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LABORATORY TEST AND MODELLING OF SMALL PM SYNCHRONOUS MACHINES

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Madrid
Junio 2016

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Laboratory Test and Modelling of Small PM Synchronous Machines

Autor: José María Hidalgo Arteaga

Director: Trond Toftevaag

Entidad colaboradora: Norges teknisk-naturvitenskapelige universitet (NTNU)

RESUMEN

Introducción

La máquina síncrona de imanes permanentes (PMSM) es una solución útil para muchos problemas diarios de ingeniería. El uso de imanes permanentes en el rotor, en lugar de campos magnéticos creados por las corrientes de excitación en los devanados del rotor, puede dar varias ventajas en muchas aplicaciones.

Las principales aplicaciones de las máquinas síncronas de imanes permanentes están en servomotores, motores eléctricos, robótica y ascensores. Es una solución adecuada para pequeños problemas de ingeniería.

El diseño es simple con imanes permanentes: el rendimiento aumenta porque no existen las pérdidas en el cobre de los bobinados del rotor, el volumen puede reducirse debido a que sólo depende de la distribución de los imanes y por lo tanto, el peso y el precio puede reducirse también.

Puede ser utilizado como un generador, pero debido a que tiene una excitación constante por imanes, ésta no puede ser controlada externamente. Esta pérdida de la capacidad de control de excitación es una limitación que provoca una caída de tensión en los terminales cuando la carga del generador se incrementa. Este fenómeno se puede ver en este trabajo, donde las máquinas síncronas de imanes permanentes se usan como generador.

Una vez visto la utilidad de las máquinas síncronas de imanes permanentes y el atractivo de su estudio, la NTNU encuentra interesante construir este tipo de generadores síncronos para aprovechar el proceso de aprendizaje durante su diseño, prueba y modelado. Como objetivo del proyecto está el explicar y modelar todo fenómeno que éstas máquinas síncronas de imanes permanentes hechas a mano pueden mostrar.

Este proyecto es parte de un estudio más grande y de la investigación que el Departamento de Ingeniería Eléctrica De Potencia de la NTNU ha estado llevando a cabo durante los tres o cuatro últimos semestres. Durante los semestres de otoño de 2014 y otoño de 2015, estudiantes de dicha universidad han diseñado y fabricado estatores para máquinas síncronas de imanes permanentes.

Mi parte en este trabajo trata de hacer pruebas a algunos de estos estatores de las máquinas síncronas de imanes permanentes, incluyendo estatores manufacturados por

profesores en el taller eléctrico, modelar los circuitos eléctricos de las máquinas síncronas y hacer una evaluación de las características y el comportamiento de estos estatores de generadores síncronos de imanes permanentes.

Con el fin de lograr resultados en este trabajo, bajo la supervisión de Trond Toftevaag, se utilizó el tiempo de trabajo para llevar a cabo mediciones en los diferentes estatores de las máquinas síncronas, hacer cálculos para obtener el modelo y analizar los resultados.

El principal objetivo de este proyecto es hacer pruebas y modelar diversas pequeñas máquinas síncronas con el fin de obtener una explicación adecuada de la conducta y el modelo estático físico que describe las máquinas. El estudio de máquinas síncronas de imanes permanentes con características distintas ayudará a entender las significativas diferencias que hay en la forma en que fueron diseñadas.

Metodología

La metodología aplicada para obtener resultados en este proyecto se ha basado en trabajo de laboratorio, tomar medidas de las pruebas en las máquinas síncronas de imanes permanentes, cálculos basados en estas mediciones y un análisis de estos resultados obtenidos.

Se utilizaron cinco estatores diferentes para la construcción de cinco máquinas síncronas de imanes permanentes diferentes, el rotor imanes permanentes fue el mismo en todos los generadores. Todas las máquinas síncronas fueron diferentes en características mecánicas como el número de espiras por bobina, espesor del alambre y similar. La medición de estas máquinas síncronas en las mismas condiciones permitió descubrir la influencia todas las características de cada máquina síncrona en su funcionamiento.

Los generadores estaban conectados a una carga puramente resistiva variable. El eje del rotor estaba conectado a un controlador de velocidad que proporcionaba par y velocidad a la máquina eléctrica. Las pruebas de laboratorio realizadas en las máquinas síncronas de imanes permanentes consistieron en hacer funcionar cada generador desde la situación sin carga a la situación de carga máxima. Las pruebas se realizaron en cuatro velocidades diferentes (1600 rpm, 1400 rpm, 1200 rpm y 1000 rpm) y con diferentes materiales en el soporte del estator.

Las mediciones hechas con este análisis de laboratorio eran básicamente tensiones de fase, corrientes de línea, potencia de la carga, par motor y la velocidad del rotor.

Los cálculos realizados a partir de las mediciones estaban relacionados con el balance de potencia, el rendimiento de la máquina, las pérdidas de potencia y la principal incógnita que era la reactancia sincrónica.

Todos estos cálculos se analizaron con Excel y a partir de ellos se sacaron conclusiones. Se utilizó un modelo de una de las máquinas síncronas en el software COMSOL para comparar los resultados de la simulación con las mediciones realizadas. Los datos de este software se analizaron con Matlab y luego se compararon con los resultados obtenidos previamente en Excel.

Resultados

Las observaciones realizadas, a partir del análisis de las mediciones hechas en el laboratorio de los generadores síncronos, llevan a ciertas conclusiones sobre el comportamiento de las máquinas síncronas. Estas conclusiones son en función de las tensiones, corrientes, rendimiento, balance de potencia, pérdidas de potencia y reactancia sincrónica.

La tensión de fase disminuye con la corriente de carga, que alcanza su valor más elevado en condición de vacío. Esto ocurre debido al aumento de la caída de tensión con la corriente, puesto que la impedancia síncrona tiene el mismo valor independientemente de la corriente. También el hecho de que no haya ninguna regulación de la tensión hace que esto ocurra.

La velocidad del rotor es también un factor importante que provoca el aumento de tensión de fase. Cuanta más alta es la velocidad, más alta serán las tensiones de fase independiente de la carga de la máquina.

La variación de las tensiones de fase y las corrientes de línea con el material de soporte de los estatores es despreciable, pero no con el número de vueltas en los arrollamientos o el espesor de alambre. De las pruebas se ha visto que cuanto mayor es el número de vueltas mayores son las tensiones de fase. También el grosor del alambre es un factor limitante para la corriente de línea, puesto que alcanza valores más altos con alambres más gruesos en las bobinas del estator.

Aunque el material de soporte de los estatores no tiene nada que ver con las tensiones, éste tiene una gran influencia en el rendimiento de las máquinas síncronas. Cuando los materiales de apoyo son metálicos, el rendimiento es bajo y cuando los materiales de apoyo son de madera o de plástico, el rendimiento aumenta. Esto sucede porque en los materiales metálicos se inducen corrientes de Foucault que producen una pérdida de potencia en la máquina síncrona.

