motor shaft.

In the torque variation analysis, from figure 2.71. for an excitation current of Ie_{rr}=3A, the maximum value of the torque was increased to 1.95Nm, so that it approaches the value of the synchronism output, the other torque variables were also increased, but the studied allure was kept. From the chart, it can be seen that the speed is kept constant with alternating torque variations, if the increase or decrease of the torque is made linearly increasing within 5s limits. Also, when the excitation current increases, the speed variations are more flattened. The intensity of the electric current in the stator circuit maintains the imposed torque curve, as does the mechanical power at the motor shaft.

Analyzing the characteristics presented in figures 2.73. and 2.75. we can conclude that with linearly increasing and linearly decreasing variations, the synchronous motor keeps its constant speed around the nominal synchronism value, if the variations are for a time period greater than 2s. Conversely, if the same variations occur in a shorter time, the motor has an alternating speed, but does not desynchronize. In conclusion, the method by which the synchronous generator can withstand these variations in a short time, up to the synchronism output torque values, was studied and the torque characteristic in figure 2.74 was generated for studying this phenomenon.

Instead, from the last charts shown in figures 2.77. and 2.79. it is observed that with sudden torque variations, the motor desynchronizes easily, the speed variability being more consistent with torque drops, which decreases if the torque value on the motor shaft is lower. Therefore, in the studies of the synchronous generator, it will be pursued how the nominal characteristics of synchronism to the grid influence these forces acting on the motor shaft.

3. Research on the synchronous machine used as a generator

3.1. Introduction

In power plants, synchronous generators (SG) are used in most cases to produce three-phase alternating current. Synchronous generators that discharge on their own network are often found in mobile installations or in isolated networks, often being used as backup sources for supplying electricity to more important objectives in case of power system failures. SG is a rotating electric machine with the stator winding connected to an alternating current network, and the rotor winding (which is part of the inductor) is supplied with direct current.

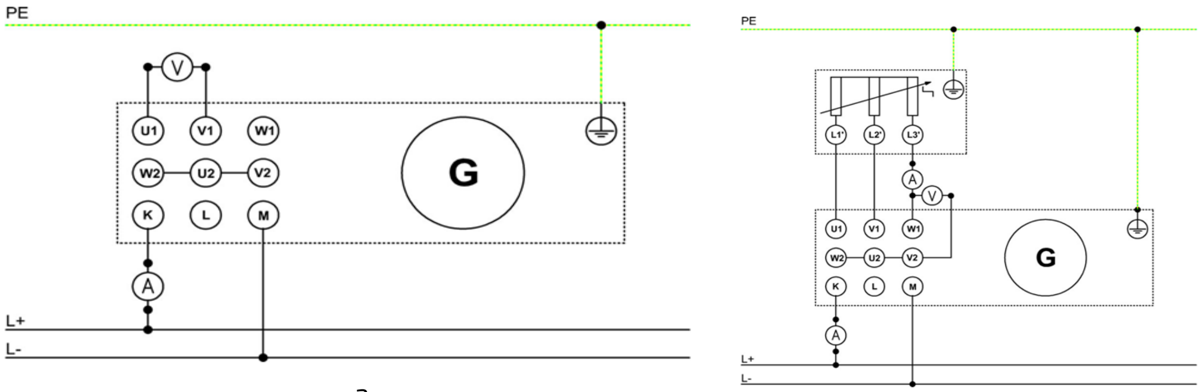
In analyzing the behaviour of the synchronous generator, we must start from the characteristics of this machine, highlighting its particularities compared to other types of generators. Characteristics of the synchronous generator are given by the no-load characteristic, $U_{eo} = f(I_e)$, the external characteristic, $U = f(I)$ and the regulation characteristic, $I_e = f(I)$. These characteristics are necessary to highlight the parameters of the tested machine and to define the way of further research, so as to determine which parameters must be influenced so that this machine supplies voltages and frequencies in the three-phase network to variations in motor torque and to variations in shaft speed.

3.2. Experimental determination of the mechanical and electrical characteristics of the synchronous generator

The stand used for the research studies related to establishing the characteristics, synchronization and protection of the synchronous generator is composed of:

- Power source of direct current and three-phase alternating current;
- Three-phase alternating current power supply;
- Adjustable direct current and three-phase alternating current power supply;
- Synchronization unit: 3 lamps, synchronization switch, frequency meters, 3 voltmeters, 1 digital synchronoscope;
- Test bench servomotor for 1kW electric cars;
- Three-phase synchronous machine 1kW;
- Additional automatic adjustable excitation resistance;
- Analogue/digital multimeter, voltmeter, power factor meter;
- Three-phase measuring device;
- Thermomagnetic switch;
- Resistive load, three-phase;
- Load coupling mode;
- Additional excitation resistance coupling switch;
- Multifunctional relay, electrical power control device, cos φ, automatic timing unit.

The electrical diagrams of the experimental setup, used to determine the characteristics of the synchronous generator, are presented in figure 3.1.



a

b

Fig.3.1. Electrical diagrams used to determine the characteristics of the synchronous generator [29]

In figure 3.1.a the synchronous generator is shown in idle operation while in figure 3.1.b it is shown after being connected to a variable resistive load (power rheostat).

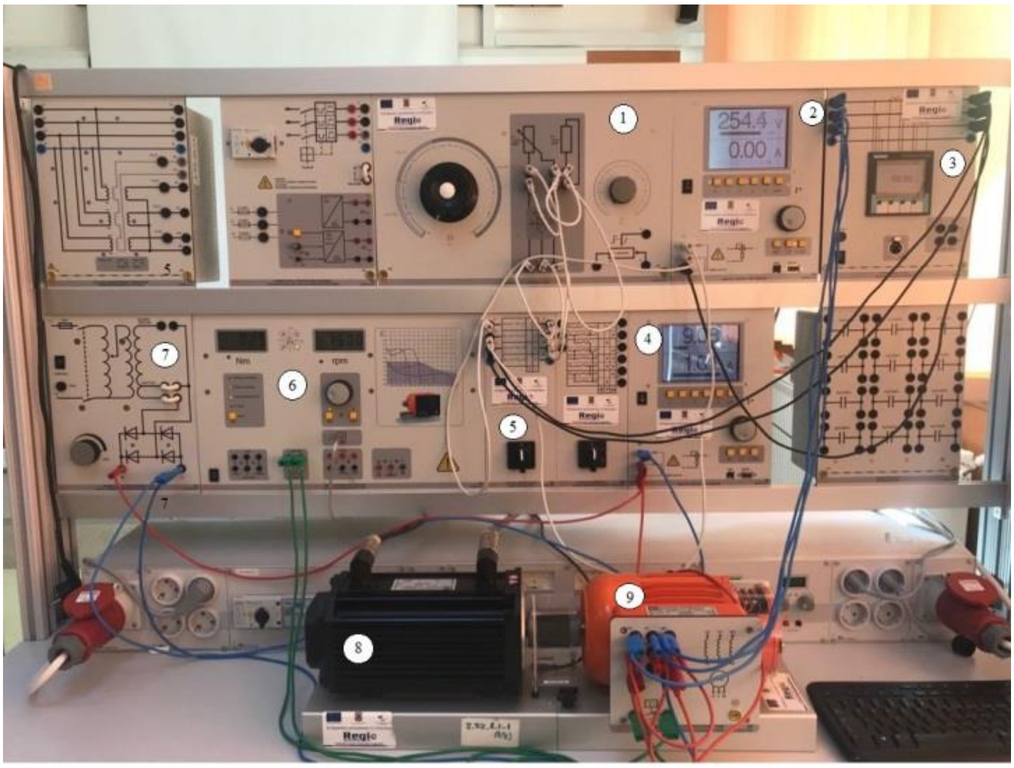


Fig.3.2. Stand for determining the characteristics of the electric generator

The stand has the following functional blocks in its structure:

1- Adjustable power rheostat 2k-1k;

2- Analogue/digital multimeter, voltmeter, ammeter – for measuring the current and voltage in the rotor winding;

3- Three-phase digital multimeter for measuring frequency and alternating three-phase voltages;

4- Analogue/digital multimeter, voltmeter, ammeter – for measuring current and voltage in the excitation winding;

5- General three-pole switch with 2 positions;

6- Servo motor controller;

7- Adjustable direct current source for the excitation winding;
8- Brake servomotor;
9- Synchronous generator.
The brake servomotor (8), by means of the servomotor controller (6), adjusts the primary machine (which is considered to be the shaft of a wind turbine), at a speed of 1500 rpm. The excitation DC source (7) supplies an adjustable current and voltage to the stator winding of the generator (9). These quantities are measured with a digital multimeter (4). The value of the excitation voltage is high until the generator (9) provides a voltage of 400V alternating current in the rotor winding. The parameters of voltage and current delivered by the generator are measured with a digital multimeter (2), the frequency obtained is measured with a three-phase digital multimeter (3). To study the behaviour of the generator under load, a resistive consumer is inserted into the circuit in the form of a 2k-1k linear adjustable rheostat (1). In order to establish the mechanical and electrical characteristics, the behaviour of the empty generator (without a consumer) will be studied, later connecting the consumer to obtain the nominal parameters of charging in the network. The characteristics of the studied synchronous generator are represented in the extended thesis.

3.4. Behaviour of the synchronous generator to imposed variations of the engine torque

To study the behaviour of the synchronous generator at different disturbing variations of wind and motor torque, the setup in figure 3.2. was considered, in which it was considered that there are several resistive loads on the output circuit starting from 2kΩ to 1kΩ. It has been considered that the rated speed, output voltage and rated frequency should be kept constant as rated parameters in the network. The speed of the wind acting on the wind turbine blades leads to changes in the motor torque at the generator shaft. Consequently, the motor torque was modified at the motor shaft so as to keep the nominal parameters mentioned above. It was found that a number of other parameters change implicitly, namely the excitation current and voltage, but also the output current charged to consumers. By changing the value of the excitation current, the generator was brought into nominal parameters keeping the nominal voltage for different resistive loads.
After carrying out the determinations, the results presented in tables 3.6 – 3.14 (extended thesis) were obtained
From the analysis of the resulting data, the following characteristics were obtained:
Ie_{rr}=f(M), for load resistance values in figure 3.7.
Ue_{rr}=f(M), for load resistance values in figure 3.8.
I_e=f(M), for load resistance values in figure 3.9.
Ie_{rr}=f(M), for output voltage values in figure 3.10
Ue_{rr}=f(M), for output voltage values in figure 3.11.
I_e=f(M), for output voltage values in figure 3.12.