Cuanto más baja es la velocidad más alto es por lo general el rendimiento observado. La mayor parte de las pérdidas de potencia están en el cobre y son cuadráticamente dependientes de la corriente de carga. También el espesor de los hilos y la resistencia del estator tienen que ver con esto. Cuando el cable es grueso, puede contener corrientes más altas, y por lo tanto, provocar el aumento de las pérdidas de potencia. La velocidad del rotor tiene un efecto en esto también debido a su efecto sobre las tensiones de fase y las corrientes de línea.

La reactancia sincrónica y las inductancias sufren una variación con la corriente de carga. En corrientes de carga bajas, las inductancias tienen un alto valor. Al aumentar la carga, las inductancias consiguen estabilizarse en un valor más bajo. Esta variación de la reactancia sincrónica no es debida a la velocidad, pero sí a las inductancias.

Las variaciones en las inductancias con la corriente se pueden explicar por un aumento del flujo magnético. Al aumentar la corriente de carga, el campo magnético del estator aumenta, sumado al campo magnético constante en el rotor, el campo magnético en el entrehierro es mayor. Esto podría causar una saturación magnética del rotor que provoca una disminución de la permeabilidad magnética. La permeabilidad magnética está relacionada linealmente con el valor de las inductancias y la reactancia sincrónica.

Los resultados de las simulaciones con el software COMSOL conducen a conclusiones similares, a pesar de que el modelo se hace para una máquina síncrona perfecta en perfectas condiciones. Las tensiones de fase y las corrientes de línea son ligeramente superiores en las simulaciones pero la reactancia sincrónica tiene valores similares y el mismo efecto con la corriente.

Laboratory Test and Modelling of Small PM Synchronous Machines

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ABSTRACT

Introduction

The Permanent Magnets Synchronous Machine (PMSM) is a useful solution to many daily engineering problems. The use of permanent magnets in the rotor, instead of magnetic fields created by excitation currents in rotor windings, can give several advantages in many applications.

The main applications of PM synchronous machines are in servomotors, electric drives, robotics and elevators. It’s a suitable solution for little engineering problems.

The design is simple with permanent magnets, the efficiency increases because the copper losses in the rotor windings doesn’t exist, the volume can be reduced due to that it only depends on the distribution of the magnets and therefore, the weight and price can be reduced too.

It can be used as a generator but having a constant excitation because of the magnets implies that this excitation can’t be controlled. This loss of the excitation control capability is a constraint that makes the terminal voltage drop when loading the generator. This phenomenon can be seen in this project work, where the PM synchronous machines are run as a generator.

Once seen the utility of PM synchronous machines and its attractiveness to study, NTNU finds interesting to build this synchronous generators to take advantage of the learning process during the designing, testing and modelling them. As a goal there is the capability of explaining and modelling every phenomenon that handmade PM synchronous machines can show.

This project is a part of a bigger study and research that the Department of Electric Power Engineering of NTNU have been carrying out during the previous three or four semesters. During autumn 2014 and autumn 2015 semesters, students from the course ‘TEP 4175: Energy from Environmental Flows’ have been designing and making stators for PM synchronous machines.

My part in this work is about testing some of this stators of PM synchronous machines, including stators made by the electric workshop, modelling the electrical circuits of the synchronous machines and make an evaluation of the characteristics and the behaviour of this PM synchronous generators stators.

In order to achieve results in this work, under the supervision of Trond Toftevaag, the labour time was used to perform measurements in the different stators of the PM synchronous machines, make calculations to get the model and analyse the results.

The main objective of this project is to test and model various small PM synchronous machines in order to get a proper explanation of the behaviour and the physical static model that describes the machines. Studying PM synchronous machines with distinct characteristics will help to understand how significant this differences are in the way they were designed.

Methodology

The methodology applied to get results in this project work has been based in laboratory work, measurements from tests in the PM synchronous machines, calculations from this measurements and a further analysis of this results.

Five different stators were used to build five different PM synchronous machines, the permanent magnets rotor was the same in all the generators. All the synchronous machines were different in mechanical characteristics as number of turns per coil, thickness of the wire and similar. Measuring this synchronous machines in the same conditions let discovering what the influence is of every characteristic in the functioning of synchronous machines.

The generators were connected to a pure variable resistive load. The rotor’s axis was connected to a speed controller that give torque and speed to the electric machine. The laboratory tests performed on the PM synchronous machines consisted on running every generator from no-load situation to maximum load situation. The tests were performed in four different speeds (1600 rpm, 1400 rpm, 1200 rpm and 1000 rpm) an with different materials in the support of the stator.

The measurements made from this laboratory tests were about phase voltages, line currents, power load, torque and speed of the rotor.

The calculations made from the measurements were about power balance, efficiency, power losses and the main unknown that was the synchronous reactance.

All this calculations were analysed with Excel and conclusions were made from them. A model of one of the synchronous machines in the software COMSOL was used to compare the simulation results with the measurements performed. The data from this software was analysed with Matlab and then compared to the results got in Excel.

Results

The observations made from the analysis of the measurements of the synchronous generators leaded to some conclusions about the behaviour of PM synchronous machines in terms of voltages, currents, efficiency, power balance, losses and synchronous reactance.

The phase voltage decreases with the load current, having the largest value in no-load condition. This happens due to the increase of the voltage drop with the current because the synchronous impedance remains the same. Also the fact that there isn’t any regulation of the voltage make this happen.

The speed of the rotor is also an important factor that makes the phase voltage increase. The higher is the speed the higher will be the phase voltages independently from the load of the machine.

The variation of the phase voltages and line currents with the supporting material of the stators is negligible but not with the number of turns or wire thickness. From the tests it’s seen that the higher is the number of turns the higher is the phase voltages. Also the thickness of the wire is a limiting factor for the line current having larger values with thicker wires in the stator coils.

Although the supporting material of the stators doesn’t have anything to do with the voltages, it has a big influence in the efficiency of the synchronous machines. When the supporting materials are metallic the efficiency is low and when the supporting materials are wooden or plastic the efficiency increases. This happens because metallic materials hold eddy currents that make a power loss in the synchronous machine.

The lower is the speed the higher is usually the efficiency observed. The largest part of the power losses is in the copper and it’s strongly dependent on the load current. Also the thickness of the wires and the resistance of the stator has to do with them. When the wire is thick, it can hold higher currents and therefore the power losses increase. The speed of the rotor has an effect on it due to its effect on the phase voltages and line currents.

The synchronous reactance and the inductances suffer a variation with the load current. At low load currents, the inductances have a high value. When increasing the current load, the inductances get stabilised in a lower value. This variation of the synchronous reactance isn’t due to the speed but to the inductances.

The inductances variations with the current can be explained with an increase of the magnetic flux. When increasing the load current, the stator magnetic field increases, summed to the constant magnetic field in the rotor, there is a higher magnetic field in the air gap. This could cause a magnetic saturation of the rotor that provokes a decrease of the magnetic permeability. The magnetic permeability is linearly related to the value of the inductances and synchronous reactance.

The results of the simulations with the software COMSOL lead to similar conclusions, even though the model is made for a perfect synchronous machine in perfect conditions. The phase voltages and line currents are slightly higher in the simulations but the synchronous reactance has similar values and the same effect.

AKNOWLEDGEMENTS

I would like to show my gratitude to the people that has made possible and have helped me to perform this specialisation project during my semester studying in the Norwegian University of Science and Technology in Trondheim.

First of all I want to express my special gratitude to my project supervisor Trond Toftevaag. He gave me the possibility to do a project work in NTNU under his supervision and guidance, spending enough time on me.

I also would like to thank Aksel A. R. Hanssen for his help with the machinery from the electric laboratory and for his availability when I needed him.

Finally I want to thank Christian Svihus for providing me data from COMSOL simulations to include a further analysis in my project.

PREFACE

This report is the result of a specialisation project performed in the course “TET5500 - Electric Power Engineering, Specialization Project” in the Department of Electric Power Engineering in the Norwegian University of Science and Technology, during my Erasmus spring 2016 semester in Trondheim, Norway.

This project work is also made as a Bachelor Thesis from the bachelor degree in Electromechanical Engineering that I study in my home school of engineering ICAI, Universidad Pontificia de Comillas, in Madrid.

With this project I wanted to gain knowledge about the behaviour and functioning of the permanent magnets synchronous machines in a more detailed way that I didn’t learn before.

Also the purpose of this report of my work is to demonstrate my abilities learned during my studies in my home university and abroad in the fields of engineering and the performance of engineering projects.

José María Hidalgo Arteaga

June 2016, Trondheim, Norway.

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1. INTRODUCTION

1.1 Background

The Permanent Magnets Synchronous Machine (PMSM) is a useful solution to many daily engineering problems. The use of permanent magnets in the rotor instead of magnetic fields created by excitation currents in rotor windings can give several advantages in many applications.

The main applications of PM synchronous machines are in servomotors, electric drives, robotics and elevators. It's a suitable solution for little engineering problems.

The design is simple with permanent magnets, the efficiency increases because the copper losses in the rotor windings doesn't exist, the volume can be reduced due to that it only depends on the distribution of the magnets and therefore, the weight and price can be reduced too.

It can be used as a generator but having a constant excitation because of the magnets implies that this excitation can't be controlled. This loss of the excitation control capability is a constraint that makes the terminal voltage drop when loading the generator. This phenomenon can be seen in this project work, where the PM synchronous machines are run as a generator.

Once seen the utility of PM synchronous machines and its attractiveness to study, NTNU finds interesting to build this synchronous generators to take advantage of the learning process during the designing, testing and modelling them. As a goal there is the capability of explaining and modelling every phenomenon that handmade PM synchronous machines can show.

This project is a part of a bigger study and research that the Department of Electric Power Engineering of NTNU have been carrying out during the previous three or four semesters. During autumn 2014 and autumn 2015 semesters, students from the course 'TEP 4175: Energy from Environmental Flows' have been designing and making stators for PMSM.

My part in this work is about testing some of this stators of PM synchronous machines, including stators made by the electric workshop, modelling the electrical circuits of the synchronous machines and make an evaluation of the characteristics and the behaviour of this PMSM stators.

In order to achieve results in this work, under the supervision of Trond Toftevaag, my labour time was used to perform measurements in the different stators of the PM synchronous machines, make calculations to get the model and analyse the results. My results are contrasted with the previous work and with COMSOL simulations of a model that Christian Svihus provided me.

1.2 Objective

The main objective of this project is to test and model various small PM synchronous machines in order to get a proper explanation of the behaviour and the physical model that describes the machines. Studying PM synchronous machines with distinct characteristics will help to understand how significant this differences are in the way they were designed.

1.3 Scope of Work

In order to achieve proper results from this project, the work is approached in the following ways:

-Study of literature about PM synchronous machines and its physical principles and models.

-Gather and study reported information about previous works with PM synchronous machines made by students.

-Test PM synchronous machines in the electric laboratory and collect data for further analysis.

-Compare results with COMSOL model simulations.

1.4 Software for Simulations

COMSOL Multiphysics Modelling Software is used as a field calculation tool and therefore to simulate the behaviour of a PM synchronous machine from a previously built model. This model used has been developed by Christian Svihus, who provided me with the results of his study.

This is used as an additional tool in this project, where the main focus of the work is the laboratory measures and analysis of the data.

1.5 Limitations

This project is limited to a study and modelling of the static electric model of PM synchronous machines. The dynamic model isn’t covered because the project isn’t focused in the transients in PM synchronous machines or in non-constant functioning but in its steady state operation.

This work is also focused in the electrical side of PM synchronous machines meaning that mechanical analysis and magnetic field studies will be briefly mentioned.

1.6 Laboratory

Most of the project is carried out in the electrical laboratory in the Faculty of Information Technology, Mathematics and Electrical Engineering in NTNU, where I had a spot to coupling every stator with the PM rotor to build the synchronous machines, to test every PM synchronous machine with the instrumentation and machines provided and to analyse the data collected.

2. THEORY

In this chapter are explained the basic physical concepts to understand how a synchronous generator works and how it will be analysed and studied in later chapters from this report.

This includes the principles of functioning, basic concepts of electromagnetism, the electrical model of the synchronous machine and the power balance analysis between source and load

2.1 Principles of Functioning

Synchronous generators are synchronous AC machines that convert mechanical power into electrical AC power. They are called synchronous because the speed of the rotor is synchronised with the frequency of the AC voltage in the stator. Depending on the number of pairs of poles that the synchronous machine has, the relation will be:

$$\omega_e = p\omega_m$$

Where:

- ω_e is the electrical speed in rad/s, that is related to the electrical frequency $\omega_e = 2\pi f_e$.
- p is the number of pairs of poles.
- ω_m is the rotor speed in rad/s. In rpm would be $n = \frac{60}{2\pi}\omega_m$

From this equations the following relation between the speed of the rotor and the electric frequency of the stator is stated:

$$n = \frac{60}{p} f_e$$

Like in every AC machine, both the stator and the rotor generate rotary magnetic fields that, when they aren't aligned, create a torque that tries to align them while they rotate. This is the principle that makes the rotor spin or the stator magnetic field rotate too. This is easily described in the next figure:

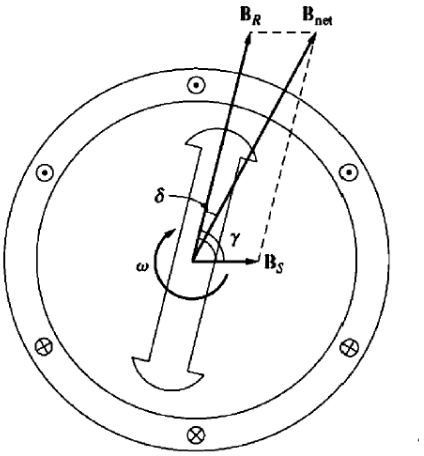


Figure 1. Rotary magnetic fields of stator and rotor.