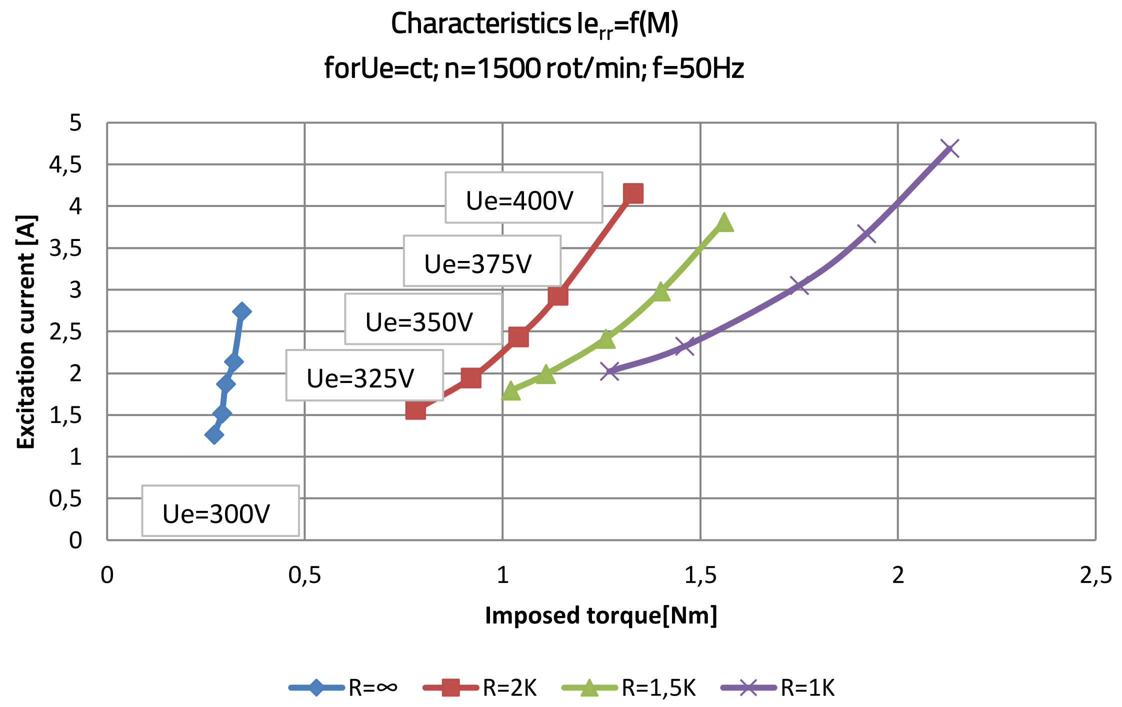


Fig.3.7. Characteristics obtained Ie_{rr}=f(M) for U_e=ct; n=1500 rot/min; f=50Hz

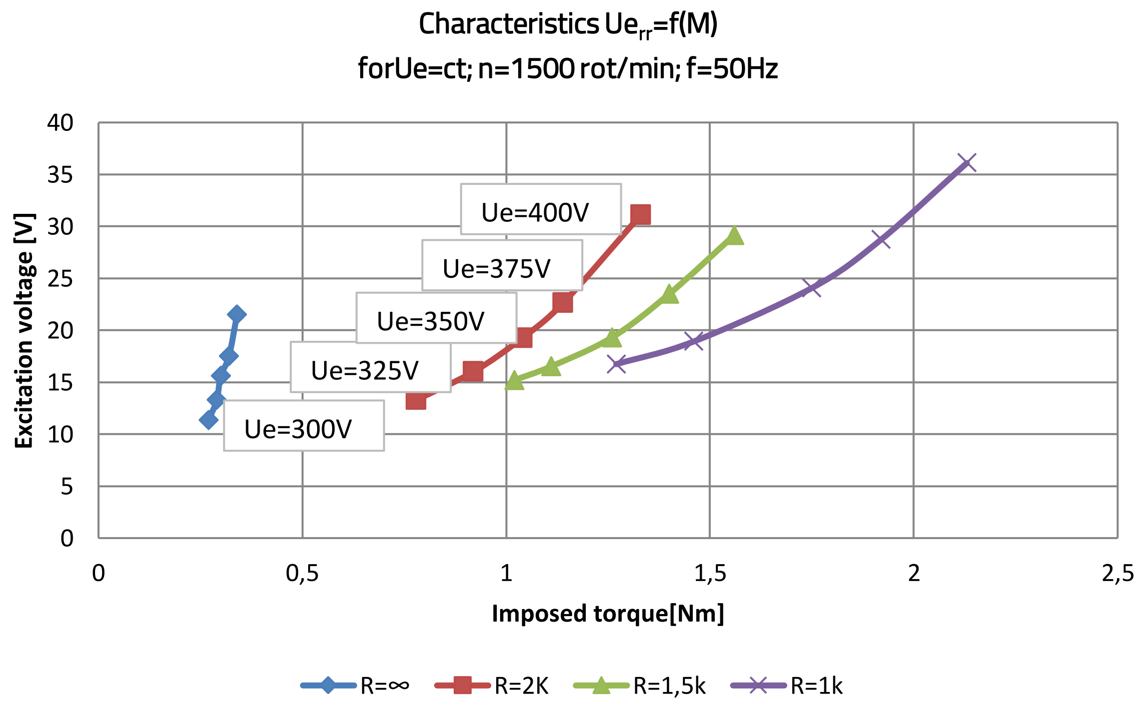


Fig.3.8. Characteristics obtained Ue_{rr}=f(M) for U_e=ct; n=1500 rot/min; f=50Hz

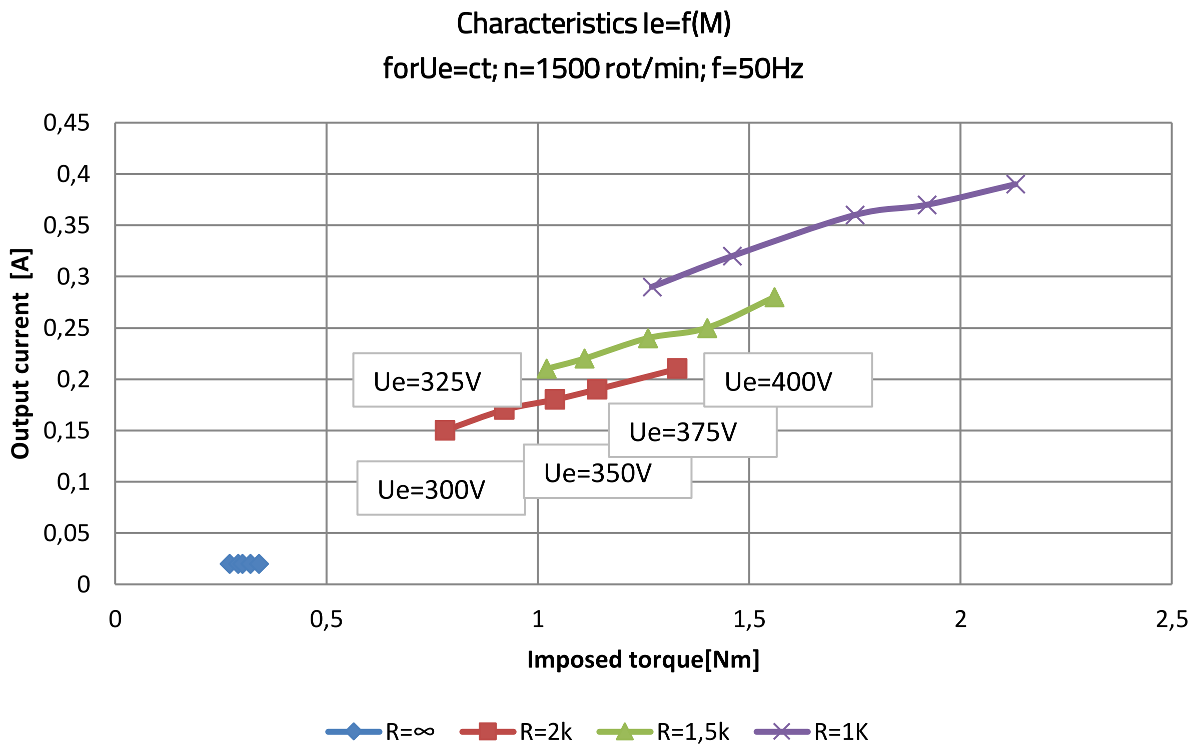


Fig.3.9. Characteristics obtained I_e=f(M) for U_e=ct; n=1500 rot/min; f=50Hz

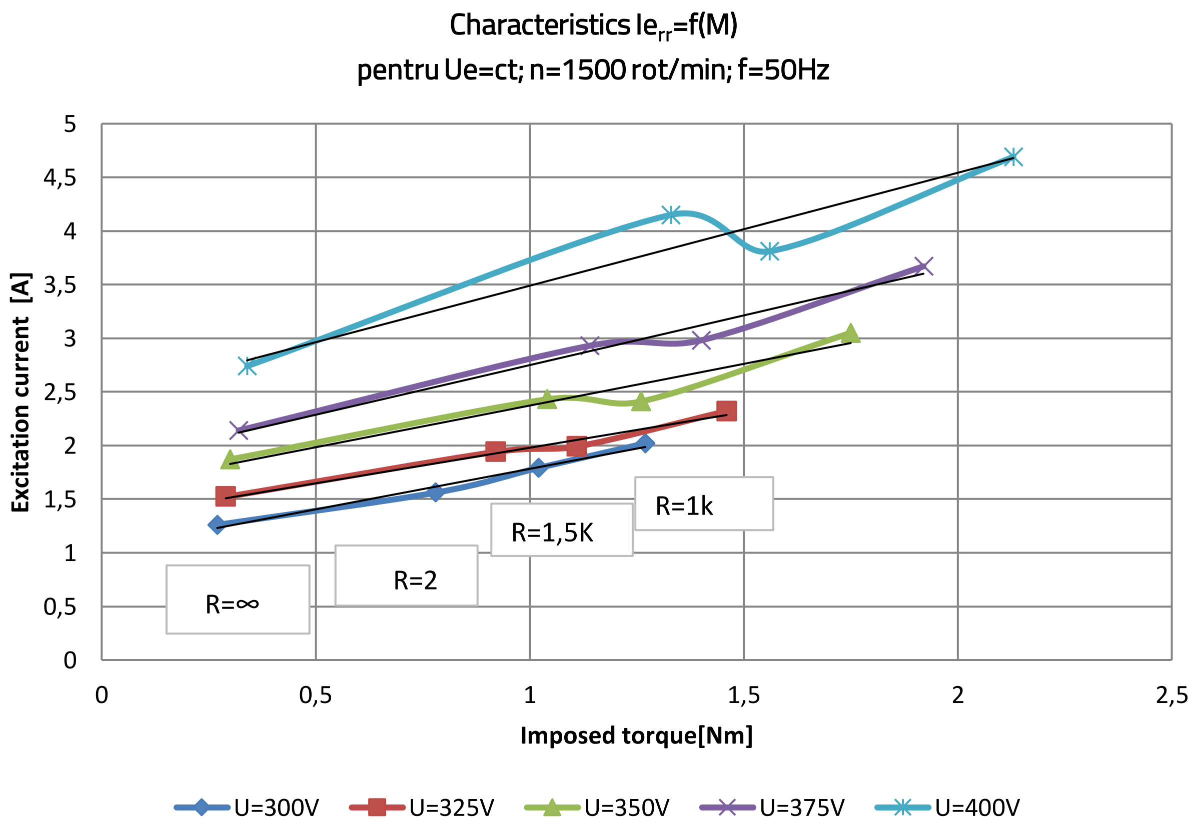


Fig.3.10. Characteristics obtained Ie_{rr}=f(M) for U_e=ct; n=1500 rot/min; f=50Hz

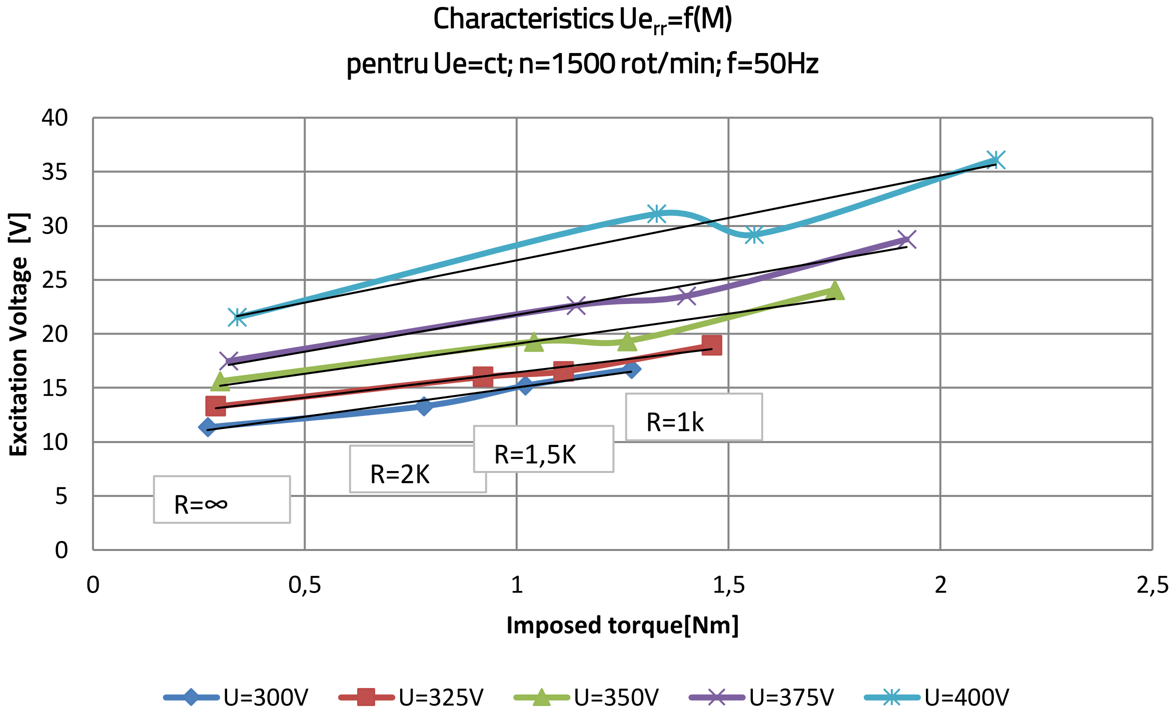


Fig.3.11. Characteristics obtained Ue_{rr}=f(M) for U_e=ct; n=1500 rot/min; f=50Hz

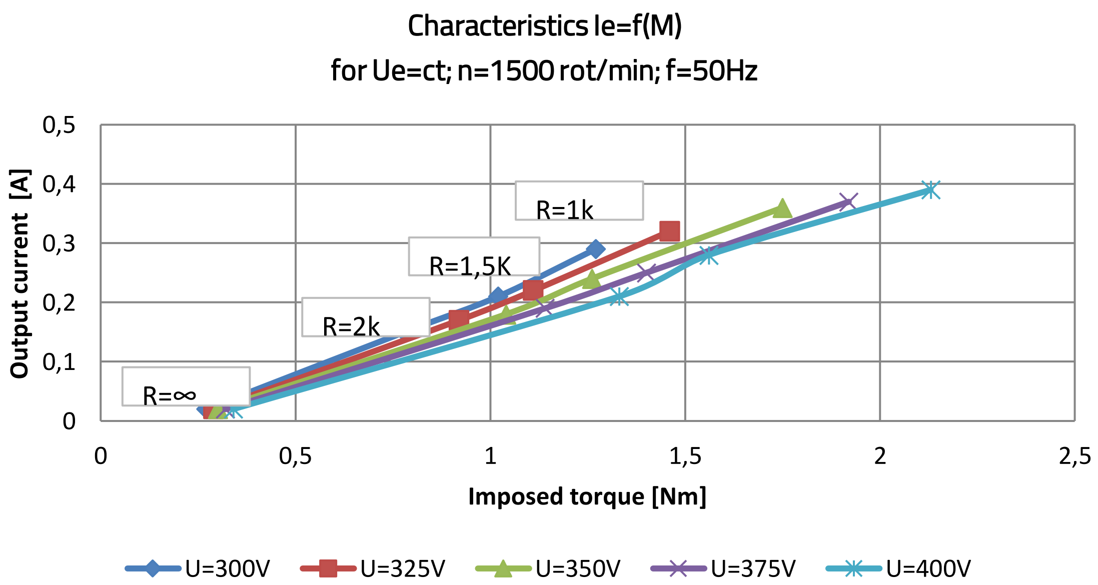


Fig.3.12. Characteristics obtained I_e=f(M) for U_e=ct; n=1500 rot/min; f=50Hz

Analysing the characteristics presented in figures 3.7., 3.8. and 3.9. in which 3 resistive loads and no-load operating situation were considered, keeping different output voltage values in the 300-400V range, keeping the speed constant at 1500rot/min and a frequency of 50Hz, 3 characteristics were obtained: of the excitation current, of the excitation voltage and of the output current depending on the imposed torque.

Thus, in figure 3.7. it is observed that, in order to be able to keep the output voltage at the imposed value, a change in the excitation current is necessary, depending on the value of the torque from the shaft. If the imposed value of the voltage increases, the tendency is increasing and the value of the excitation current increases with the torque.

In figure 3.8. it is observed that the excitation voltage has the same increasing tendency and is similar to the previous characteristic shown in figure 3.7.

In figure 3.9. the value of the output current is represented depending on the imposed torque.

It is observed that at different increasing values of the output voltage, the output current increases for different values of the motor torque.

In figures 3.10., 3.11. and 3.12. we have the same characteristics considering constant output voltage for different values of load resistance.

In figure 3.10. it is observed that for constant values of the output voltage the curve is relatively linear with an increasing tendency, the excitation current being necessary to be increased to keep the speed constant at different values of the motor torque.

In figure 3.11. it is observed that the excitation voltage has the same increasing trend as the excitation current shown in figure 3.10.

In figure 3.12. keeping the output voltages constant, it is observed that with the increase of the force at the shaft, the output current charged in the network increases with the increase of the resistive load.

3.5. Conclusions

In chapter 3 research was done on the synchronous machine as a generator. Emphasis was placed on the mechanical characteristics of the torque in order to track its behaviour under abnormal or accidental conditions. Influenced mechanical and electrical parameters were identified and necessary conclusions were expressed in order to proceed to the synchronization process.

In the first part of this chapter, experimental determinations were made, in order to study the characteristics, a synchronous generator with the following characteristics was considered: P_n=0.27kW, I_n=1.5A, f=50Hz, n=1500rot/min, Ue_{rr}=20Vcc; Ie_{rr}=4A. The excitation source generated a step voltage from (0-20) Vdc at imposed excitation current values of 0.5A, 1A, 1.5A, 2A, 2.5A, 3A.

For the studied generator, the idle operation characteristic $U_{eo}=f(Ie_{rr})$ was established. The excitation current was changed incrementally from 0.5A to 3A. The value of the output voltage increased in direct proportion to the value of the excitation current. The characteristic is approximately linear, with the observation that the value of the excitation current was limited to the supply value of the nominal line voltage in the network of 400V.

The external characteristic U=f(I) was obtained for an adjustable resistive load from 2 kΩ-1kΩ, under the nominal conditions where the speed was kept at the value of 1500rot/min. The output current increases as the voltage decreases. It results that the value of the output voltage depends both on the load inserted in the circuit and on the value of the excitation current.

To establish the adjustment characteristic Ie=f(I), at a nominal constant speed of 1500 rpm, charts were made with 2 constant values of the nominal voltage supplied in the load network, 400V and 300V, for a variable load from 2kΩ-1kΩ. At a constant speed and rated voltage, implicitly at a rated frequency of 50 Hz, similar curves are obtained that have an increasing tendency of the output current depending on the excitation current up to the maximum point after which it stabilizes around this value.

From the analysis of these characteristics, for the studied generator, the variable value of the excitation current is identified, which influences the nominal parameters of the synchronous generator. On the other hand, this variability must be carefully controlled so that the generator supplies nominal three-phase voltages in the network, given that, according to the regulations in force, the frequency can vary within a range of ± 10%.

Analysing the characteristics presented in figures 3.7., 3.8. and 3.9. in which 3 resistive loads and a no-load operation situation were considered, keeping different output voltage values in the 300-400V range, keeping the speed constant at 1500 rpm and a frequency of 50Hz, 3 characteristics of excitation current, excitation voltage and output current were obtained, depending on the imposed torque. Thus, in figure 3.7. it is observed that in order to be able to keep the output voltage at the imposed value, a change in the excitation current is necessary, depending on the value of the torque from the shaft. If the imposed value of the voltage increases, the tendency is increasing and the value of the excitation current increases with the torque. In figure 3.8. it is observed that the excitation voltage has the same increasing tendency and is similar to the previous characteristic shown in figure 3.7. In figure 3.9. the value of the output current is represented according to the imposed torque. It is observed that at different increasing values of the output voltage, the output current increases for different values of the motor torque.

In figures 3.10., 3.11. and 3.12. we have the same characteristics considering constant output voltage for different values of load resistance. In figure 3.10. it is observed that for constant values of the output voltage the curve is relatively linear with an increasing tendency, the excitation current being necessary to be increased to keep the speed constant at different values of the motor torque. In figure 3.11. it is observed that the excitation voltage has the same increasing trend as the excitation current shown in figure 3.10. In figure 3.12. keeping the output voltages constant, it is observed that with the increase of the force at the shaft, the output current charged in the network increases with the increase of the resistive load.

4. Original contributions on the design and development of the stand for synchronizing the generator to the grid

4.1. Manual synchronization of the synchronous generator

4.1.1. Theoretical notions

In order to achieve the synchronization of the synchronous generator with the three-phase supply network, the following steps were carried out:
- the turbine was brought up to synchronism speed, so that it could reach the grid frequency of 50Hz (n=1500 rpm)
- the excitation voltage was increased until the voltage produced by the generator became equal to the network voltage
- by fine-tuning the excitation current from the additional excitation resistance, the phasor synchronization of the three three-phase voltages produced with the three three-phase network voltages is obtained. Voltages can be in phase or out of phase.

For manual synchronization of the synchronous generator, 3 connection schemes are used:
- the dark-lamp synchronization circuit – phase opposition
- the bright-lamp synchronization circuit – in phase
- the three-lamp synchronization circuit – in phase

4.1.2. Experimental determinations and setups

As an example, the installation diagram for synchronizing the synchronous generator with the three-phase network "three-lamp synchronization circuit" was built.

Objective:

- connecting the synchronous generator to the turbine;
- bringing the turbine into synchronism;
- changing the excitation voltage until the generator produces a voltage equal to that of the network;
- synchronization with the digital synchronoscope, through the fine adjustment of the excitation voltage;
- connecting the synchronous generator to the network.

Equipment used:

SE2662-5Q - Three-phase synchronous machine 1kW
CO3636-6W – 1kW machine test bench servo motor
CO3212-5U - Adjustable universal power supply for direct current and three-phase alternating current
CO3212-6V – Synchronization unit: 3 lamps, synchronization switch, 2 frequency meters, 2 voltmeters, 1 voltmeter, 1 digital synchronoscope
CO3301-5F – Adjustable resistor for excitation voltage regulation
CO5127-1Z – Analogue/digital multimeter, voltmeter, power factor meter
CO3212-1P – Thermomagnetic switch, 1.6-2.5A
CO5127-1Y – Three-phase measuring device

Electrical diagram used for starting and synchronizing the generator

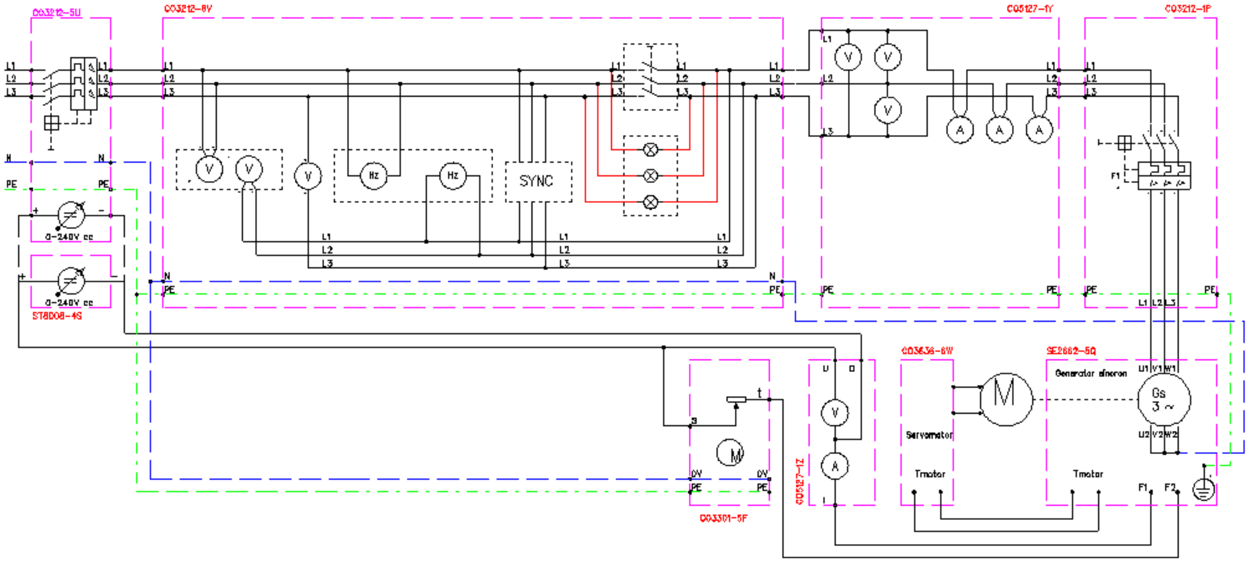


Fig.4.4. Electrical diagram used for manual synchronization of the synchronous generator with the three-phase supply network

Practical setup of the diagram:

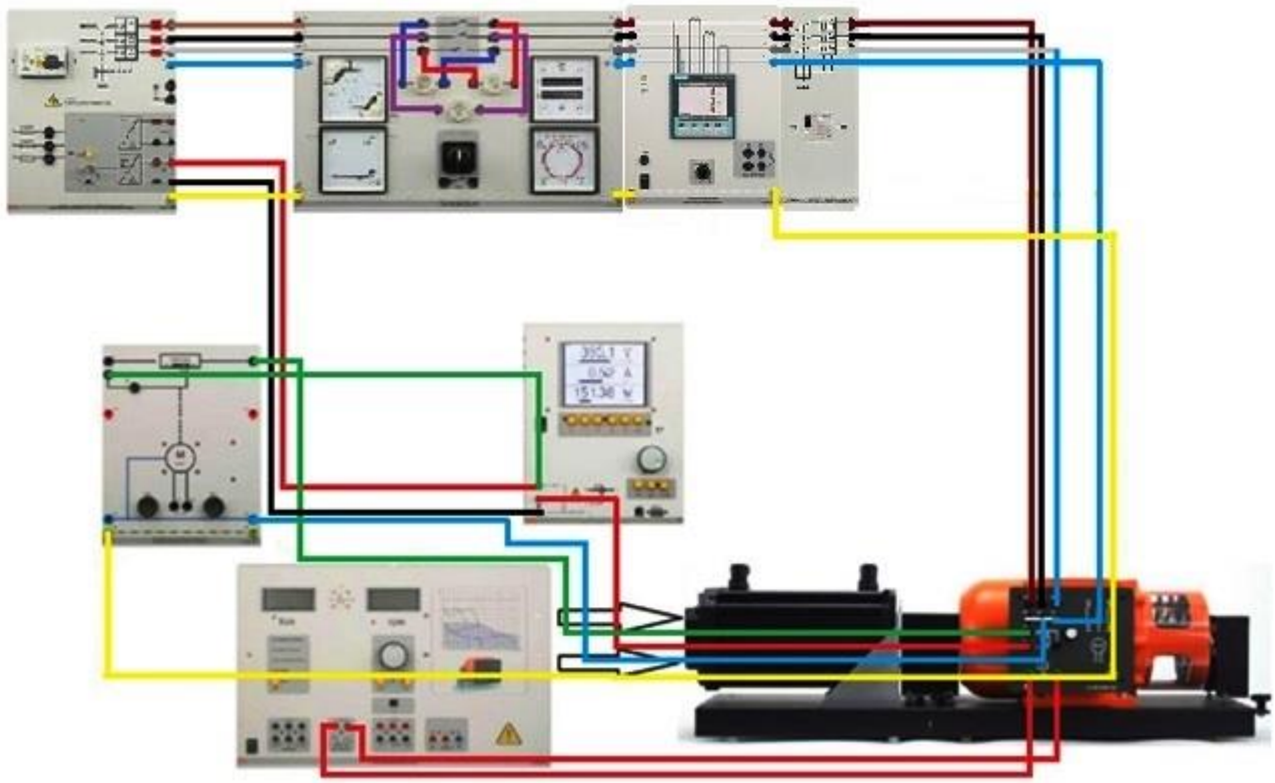


Fig.4.5. Setup diagram for starting and synchronizing the generator

Starting and synchronizing the synchronous machine:

- the setup is carried out according to the electrical and setup scheme
- the primary machine (servomotor) is powered
- if the circuit is well made, the servomotor control unit is initialized without an error code appearing
- the primary machine (servomotor) is brought to the synchronism speed, by increasing the speed until the bulbs light up and go out successively.
- check the speed of 1500 rpm on the display of the servomotor control unit
- the value of the excitation voltage is changed until the generator produces a voltage equal to that of the network (~400V)
- the synchronization with the digital synchronoscope is pursued, through the fine adjustment of the excitation voltage. This is done from the excitation resistor module buttons. When the synchronoscope lights up the green LED, the generator can be connected to the grid.
- the synchronous generator is connected to the network, by switching on the switch.

Shutting down the synchronous machine:

- the synchronous generator is disconnected from the network, by disconnecting the switch;
- the value of the excitation voltage is decreased until the generator no longer produces voltage;
- the power supply to the excitation circuit of the synchronous generator is interrupted;
- the supply of the primary machine (servomotor) is interrupted.

The manoeuvres performed at start-up depend on the specifics of the primary motor. To stop the primary machines that drive the synchronous generators, the following sequence of operations is recommended:

- active and reactive loads are reduced;
- the group is disconnected from the bars;
- the speed of the machine is reduced;
- the power supply to the excitation circuit of the synchronous generator is interrupted;
- the power supply to the primary machine is interrupted.

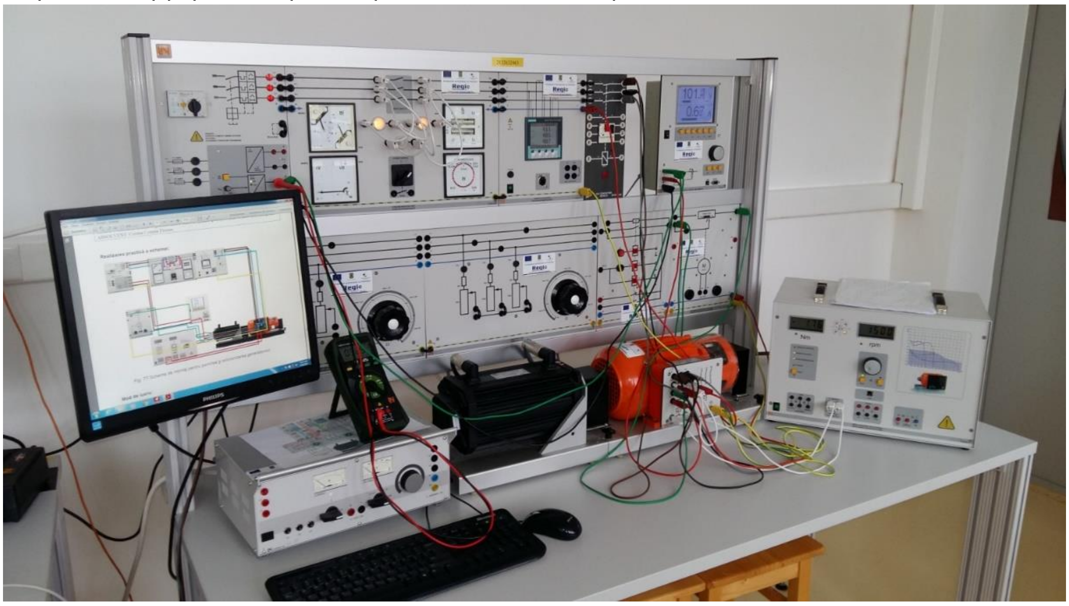


Fig.4.6. Experimental stand for starting and synchronizing the generator manually

After completing the experimental setup, the generator was connected to the three-phase supply network complying with the synchronism conditions.

- The line voltages charged by the generator must be equal to the line voltages of the three-phase network. This can be monitored with the two voltmeters measuring the two voltages, or with the voltmeter assembled between the input and output lines, which when synchronizing should read 0. This is regulated from the DC voltage source, which provides the excitation voltage and current value.
- The nominal frequency must be 50 Hz. This is adjusted from the speed of the primary motor which must reach the synchronism value of 1500 rpm. The phases must be in the same sequence
- The phases must be in sync. This is tracked with the bulb system or synchronoscope
- With the help of the synchronoscope, the influence of the excitation voltage and current on the synchronism conditions is observed.

4.2. Behaviour of the synchronous generator at imposed torque variations on the motor shaft

4.2.1. Equipment used

To improve the mechanical and electrical characteristics of the synchronous generator, the following equipment was used:

1. Three-phase synchronous machine 0.3 kW; 2. Three-phase asynchronous machine 0.6 kW; 3. ELECTROZEP frequency inverter; 4. Servomotor with brake; 5. DC voltage source 0-30 V, 5A; 6. Analogue/digital multimeter, voltmeter, power factor meter, three-phase multimeter; 7. Three-pole switch with two positions; 8. Three-phase measuring device; 9. Load rheostat; 10. Servomotor controller

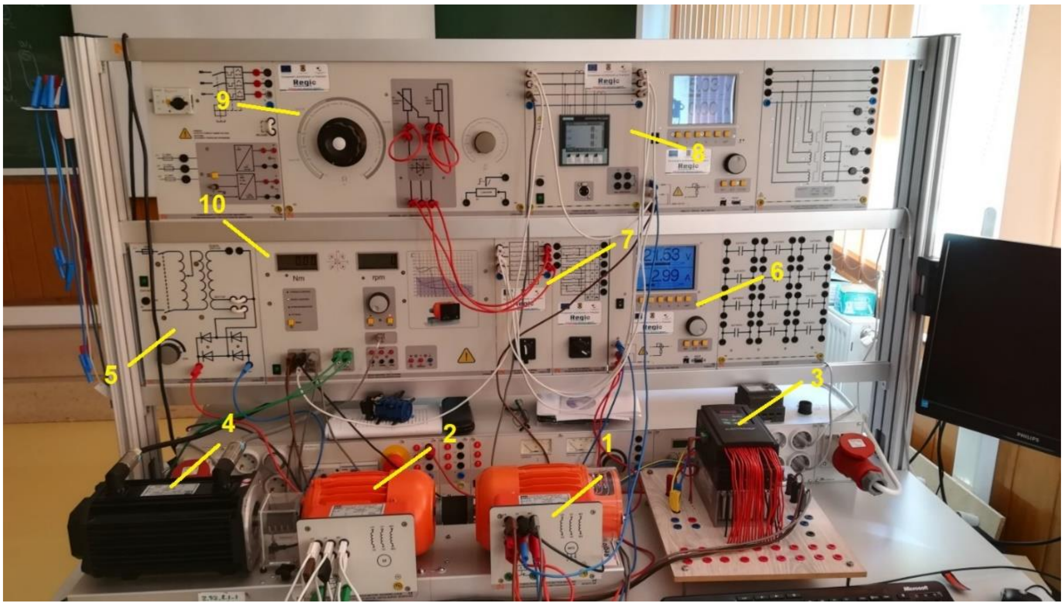


Fig.4.7. Stand for establishing the characteristics of the synchronous generator

4.2.2. Experimental determinations – Step-increasing variation curve

After studying the behaviour of the synchronous motor at torque variations, the stand in figure 4.7 was assembled, to observe the behaviour of the synchronous machine in generator mode at the same torque variations.

The direct current voltage source (5) provides a direct current voltage to the rotor winding of the synchronous machine (1), the stator winding being connected in a star connection. The analogue/digital multimeter (6) measures the DC values of the excitation current and voltage variably supplied by the DC voltage source (5).

The asynchronous motor (2), controlled by the frequency inverter (3), ensures the synchronous speed of the synchronous generator (1). The brake servomotor (4), through the controller (10), generates torques imposed on the shaft simulating possible variations. The system is connected to the load rheostat (9), by means of the three-pole switch with two positions (7). The output parameters are displayed with the three-phase measuring device (8).

To begin with, a torque characteristic was considered that pursues the successive increase of the torque at the shaft during 30s.

Up to 10s, the motor has a minimum torque, after which the torque value is increased to 0.1 Nm, after 20s it is increased to the value of 0.2Nm and finally returns to the starting value. This torque characteristic is shown in figure 4.8. The excitation winding was considered to have a load of 2.5A and 3A.

The mechanical and electrical characteristics presented in figure 4.10 have resulted.

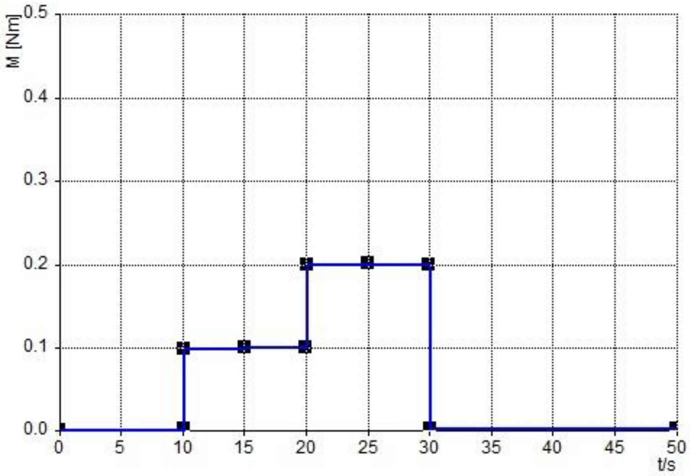


Fig.4.8. Imposed torque characteristic for 50s

On the same torque chart, the same characteristics were represented for a load of Ie_{rr}=2.5A and Ie_{rr} =3 A of the excitation current. The resulting chart is shown in figure 4.10.