The torque induced by the magnetic fields of the stator and rotor is:

$$\tau_{ind} = kB_R \times B_S$$

Simplifying the vector multiplication we get:

$$\tau_{ind} = kB_R B_S \sin\gamma$$

Where:

- τ_{ind} is the induced torque.
- B_R is the magnetic field of the rotor.
- B_S is the magnetic field of the stator.

In a synchronous generator, the magnetic field in the stator B_S will always come from the induced voltage or electromotive force E in the windings. This electromotive force is induced by the magnetic field in the rotor B_R.

Depending on how is the rotor, the magnetic field B_R can be generated in different ways. Commonly, the rotor induces this magnetic field from an excitation DC current that flows through windings in the rotor, or it generates the magnetic field with magnets adhered to the rotor, this generators are called Permanent Magnets Synchronous Machine (PMSM). The rotor used in this project has this second technology. In the next figure is represented a schematic of a section form a PMSM.

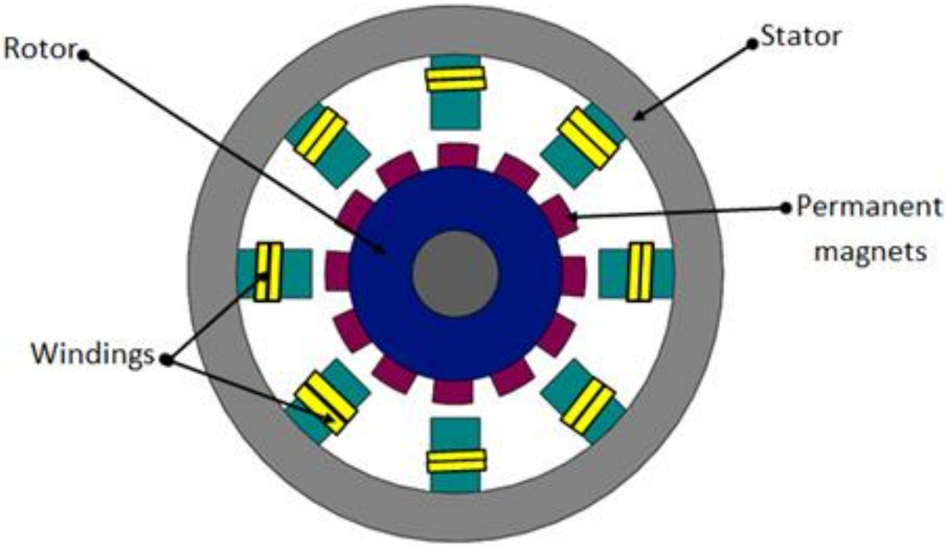


Figure 2. Permanent Magnets Synchronous Machine

To make the rotor spin when working as a generator, an external torque applied to the rotor's shaft is needed. It can come from a turbine or a DC machine for example.

2.2 Electromagnetism in Synchronous Generator

The induction of a voltage in the synchronous generator is explained by Faraday’s law:

$$E = -\frac{d\phi}{dt}$$

This law states that a voltage or electromotive force E is induced in a wire when a time variable magnetic flux ϕ passes through it.

To calculate the flux ϕ we can start with the Ampère’s law:

$$\oint Hdl = \sum_{k} i_k$$

In this law is stated that the line integral of the intensity of magnetic field H along a circumference surrounding perpendicularly the wires is equal to the sum of the intensities, in this case, the number of windings N multiplied by the current in one winding i. Solving the integral we get:

$$Hl = Ni$$

$$H = \frac{Ni}{l}$$

The magnetic field B can be calculated from the intensity of magnetic field H.

$$B = \mu H$$

Where μ is the magnetic permeability of the medium, air in this case. So from this we have that:

$$B = \mu\frac{Ni}{l}$$

As the magnetic field is rotating, the magnetic field will be dependent on time:

$$B(t) = \mu\frac{Ni}{l}\cos(\omega_e t - \theta)$$

The magnetic flux through the surface S is calculated from the magnetic field:

$$\phi(t) = \int_S BdS = \mu\frac{Ni}{l}\mathrm{S}\cos(\omega_e t - \theta)$$

The magnetic flux that induces the voltage in the stator coils is in the air gap between rotor and stator. From the magnetic flux dependent on time, an electromotive force can be induced:

$$E = -\frac{d\phi}{dt} = \mu\frac{Ni}{l}\mathrm{S}\omega_e\sin(\omega_e t - \theta)$$

2.3 Equivalent Electric Circuit

To analyse phase voltages, currents and power balance an equivalent electrical circuit of the synchronous generator is needed. The model used is the static model due to the measurements of the generators are in steady state, a transient analysis isn’t required here.

This electrical model shows the behaviour of a single phase synchronous machine, or in one phase of a three phased generator:

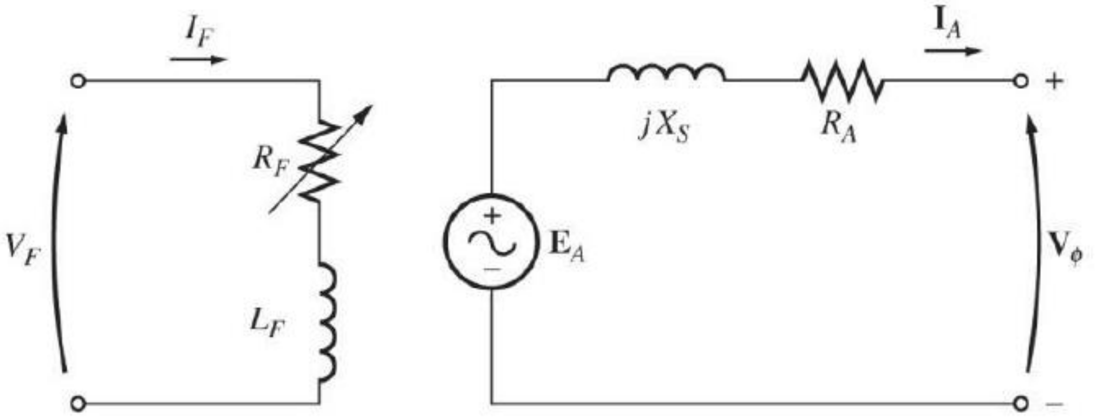


Figure 3. Equivalent circuit of single phase synchronous machine. Stator in the right, rotor in the left.