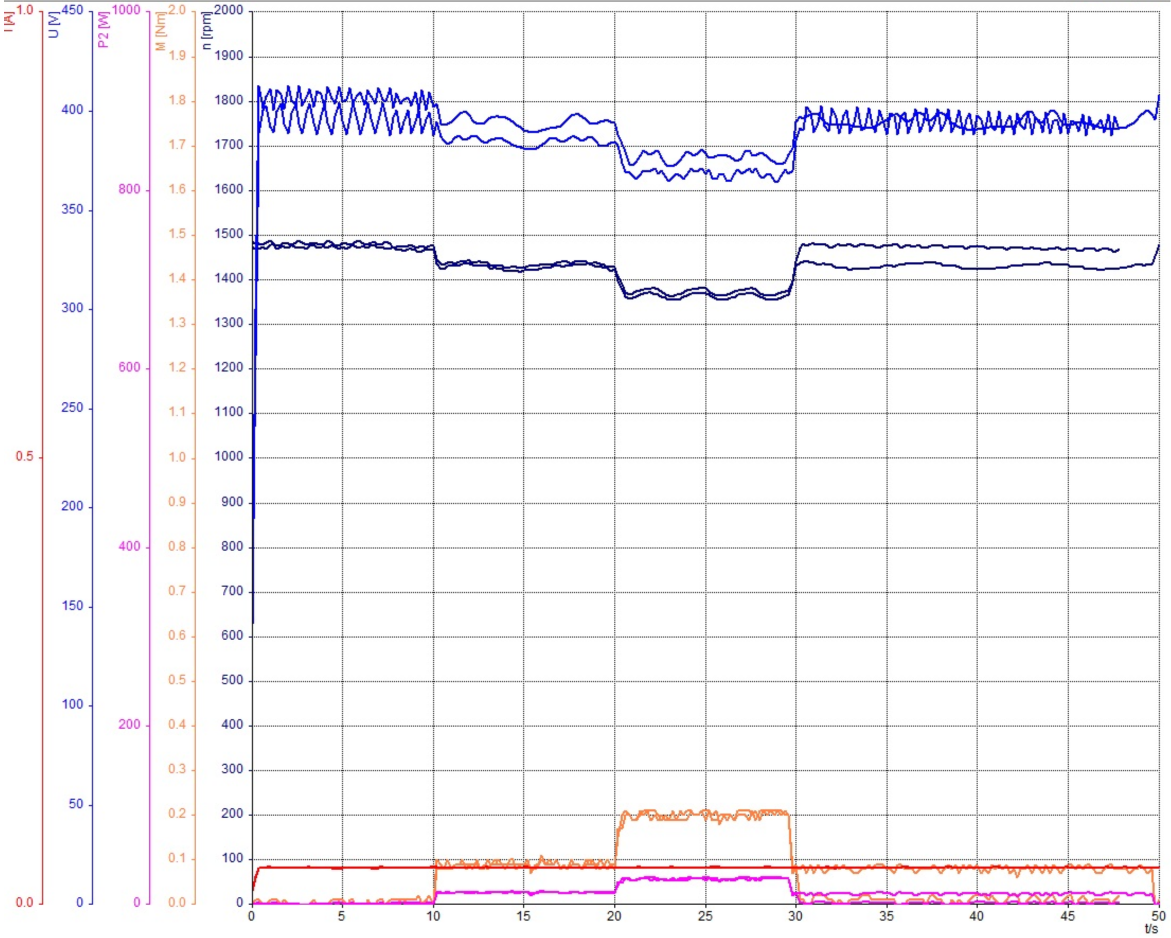


Fig.4.10. Mechanical and electrical characteristics of synchronous generator for Ie_{rr}=2.5A și 3A

From the comparative analysis of these charts (figure 4.10.), it can be seen that with imposed variations of the motor torque at the shaft of the synchronous machine, the voltages supplied to the terminals keep the same inversely proportional trend in relation to the moment resisting the shaft, but the value of the electrical parameters changes with the increase of the direct current excitation current on the rotor winding. Consequently, the value of the excitation current must be changed to compensate for the resistive torques from the shaft of the synchronous machine.

From these data, it results the need to monitor the behaviour of the synchronous generator to variations imposed on the shaft, and possibly compensation through the variability of the excitation resistance.

4.2.3. Experimental determinations – Drive shaft shock imposed variation curves

For similarity, a load with variable torques that were applied in the study of the synchronous motor was considered. Thus, the following torque characteristic presented in the research of the synchronous machine used as a motor, in figure 2.68, was applied to the experiment.

It was considered that these loads should be pursued for three excitation current values of 1A, 2.5A and 3A.

For example, in the summary of the doctoral thesis the characteristic obtained for the value of Ie_{rr}=3A was represented.

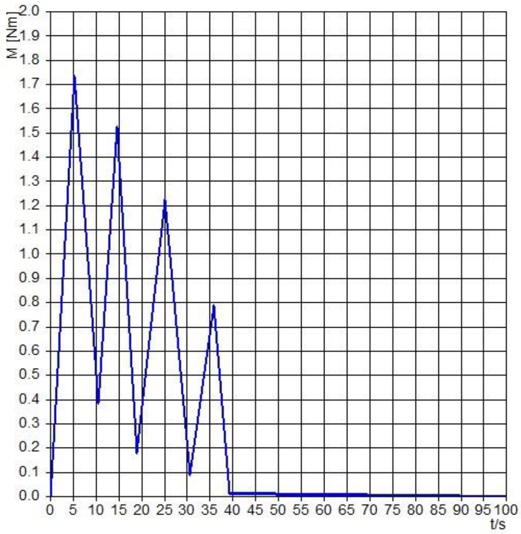


Fig.4.11. Torque characteristic imposed on the generator shaft

For Ie_{rr}=3 A the following results and characteristics were obtained:

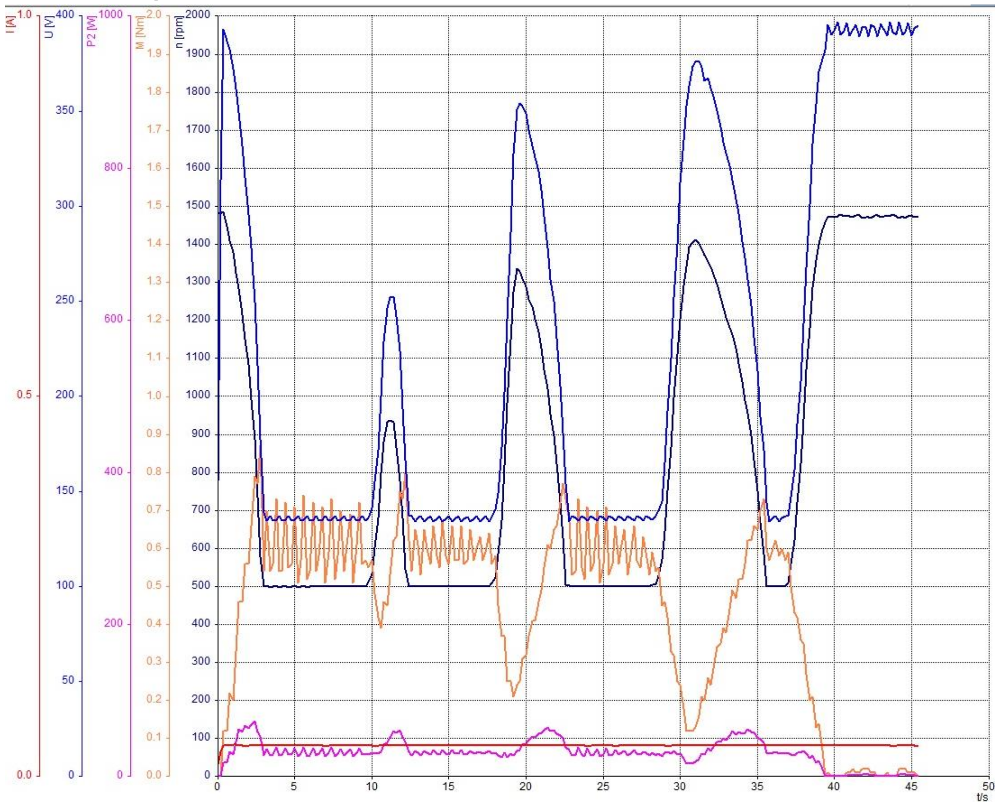


Fig.4.14. Mechanical and electrical characteristics of synchronous generator for torque variation imposed at Ie_{rr}=3A

Analyzing the three comparative charts presented in figures 4.12, 4.13. and 4.14., for different values of the excitation current it is observed that the value of the output current is influenced by the value of the excitation current from the rotor winding. The speed maintains the allure of the torque characteristic, the nominal voltage that tends to destabilize the system is brought back to the nominal value of synchronism, something also highlighted in the case of previous researches of the synchronous machine used as a motor.

4.3 Experimental study on automatic voltage regulation in the case of synchronous generator speed oscillations

4.3.1. Theoretical notions

In this research, the behaviour of the synchronous generator was experienced by simulating the occurrence of speed variations and shocks at the primary machine shaft. For this, the experiment was carried out on a stand with laboratory equipment, to which additional equipment was added.
A timed overcurrent protection mechanism is added for thermal overload protection and differential protection for the wiring diagram. This mechanism measures the individual currents in each phase and must be set to 1.2 – 1.5 times the rated current of the machine.
The delay time must be long enough because the overcurrent protection must not trigger until the grid protection has triggered. Relatively long trigger times of 2 – 10 s are thus configured. An automatic synchronizer (GCP-30) is also configured, used to bring the three-phase voltage system back to network synchronization nominal values. The electromagnetic relay is used to control the triggering of the synchronous generator, in extreme desynchronization conditions, when nominal parameters can no longer be ensured in the system.

4.3.2. Experimental measurements and setups

Objectives

- Configuring and starting the synchronous generator
- Setting the parameters for the multifunctional relay (GCP-30):
- Configuration of the relay management system
- Configuration of overcurrent protection time monitoring
- Preset response thresholds for overcurrent time protection for:

- increasing the burden on the consumer
- changing the speed of the generator (producing shocks to the shaft)
- testing the preset values

Equipment used:

CO3212-5U Universal three-phase DC and AC power supply;
CO3301-5P Load coupling module;
CO3301-5Y Multifunctional relay, electrical power control device, cos φ, automatic timing unit;
CO5127-1Y Three-phase measuring device;
CO3212-1P Thermomagnetic switch;
CO3636-6W Servomotor - test bench for 1kW electric machines;
CO3301-4F Additional Excitation Resistor Coupling Switch;
CO5127-1Z Analogue/digital multimeter, voltmeter, power factor meter;
CO3301-3F Three-phase resistive load;
CO3301-5F Automatic additional excitation adjustable resistor.