Where:

- E_A is the electromotive force induced by the air gap magnetic flux. It can be measured from the terminals of the stator when there is no load ($I_A = 0$).
- V_ϕ is the phase voltage measured in the terminals of the stator.
- I_A is the line current.
- R_A is the stator resistance of the coils.
- X_S is the synchronous reactance of the stator. This synchronous reactance is the sum of two other reactance: $X_{\sigma S}$ (leakage reactance) and X_A (self-reactance). So we have that $X_S = X_{\sigma S} + X_A$. The self-reactance is bigger that the leakage reactance so this last one can be neglected in some cases.
- The circuit in the left side with its parameters V_F, I_F, R_F, L_F represent the circuit of the rotor that results in a magnetic flux that creates the electromotive force in the stator.

When the synchronous machine is three phased, it will be an equivalent circuit per phase. The values of the resistances, reactance and electromotive forces must be similar when the three phase system is equilibrated.

According to the stators analysed are handmade, they aren’t perfectly manufactured so when testing the synchronous machines is important to distinguish between each phase circuit and its own ‘different but similar’ resistances, reactance and electromotive forces.

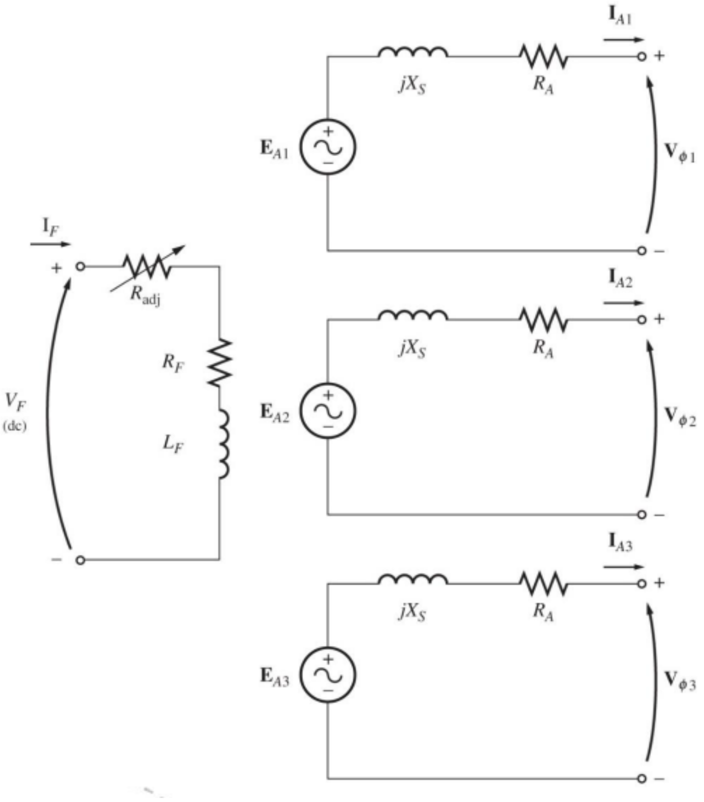


Figure 4. Equivalent circuit of three phase synchronous machine.

All the calculations of electrical parameters per phase will be handled with this formula:

$$E_A = V_\phi + jX_S I_A + R_A I_A$$

This can be easily seen in the phasor diagram of the stator of the synchronous generator:

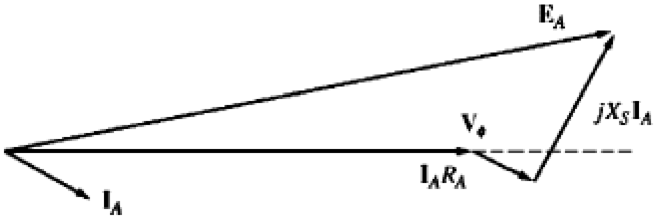


Figure 5. Phasor diagram of the stator when phase lag between phase voltage and current.

The load used for the tests of the synchronous generators is pure resistive so $\cos\varphi = 1$. This will change the phasor diagram into a simplified one:

Figure 6. Phasor diagram when pure resistive load.

The calculation we are more interested in is the synchronous reactance of the stator so when power factor is unitary, the synchronous reactance is:

$$X_S = \sqrt{\frac{E_A^2 - (V_\phi - R_A I_A)^2}{I_A^2}}$$

The inductance L_S, which is strongly related to the reactance can be easily calculated:

$$X_S = \omega L_S$$

2.4 Power Balance

To analyse the efficiency and calculate the losses a power balance is needed. First of all, to calculate the input power, the power from the rotor's shaft P_{in}, it's only needed the following formula:

$$P_{in} = \tau_s \omega_m$$

Where τ_s is the torque in the shaft. The output power is calculated from the phase voltage and current (with resistive load), in single phase:

$$P_{out} = V_\phi I_A$$

In three phase is:

$$P_{out} = V_{\phi 1} I_{A1} + V_{\phi 2} I_{A2} + V_{\phi 3} I_{A3}$$

The total power losses are calculated from the difference between the input power and output power:

$$P_{loss} = P_{in} - P_{out}$$

To calculate the power losses in the wires:

$$P_{Cu} = R_A I_A^2$$

Or in the case of three phase generator:

$$P_{Cu} = R_{A1} I_{A1}^2 + R_{A2} I_{A2}^2 + R_{A3} I_{A3}^2$$

From the difference between the total power losses and the copper loses in the wires we get the power losses in the iron and mechanical losses. This losses can be observed separately when the current is zero because the copper power losses will be zero too.

$$P_{loss} = P_{Cu} + P_{Fe} + P_{mech}$$

Finally the power efficiency of the synchronous machine is:

$$\eta = \frac{P_{out}}{P_{in}}$$

3. DESCRIPTION OF PM SYNCHRONOUS MACHINES UNDER STUDY

This chapter analyses the characteristics of the different permanent magnets synchronous machines tested. As I have tested five different synchronous generators, the same permanent magnets rotor is used for the five machines.

This means that there are five different stators and only one rotor, which has to be changed from one stator to another every time I want to performance a test in other synchronous machine.

3.1 Permanent Magnets Rotor

The permanent magnets rotor has 6 magnetic poles (3 pairs of poles). As the magnetic flux of the rotor is radial, in a section of the rotor, the flux has to go from the centre to the exterior of the rotor. This means that the permanent magnets from each pole are in the surface of the rotor, each pole 60 degrees form the next one and 60 degrees from the previous one.

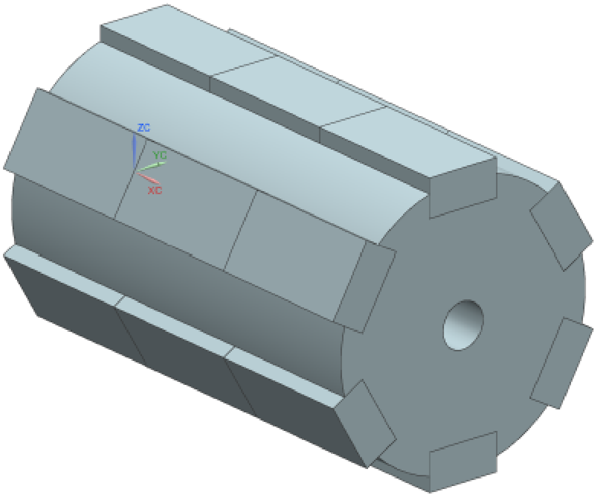


Figure 7. 3D model of the permanent magnets rotor.

The rotor is made from a black steel cylinder with magnets fitted in six grooves in the cylinder. As the black steel is a material with magnetic properties, the magnets aren't screwed or glued, they are just hold by the strong magnetic forces between the magnets and the black steel cylinder, in the grooves.

The rotor has an axle hole of 12 mm of diameter in the centre to hold the shaft that will make the rotor spin about axis.

The steel cylinder is 120 mm long and its radius is 36 mm. The distance from the axle axis of the rotor and the top of every magnet in the grooves in the rotor is 39 mm.

In each one of the six grooves where the magnets are placed, there are three magnets in a row, eighteen strong magnets in total. Every magnet has the dimensions shown in Figure 8.

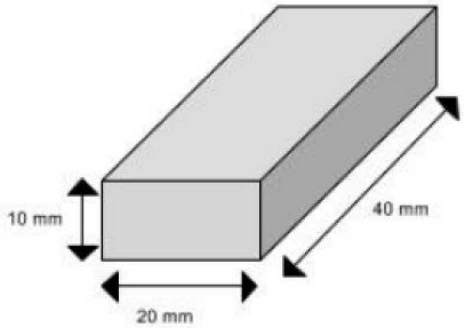


Figure 8. Magnet dimensions.

This makes every row of three magnets be 120 mm long, as the cylinder length. This 120 mm is also the active copper length in the stator because its windings can only take advantage of this part, where the magnetic flux of the magnets goes directly through them.

Every magnet creates a radial magnetic field of $B_r \geq 1.29\ T$. The magnetic field in the stator coils is dependent on the length of the air gap between the stator and the rotor and it's not linear so it isn't estimated for the different stators.

The main magnitudes and dimensions from the rotor are easily seen in the next table:

Dimension/Magnitude	**Value**
l_{active} (cylinder and total magnet length)	120 mm
$r_{cylinder}$	36 mm
r_{max}	39 mm
d_{hole}	12 mm
B_r	1.29 T

Table 1. Magnitudes of the Rotor.

In Figure 9 it can be observed how the permanent magnets rotor used is:

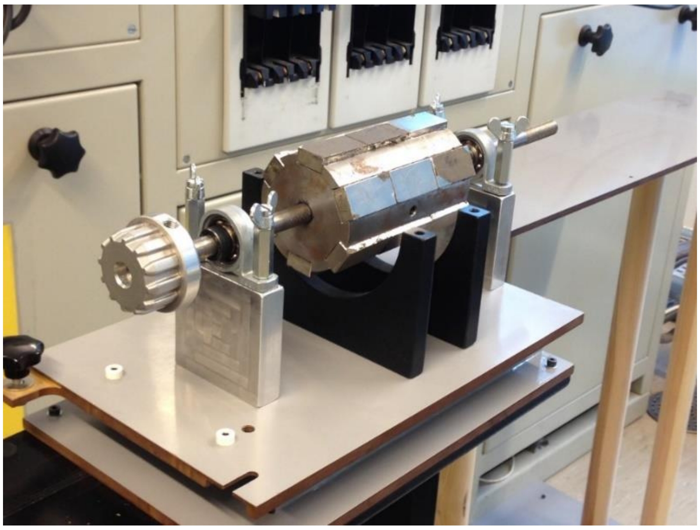


Figure 9. Permanent magnet rotor used in the synchronous generators.

3.2 Stators

There are five different handmade stators, three of them are made by NTNU professors, and the other two are made by students in the course ‘TEP 4175: Energy from Environmental Flows’. From now, to distinguish them, the professor’s stators will be called P1, P2 and P3, and the student’s stators S1 and S2.

All of the stators are three phased except P2, which is single phased. All of the three phase stators are Y-connected with neutral wire. Single phase stator P2 has two connections, one to the load and one to the neutral.

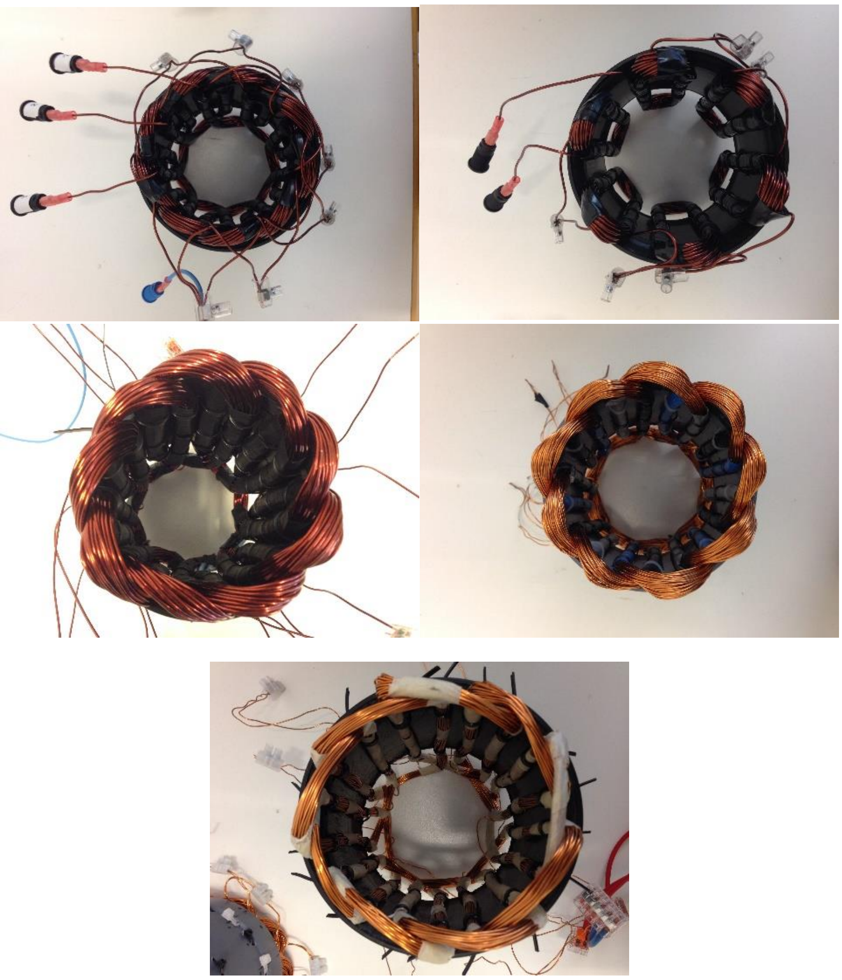


Figure 10. Stators tested. From left to right, first row: P1 and P2; second row: P3 and S1; third row: S2.