Electrical diagram used

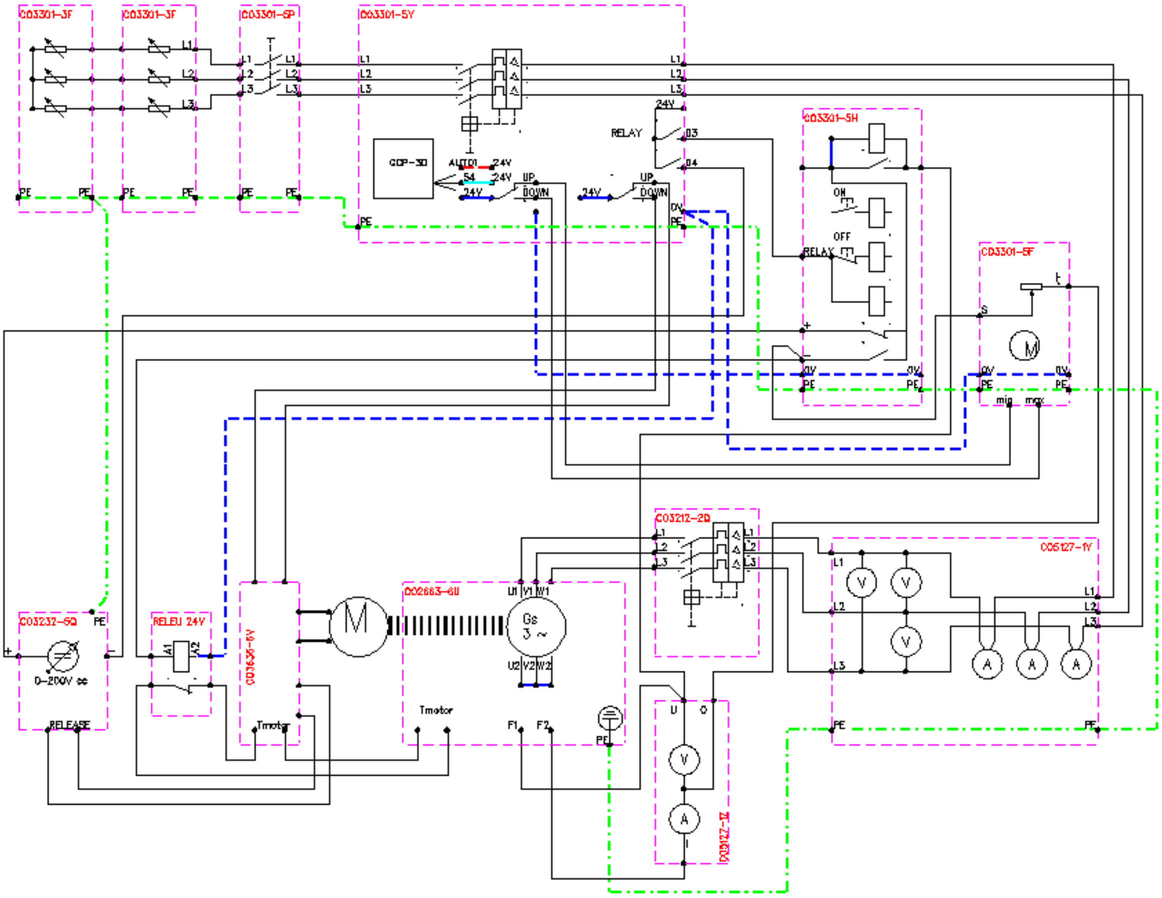


Fig.4.15. Electrical diagram used for automatic voltage regulation in case of synchronous generator speed oscillations.

Practical completion of the scheme

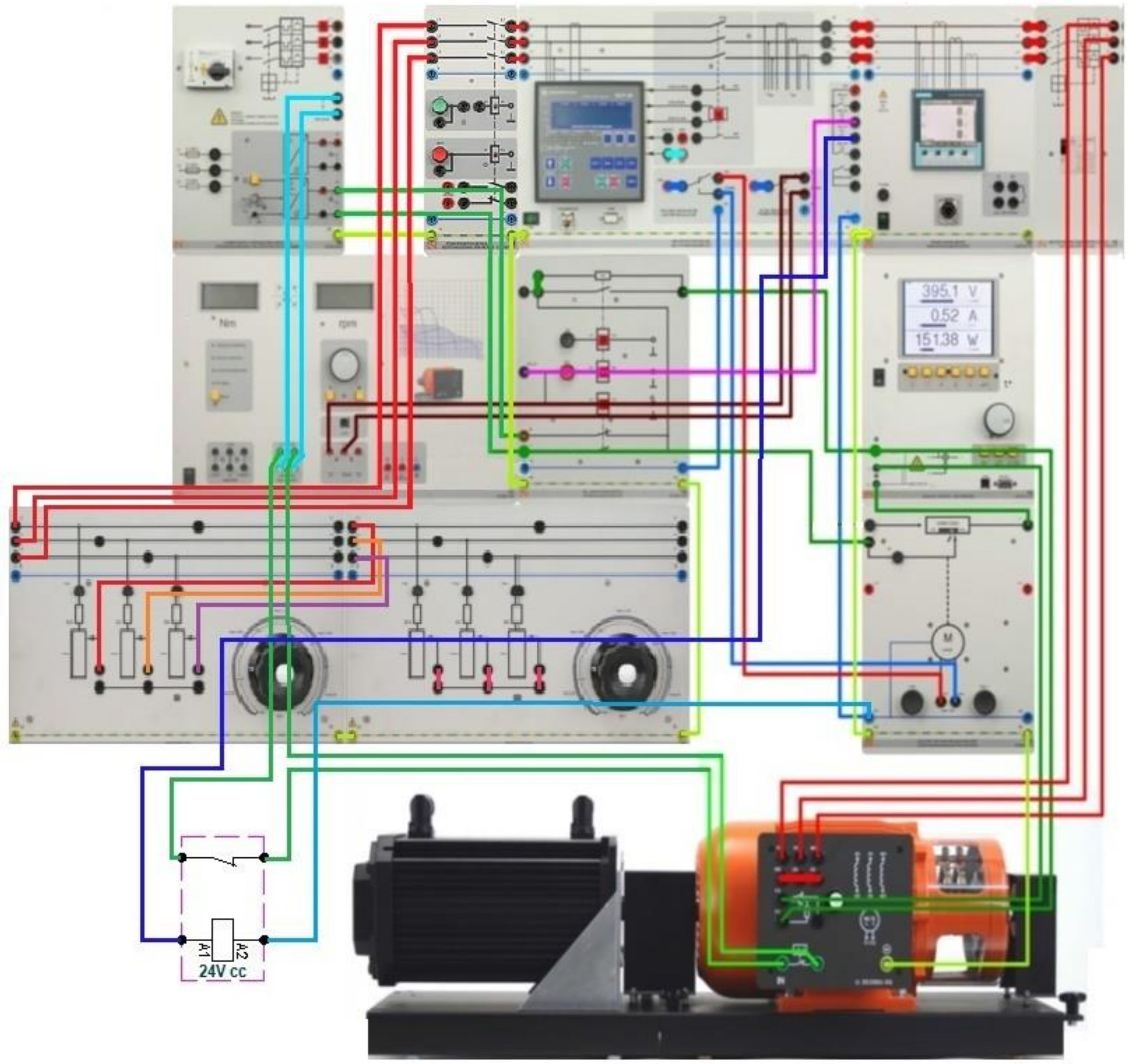


Fig.4.16. Schematic diagram used for automatic voltage regulation in case of speed oscillations of the synchronous generator

The following settings are made:

- **Servomotor**:
  - Speed regulation: Nominal synchronous speed of the generator (synchronous machine)
  - Synchronous generator rotation direction: positive (clockwise)
  - "Sync" mode **not** connecting

Mode: "**Sync**" set from

- **Electrically controlled variable excitation resistance**: will be set to an average value by pressing the "Min" or "Max" buttons of the additional excitation resistance
- **DC power supply**: between 60-65V (for powering the rotor excitation winding)

- **Three-phase load resistance**: Adjust the resistance to its maximum value
- **Multifunctional relay**:
  - We activate the overcurrent protection in time using the following parameters: (refer to the instructions for use of the GCP-30 relay, "Overcurrent protection in time ").
  - Power overcurrent monitoring: "Yes"

o Step 1
- Overcurrent step 1: 100%
- Overcurrent delay step 1: 2s

o Step 2
- Overcurrent step 2: 300%
- Overcurrent delay step 2: 0.03s

  - The new standard values are loaded into the multifunction relay.
  - After the data transfer, the multifunction relay is ready for the "Black start" procedure.
  - The LeoPC1 program, and the parameter interface, must remain functional.

The installation will start:

- Set the excitation voltage regulator to a medium level using the two buttons (min. and max.)
- Start the servomotor and bring it to the synchronization speed, (1500rot/min)
- Change the excitation voltage until it reaches the value of 60-65V
- Turn on the GCP-30 relay. Wait for it to initialize. "Gender" appears on the screen
- Set the GCP-30 relay in automatic mode by pressing the "Auto" button
- Connection is made between 24V and AUTO1 by inserting the short-circuit key
- "PREGLOW" will appear on the screen followed by "START"
- Press the "ON" button on the excitation start button (CO3301-5H). It contains an additional adjustable excitation resistor, in series with the rotor circuit, which acts as a consumer for the excitation circuit
- During the process, no changes will be made to the experiment or device settings
- As soon as the required parameters are met, including identical phase angles, phase sequence, frequency and the same RMS voltage value has been reached, the multifunctional relay switches the generator to the grid
- Connect the three-phase consumer in the circuit
- The speed of the primary machine, of the servomotor is changed until the time protection against overcurrent is triggered. Slowly rotate the control element so that the voltage regulator of the multifunctional relay can keep up with the generator speed increasing or decreasing
- Observe how the multifunctional relay responds and note the response values
- To finish the experiment, the motor and the excitation source will be stopped
- After complete reset, the setup can be used for a new experiment

- After triggering the multifunctional relay alarm and disconnecting the generator, the excitation triggering mechanism will be disabled by the "OFF" button.

It was observed at start-up that the resistive load CO3301-3F used in the circuit as a three-phase consumer has a value that is too small, which led to the entry of the generator into oscillation and the sudden increase of the generator current. For this, a resistive load was connected to increase the resistance and thereby eliminate the sudden increase in generator current. The resistive load being adjustable, it was set to its maximum value and the generator was brought to the synchronism speed of 1500 rpm, and then by adjusting the excitation voltage on the rotor winding of the generator, the generator voltage was brought to the value of 410V. From this moment, the resistance of the three-phase resistive load started to be reduced in order to increase the current obtained from the generator. The automatic excitation regulation resistor, driven by the GCP-30 multifunctional relay, began to bring the generator into balance to compensate the load and ensure the output voltage of the generator, by increasing the excitation voltage on the rotor winding.
The speed of the step-by-step generator was reduced, so that the compensation of keeping the three-phase output voltage conditions was achieved by the automatic adjustment of the additional excitation resistance, given by the CGP-30 multifunctional relay. After the limit value set on the GCP-30 multifunctional relay was exceeded, it automatically disconnected the generator from the consumer. The same measurements were made for an increase in generator speed.
It was also observed that, when the load on the generator was high, the voltage and synchronism frequency began to decrease.
It is noted that the protection of the generator through the GCP-30 relay disengages at a speed of 1370 rpm or a frequency value of 45Hz, or increasing at a speed of 1680 rpm or a frequency value of 55Hz.
Thus, the relay disconnects the primary machine at a value of ±10% of the nominal values of current or frequency, protecting the network and the generator.

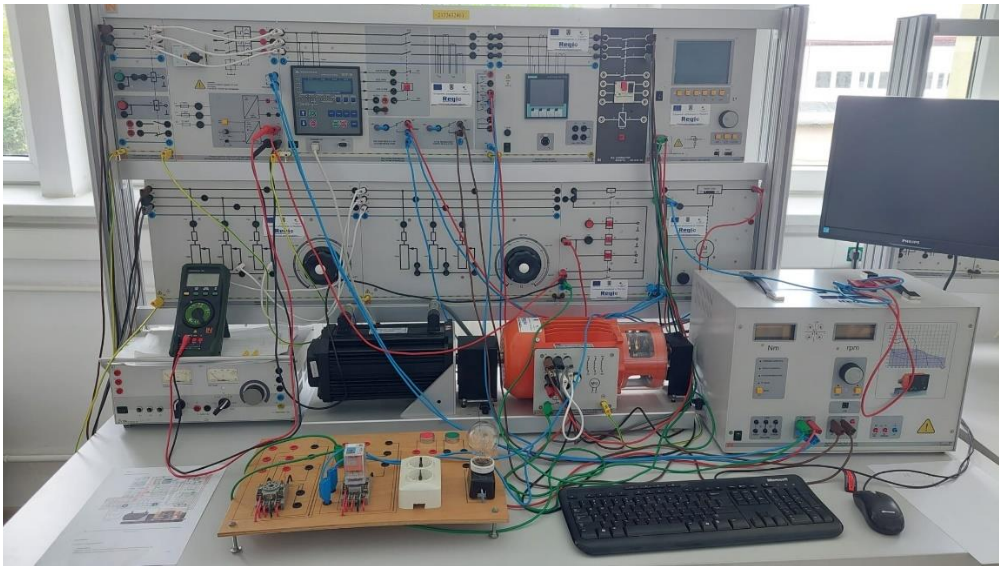


Fig.4.17. Stand for automatic voltage regulation in case of speed variations of the synchronous generator