Every three phased stator has nine coils, three coils per phase that are connected in series. Every coil is 40 degrees from the next one and 40 degrees from the previous one. In each one of the three phases, the three coils are separated 120 degrees from the other two coils. This makes that the same magnetic flux will pass through every coil from the same phase because in the rotor, the north poles are separated 120 degrees from each other, as well as the south poles. Every phase is 40 degrees separated from the other two phases.

Next figure shows the spatial disposition of the coils in the stator and related to the permanent magnets of the rotor.

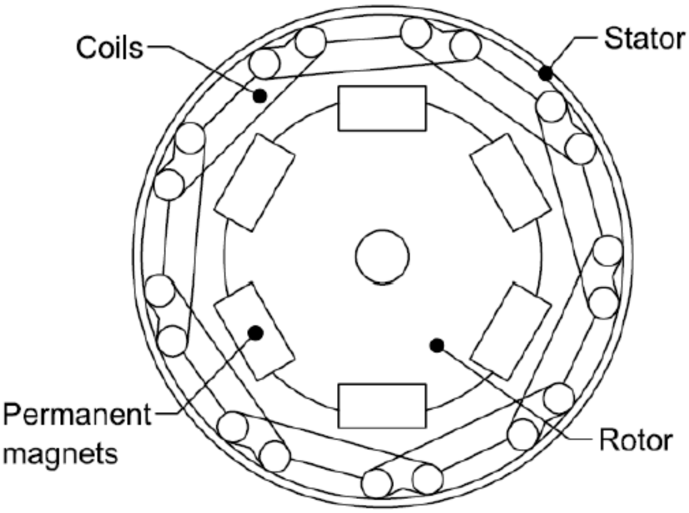


Figure 11. Cross section of three phase stator and rotor.

This spatial disposition of the coils and phases makes that the voltages and currents from each phase have a 120 electrical degrees lag from the other two phases, that is how we get a three-phase current or voltage.

The single phase stator P2 has six coils connected in series and separated 60 degrees from the next one and from the previous one, they are located the same as the permanent magnets in the rotor, that when rotating, the time variable magnetic flux creates the electromotive force in the single phased stator.

The coils are fastened to the interior walls of PVC pipes. This pipes are approximately 130 mm long and its diameters are about 110 mm long.

Every stator has a different design from the rest one. This differential characteristics are windings per coil, diameter of the copper wire section, the number of wires per winding, diameter of coil section and inner stator diameter (minimum distance from opposite coils) and the resistance of each phase at 20ºC, which was measured with a precision ohmmeter.

In the next table are shown this characteristics in every stator:

	P1	**P2**	**P3**	**S1**	**S2**
N	28	28	42	28	28
$d_{wire}(mm)$	1.4	1.4	1.4	0.75	0.75
$d_{coil}(mm)$	12	11.8	14.5	8	5.475
$d_{min}(mm)$	84	84.4	81	92	97.45
$R_{A1}(\Omega)$	0.3888	0.7253	0.5788	0.582	1.3867
$R_{A2}(\Omega)$	0.3901	-	0.5806	0.5984	1.3774
$R_{A3}(\Omega)$	0.39	-	0.5793	0.5789	1.3704

Table 2. Characteristics of the stators.

In the stator S1 there is a peculiarity that every winding has two wires in parallel. This means that every coil will have 28 windings but 56 wires because there are two wires in parallel.

The air gap length, that is important to estimate the magnetic flux that creates the electromotive force, can be calculated with the next equation:

$$r_{air\ gap} = \frac{d_{\min stator}}{2} - r_{\max rotor}$$

From this equation we get the air gap in every stator:

	P1	**P2**	**P3**	**S1**	**S2**
$r_{air\ gap}(mm)$	3	3.2	1.5	7	9.725

Table 3. Air gap length in every synchronous generator.

4. LABORATORY EXPERIMENTS

This chapter shows everything about the work and measurements performed in the electric laboratory. The procedures of this measurements are explained, as well as the measuring and control equipment used, passing through the data collection of the synchronous generators and the parameter calculations.

4.1 Procedures

The aim of the measurements is to study the behaviour of the synchronous generator with different loads and frequencies to get at the end the electrical model of the stator of the generator. The biggest unknown before performing the measurements is the synchronous reactance X_S and therefore the synchronous inductance L_S. The other elements of the electric model are already measured as the stator resistance R_A. The electromotive force E_A is measured when there is no load in the synchronous generator so the phase voltage is equal to the electromotive force $E_A = V_\emptyset$.

Each 'basic measurement round' is taken in four different rotor speeds: 1000 rpm, 1200 rpm, 1400 rpm and 1600 rpm; this makes the electrical frequency be 50 Hz, 60 Hz, 70 Hz and 80 Hz respectively.

In every rotor speed that the synchronous generator is run, the load is varied from no-load to maximum load by the variable resistive load in six steps. In the first step, when there is no load, the electromotive force can be measured.

This 'basic measurement round' is done in every stator with different support equipment for the synchronous machine. This support equipment is referred to the material of the base and the brackets of the stator that is changed in order to study the efficiency with different materials. There are three kinds of combinations for the base and brackets of the stator, first of all metal base and metal brackets, then metal base and plastic brackets, and finally wooden base and plastic brackets. To change between combinations, sometime it's needed to remove and fix again the new base and brackets with the tools provided by the Service Lab from the Department of Electric Power Engineering.

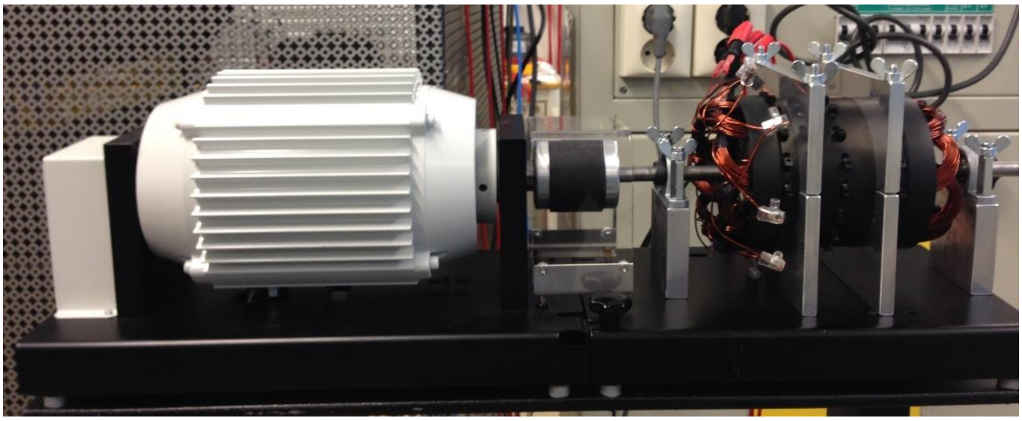


Figure 12. Stator P1 tested with metal base and metal brackets.

Stator P1 is tested with this three combinations; stators P2, S1 and S2 the last two combinations; and stator P3 is run only in the last combination, supposed to be the ideal case.