After the measurements were made, the following data were obtained

Table 4.6. Results obtained for automatic voltage regulation in case of synchronous generator speed oscillations

Generator speed [rot/min]	Frequency [Hz]	Ue [V]	Uerr [V]	I_{err} [A]	Rtotal [Ω]	Rex [Ω]	Rex reg [Ω]	LED status
1344	44.8							disconnect
1378	45.9	396	65.2	0.72	90.56	14.7	75.86	red 5
1400	46.65	397	65.2	0.7	93.14	17.7	75.44	red 4
1422	47.4	396	65.1	0.67	97.16	21.3	75.86	red 3
1444	48.1	398	65.1	0.66	98.64	23	75.64	red 2
1466	48.8	399	65.1	0.64	101.7	26.8	74.92	red 1
1488	49.6	399	65.2	0.62	105.2	29.9	75.26	yellow
1500	50	400	65,1	0,62	105	29,9	75,1	green
1512	50.4	403	65.1	0.61	106.7	31.7	75.02	yellow
1534	51.1	404	65.1	0.6	108.5	33.3	75.2	red 1
1556	51.8	405	65	0.6	108.3	33	75.33	red 2
1578	52.6	405	65.2	0.58	112.4	37.5	74.91	red 3
1620	54	406	65.1	0.565	115.2	40.3	74.92	red 4
1642	54.7	401	65.2	0.54	120.7	45.3	75.44	red 5
1662	55.3							disconnect

After analyzing the results, the following characteristics were established

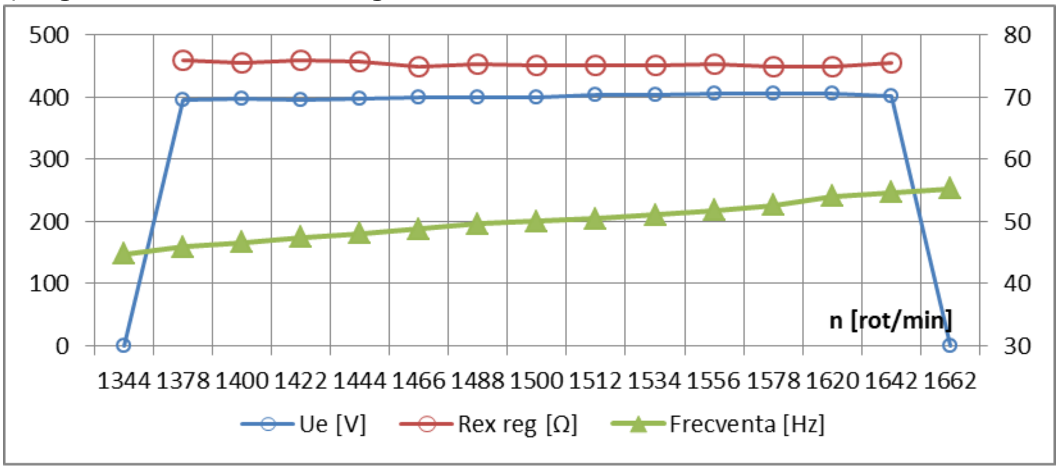


Fig.4.18. Electrical characteristics of the synchronous generator depending on speed

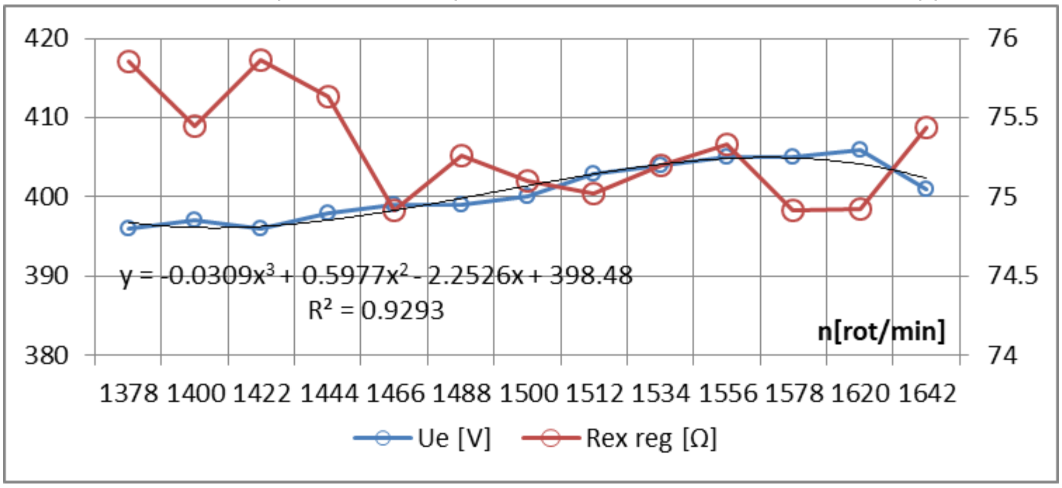


Fig.4.19. Characteristics Ue[V], Rex[Ω]= f(n)

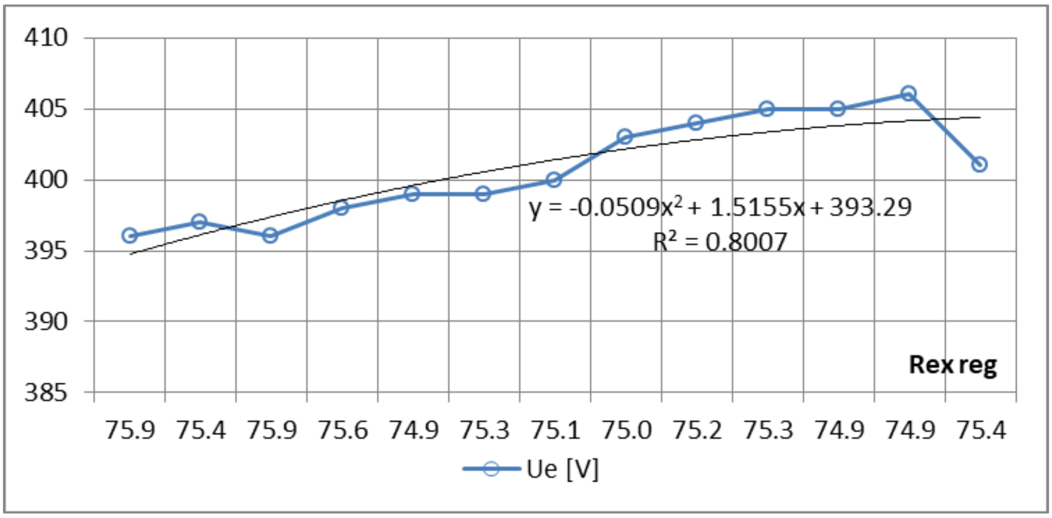


Fig.4.20. Characteristics Ue=f(Rex_{reg})

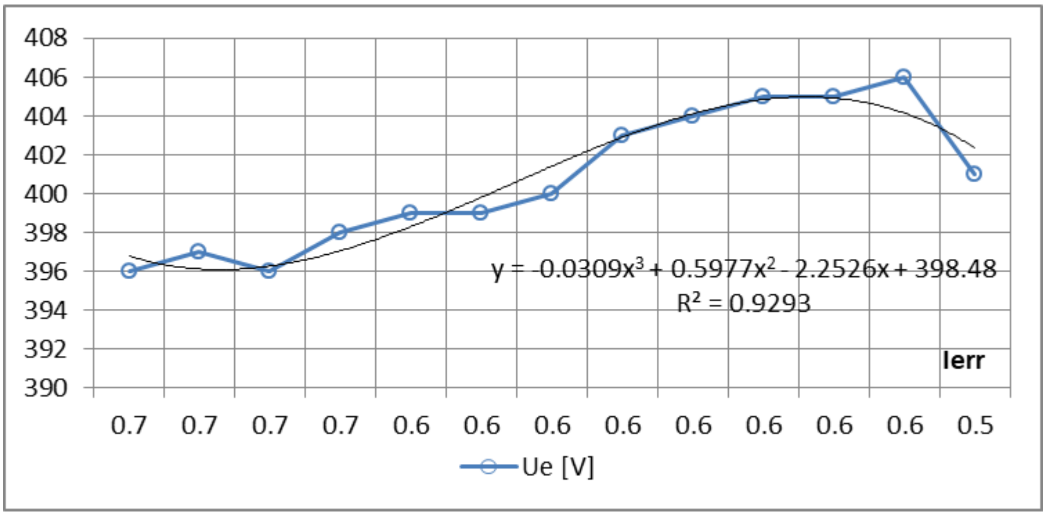


Fig.4.21. Characteristics Ue=f(Ie_{rr})

Analyzing the results obtained in table 4.6, it can be seen how the speed variations from the generator shaft influence the excitation resistance of the rotor winding and implicitly the excitation current. This is sensed by the timing mechanism and controls the excitation resistance so that a constant voltage can be maintained at the output terminals of the generator within the variable frequency limits of ± 10%. In figure 4.18 it can be seen how the generator, at the variation of the frequency f, implicitly the variation of the speed, maintains nominal voltages in the three-phase supply network, through the fine variability of the additional excitation resistance. In figure 4.19. the variation of the additional excitation resistance is observed, showing the dynamism of the automatic regulation system. In the diagrams shown in figures 4.20. and 4.21., the characteristics $Ue=f(Rex_{reg})$ and $Ue=f(Ie_{rr})$ were represented, respectively, which highlight the influence of the excitation resistance and the excitation current in the regulation of the automatic system according to the mechanical variations from the generator shaft.

4.4. Conclusions

Starting from the influenced mechanical and electrical parameters, necessary conclusions were expressed in order to move to the synchronization process. Thus, in this chapter, a stand for manual synchronization with the power grid was made and an electrical diagram was made that performs an automatic synchronization with the grid under the conditions of a variable torque at the shaft in a certain variable range of the generator speed.

In order to continue the research, an experimental assembly was built to achieve the manual synchronization of the synchronous generator with the three-phase power supply network. It was found that, to achieve the four synchronization conditions, an important role is played by the excitation current of the generator provided by the DC power supply. From the four conditions, which relate to the nominal voltages discharged in the network, the nominal frequency, the synchronism and the phase sequence, the nominal frequency can be modified by the value of the excitation current discharged in the rotor winding.

From this point of the research, reaching these conclusions, an experimental assembly was made to identify and monitor the behaviour of the synchronous generator to variations imposed by the torque on the motor shaft. Experimental measurements were made by generating some torques that follow a curve of increasing variation in steps, for two values of the excitation current, 2.5A and 3A. Analyzing these charts comparatively, it is observed that with imposed variations of the motor torque at the shaft of the synchronous machine, the voltages supplied to the terminals keep the same inversely proportional trend in relation to the moment resisting the shaft, but the value of the electrical parameters changes with the increase of the direct current excitation current on the rotor winding. Consequently, it was determined that the value of the excitation current must be changed to compensate for the resistive torques from the shaft of the synchronous machine.

These results led to the need to generate curves of sudden variations in time. The goal was to monitor the behaviour of the synchronous machine in extreme conditions at the shaft of the primary machine (of the wind turbine), so that, at a more pronounced desynchronization, to identify the parameter element capable of returning the synchronous generator to the nominal synchronism conditions. Thus, for a torque characteristic imposed on the machine shaft, the generator speed was destabilized and it was found that the value of the output current is the more stable and linear the closer the value of the excitation current is to the nominal value of the generator. The rest of the parameters are influenced to a small extent by desynchronization from the shaft, but due to the voltage and current in the rotor circuit, the generator has the ability to return to the synchronism conditions.

The following research was based on the design and development of a system that would allow the provision of nominal parameters in the system in the case of torque changes at the wind turbine shaft, or in the case of speed changes.

At the shaft of a wind turbine, in conditions where the wind speed is not constant, variable torques appear that tend to destabilize the speed of the shaft of the synchronous machine. Due to the characteristics of the synchronous generator, the speed can be changed by ±10% compared to the nominal value of 1500 rpm. For various values of the motor torque, the electric circuit was modified and the value of the direct current voltage and the excitation current in the rotor winding was changed. It was found that, with the increase of the engine torque, these values must also be increased, so as not to exceed the nominal value imposed by the studied generator and especially not to exceed the motor torque values in order not to go out of synchronism. Through the designed and studied assembly, the system can take over the variations from the wind turbine shaft and keep within certain limits nominal parameters in the system.

5. FINAL CONCLUSIONS, ORIGINAL CONTRIBUTIONS, DISSEMINATION OF RESULTS, FUTURE RESEARCH DIRECTIONS

5.1. Final conclusions

This doctoral thesis describes the activities carried out by the author for the substantiation of research in the field of wind turbines with synchronous machines together with the theoretical and experimental results obtained, conclusions and future research directions. At the same time, the doctoral thesis presents complex solutions for the automatic synchronization of the synchronous generator with the three-phase power supply network, in order to establish a method of compensating the variable torques at the shaft through the variation of the excitation current on the rotor winding of the generator.

Chapter 1, titled **State-of-the art in the field of wind turbines and synchronous machine** summarizes international, European and national legislative aspects due to the commitments that Romania has taken as a member of the European Union, as a starting point and substantiation for the need to research the thesis considering the current economic context.
Thus, the need for the continuous improvement of wind systems is given by several aspects, namely, the need to increase the production of electricity from renewable sources, a fact that involves the analysis and development of new technical solutions, aspects related to the availability and ability to convert wind energy into electricity, aspects related to the location and namely where they can be located, what architectures of the wind systems are necessary to achieve a high-efficiency conversion, what is the profile of the primary source, aspects related to the increase in energy density on surface, legislation issues, standardization issues and reliability and maintainability issues.
Therefore, in this chapter, theoretical aspects have been systematized related to: the method of converting wind energy into electricity by analysing the primary source and the quantities that influence the yield of the primary conversion (the transformation of the kinetic energy of the wind into mechanical energy), as well as the quantities that influence the secondary conversion (the transformation of mechanical energy into electricity); classification of wind systems according to the principle of operation; of the structure of the wind systems from the point of view of the components taking into account the principle of operation; classification of wind turbines in terms of electrical power given to a consumer or in the network; aspects related to electricity storage and the advantage of grid connection of wind systems that also have storage systems; issues related to the existence of international and national standards that must be complied with by manufacturers; aspects related to the individual reliability of the components of the wind systems and the global reliability that have an economic impact on both the energy producer and the consumer in case of operational problems; network connection issues.

Analyzing all these aspects it was considered that the improvement that could be achieved through this research, to a new wind system or even to an existing one, can be achieved through the command and control of synchronous generators.

In this chapter, the synchronous machine was presented as a component part of the wind turbine, theoretical aspects regarding its construction, its particularities in relation to other rotating electric machines, as well as its role in applications as a motor or as a generator. The synchronous machine was defined, references were made about its role in industrial applications, the role of the stator and rotor in the operation was described, exemplifying two models of synchronous machines depending on the construction variant with a rotor core with submerged poles or with apparent poles.

It should be noted that, at present, all power wind turbines as well as hydroelectric turbines have in their composition, in order to produce three-phase electricity in the network, synchronous generators, which benefit from a very important characteristic that distinguishes them from other electric machines: they have a constant speed, regardless of the operating mode (stabilized) and independent of the value of the load (within considered normal limits).

The synchronous machine is also characterized by the fact that the speed of rotation n of the rotor is found in constant relation to the frequency of the network to which it is connected, and the inductive magnetic field is produced by a system of pairs of poles whose excitation winding is supplied with direct current [24]. It can operate in generator mode or motor mode.

The peculiarity of this machine is related to the fact that the stator winding has three coils that can be supplied with a three-phase system of voltages, if the synchronous machine operates in motor mode, or can discharge three-phase voltages into the network if it operates as a generator. In both situations, the rotor winding must be supplied from a direct current source with a voltage called the excitation voltage. Depending on how this voltage is obtained, there are connection variants that differentiate the assembly of the synchronous machine. In chapter 1, two ways of supplying the excitation system of the synchronous machine were exemplified. In order to cut off a three-phase voltage system at a nominal frequency, it is important to know that with a synchronous machine the speed is that of synchronism and is strictly linked to the frequency of the alternating current network to which the machine is connected, which in Europe is 50Hz [23].

The expression of the electromagnetic torque of the synchronous machine, the power balance as well as its efficiency of 98-98.5%, make it very important in industrial applications, especially where high mechanical torques are needed at low speeds.

For the study of the synchronous machine, it was treated separately, both as a generator and as a motor. The synchronous motor has a wide applicability due to its robustness, it develops a high torque at an acceptable overall size, and due to its air gap, which can be increased compared to other electric machines, it makes it resistant over time. In the study of the synchronous motor, the operating equations were described, its most important characteristics were exemplified, from which it emerged that the excitation voltage and current play an important role in its start-up and regulation. Theoretical notions about synchronous motor starting highlight their heavier starting, operational problems that have been solved nowadays by using frequency inverters and automation systems.

The synchronous generator is treated separately in the work presented, where the role of the stator windings wound offset, at a phasor angle of 120 degrees, as well as the role of the excitation winding, which with a direct current system, provides three-phase parameters in the three-phase supply network, at a nominal frequency of the network, was exemplified. The variability of the synchronous generator is closely related to its control by controlling the excitation voltage and current, a fact that led to the study of this aspect in the following chapters.

Chapter 2, titled **Research on the synchronous machine used as a motor**, presents several experimental researches and case studies that highlight the role and influence of the excitation current in the control of the synchronous motor.

In this chapter, with the help of an experimental stand, mechanical and electrical characteristics n=f(M), I=f(M), P_1=f(M), P_2=f(M), cosφ=f(M), η_f=f(M) were measured for different values of the excitation current from step to step in the range 0.5A – 3A, at different motor torques at the shaft. Research related to this aspect, also presented in published scientific articles, highlighted the role and necessity of excitation current variability in synchronous motor control.

The research continued with the generation of torque curves to demonstrate that the synchronous machine maintains constant speed regardless of shaft load within normal limits. Different torque characteristics were generated at different excitation current values. Research has shown that the synchronous machine maintains constant revolutions at variable and imposed torques, so that they continue their operation and do not reach the out-of-synchronism state. Load peaks can be reduced and in some cases canceled by adjusting the excitation current in the rotor winding, thus by influencing the rotor inductor magnetic field.

In the last part of Chapter 2, different load curves were created and applied to the machine shaft. Torque curves were created to simulate possible wind gusts from the shaft of a wind turbine, increasing both the motor torque value and the time interval in which an anomaly is stationary on the turbine blades. Part of the load curves were also applied in chapter 4, where the synchronous machine in generator mode was studied.

The resulting characteristics showed the stability over time and at variable loads of the synchronous machine. The motor, even if it was destabilized in some situations, returned to nominal parameters when cancelling the undesirable conditions.

Following the conclusions of the experimental research, we moved to the next level, namely to studies related to the research on the synchronous generator.

The research results on the synchronous motor from this doctoral thesis, disseminated through the publication of 4 articles in international databases, were the basis of future research directions and will strengthen the already existing collaborations.

Chapter 3, titled **Research on the synchronous machine used as a generator** continues the previous research through original contributions related to the construction of an assembly that allowed the research of the synchronous machine in generator mode. Since the characteristics of the generator are important in further research, these characteristics have been established for a synchronous machine with the following nominal data. P_n=0.27kW, I_n=1.5A, f=50Hz, n=1500rot/min, Ue_{rr}=20Vcc; Ie_{rr}=4A. Tracing the characteristics of the generator led to further research, presented in the next chapter.

Chapter 4 titled **Original contributions on the design and development of the stand for synchronizing the generator to the grid** presents research that leads to the implementation of a system for automatic adjustment of the parameters of synchronization with the three-phase network according to the variability of the speed of the generator shaft.

To really see the role and influence of the excitation current, the stand in figure 4.6 was built, which represents an original contribution in this study. Certain modules were assembled to highlight the manual synchronization process, keeping the 4 conditions of coupling to the three-phase electricity network: line voltages of the same value as the network, generator frequency equal to the network, phase sequence and phase synchronism. By developing any of the diagrams presented in figures 4.2., 4.3., 4.4. it is possible to synchronize the synchronous generator with the three-phase supply network. The fine adjustment of the excitation voltage is highlighted, which influences the excitation current required to adjust the connection parameters.

Thus, through the stand made in figure 4.7. which represents an original contribution, a three-phase asynchronous motor controlled by a frequency inverter was connected to the gear chain. This brought the speed of the generator to 1500 rpm, which allowed the servomotor assembly to apply the variable and imposed load curves, which were also studied in chapter 3 but in the mode of operation as a motor. Applying torque characteristics to different values of the excitation current, the influence of the excitation current on the rotor winding, in the stability of the synchronous machine when a stepwise, imposed or sudden variable motor torque appears on the shaft of a wind turbine, has been observed.
Research has been done on choosing the right automatic synchronization scheme so that the expenses be minimal, feasible and efficient. The final assembly presented in this work in figure 4.17. is an original contribution that studied the automatic regulation of the excitation current in the case of speed oscillations of the synchronous generator. The assembly contains an automatic synchronizer that stabilizes the output voltage of the generator around 400 V at speed variations up to a minimum value of 1367 rpm and a maximum value of 1650 rpm, under the conditions of a nominal speed of 1500 rpm, which is a nominal parameter of the synchronous generator. Thanks to an automatically controlled additional resistance assembled in series with the excitation rotor winding, the system allows automatic control of this resistance, at variable or sudden speeds, while maintaining the output voltage of the generator. The resulting charts highlighted the importance of the current and implicitly the excitation resistance in the stability of the wind system.

5.2. Original contributions

As the author of the doctoral thesis, I consider the following to be novelty, the result of creative effort:
1. Determination of the mechanical and electrical characteristics of the synchronous motor by configuring a system that allowed studying them according to different values of the excitation current.
2. Studying the parameters of the synchronous generator in different scenarios of variation of the mechanical parameters (increasing, imposed or sudden variations).
3. Construction and configuration of a system that allowed accurate determination of the characteristics of the synchronous generator.
4. Development of the test procedure that allowed the manual synchronization of the synchronous generator with the three-phase power supply network.
5. The configuration and construction of a system that allowed the automatic synchronization of the generator with the three-phase supply network by the automatic adjustment of the excitation current in case of speed variations on the shaft of the synchronous generator.
6. Conception, design and construction of stands in order to carry out experimental determinations:

- Stand for starting and synchronizing the generator manually;
- Stand for determining the characteristics of the synchronous generator;
- Stand for automatic voltage regulation in case of speed variations of the synchronous generator.

5.3. Dissemination of results

In the paper presented, three stands were described and developed, they represent original contributions related to the study, coupling and synchronization of the synchronous generator. These stands were made in the laboratories of Remus Raduleț Brașov Power Systems Technical High School.

The research results have been published like this:

1. **C Cristea**, I. Stroe, Study of the mechanical and electrical characteristics of the synchronous motor with varying resistive torque, IOP Conf. Series: Materials Science and Engineering 568 (2019) 012011, **DOI**10.1088/1757-899X/568/1/012035
2. **C Cristea**, I. Stroe, Modelling the mechanical and electrical characteristics of the synchronous motor for different variations of torque in time, IOP Conf. Series: Materials Science and Engineering 568 (2019) 012011, **DOI** 10.1088/1757-899X/568/1/012011
3. **C Cristea**, I., Stroe, Modelling the mechanical and electrical characteristics of the synchronous motor, IOP Conf. Series: Materials Science and Engineering 514 (2019) 514 012022, DOI 10.1088/1757-899X/514/1/012022
4. **C Cristea**, I. Stroe, The study of the synchronous motor, Bulletin of the Transilvania University of Braşov Vol. 10 (59) No. 2- 2017, Series I: Engineering Sciences, pp. 31-38,
   ISSN (Online): 2971-9364

5.4. Future Research Directions

Starting from the study of the synchronous machine used in wind applications, the author's future research objectives are directed towards:
- Modelling the processes that take place during automatic synchronization by adjusting the additional excitation resistance and the excitation current;
- Conception, characterization and patenting of electrical and mechanical schemes, together with researchers from the Department of Product Design, Mechatronics and Environment from Transilvania University in Brașov;
- Development of methods for testing wind influences in the synchronization process with the three-phase power supply network;
- Creating a collaborative partnership with companies that install wind turbines in order to implement the solutions obtained in the field;
- Creating partnerships and collaborations with other research groups in the field of wind turbines and synchronous generators.

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