In order to make the measurements in the different PM synchronous machines with different stators, the rotor has to be removed every time it's needed to change the generator and therefore a new stator has to be coupled to the PM rotor.

To perform this tests on the synchronous generators, a power source that gives torque and speed to the rotor shaft is needed to spin the rotor; a power meter is used to measure voltages, currents and power in the terminals of the synchronous machine; and a resistive variable load to increase the current during the tests. The electric system used to perform the measurements is shown in Figure 13:

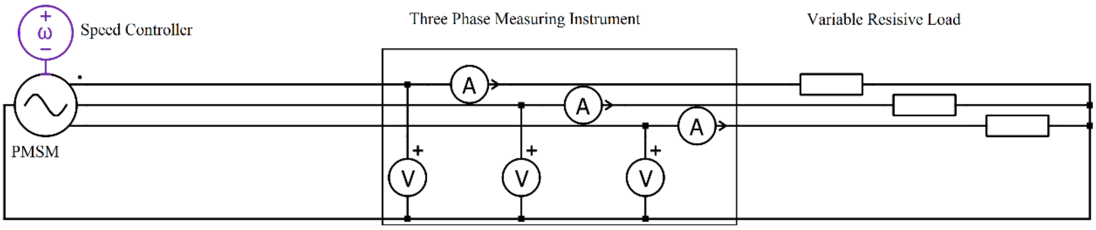


Figure 13. Electric system used in measurements.

4.2 Equipment used

To carry out the tests in the synchronous machines and collect the measurements, I used some specific equipment from the electric laboratory in NTNU that I want to have specified in order to a possible repetition of my tests looking for a further analysis in the future.

The way to use the equipment during the measurements, their functions and operation, as well as the identification codes from NTNU are given.

This equipment is classified in set up and instruments depending on the function inside the experiment. The following equipment is used:

4.2.1 Set up

-Machine Test System: This system provides the input power to the shaft of the synchronous generator. It's composed by a three-phase asynchronous machine and a control unit that can vary the speed of the rotor in the asynchronous machine.

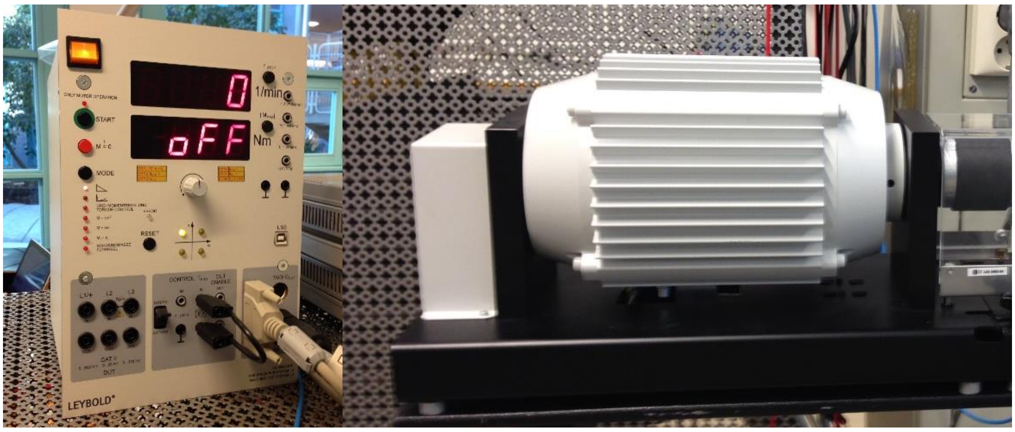


Figure 14. Machine Test System.

The asynchronous machine has a squirrel cage rotor and it can reach speeds of $\pm\, 5000\ rpm$ and torques of $\pm\, 19.9\ Nm$. Maximum voltage 400 V and maximum active power 1kW. The control unit controls the speed of the rotor and depending on the load of the synchronous generator, the torque given in the shaft will vary as well. The asynchronous machine can be run by the control unit as a motor or as a generator in the four quadrants. In the tests is used as a generator but the power input in the shaft will be considered as positive in the power balance of the synchronous generator.

The model of this system is Leybold Machine Test System 1.0 732 689USB. The identification code from NTNU of the control unit is B03-0508 and for the asynchronous machine is A03-0089.

-Resistor Bank: A three phase variable pure resistive load that can also be connected as a single phase load. Maximum voltage per phase 60V and maximum power load 15kW. Every resistor is about 7.2 ohms, there are 10 resistors per phase so the maximum resistance can be 72 ohms per phase (resistors in series).

I vary it manually and it changes when connecting or disconnecting the parallel resistors. The system is earthed in this resistor bank, just in case that there is a fault.

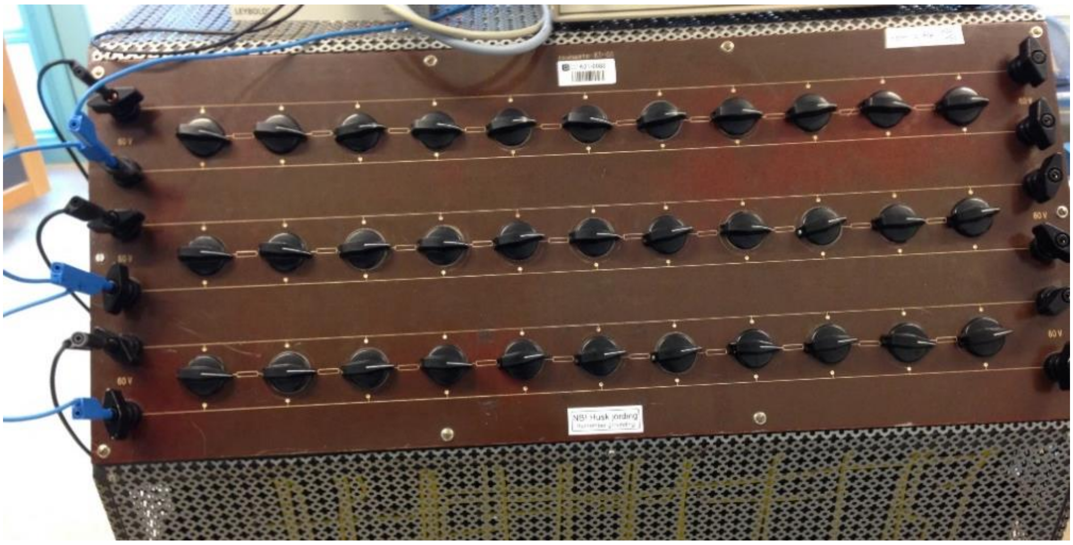


Figure 15. Resistor Bank.

This resistor bank belongs to NTNU and the identification code is K01-0088.

4.2.2 Instrumentation

-Digital Power Meter: This instrument is used as the three phase (or single phase) measuring system. It is connected to the terminals of the stator and to the variable resistive load. It can operate with maximum voltage 600V and maximum current 20A. When it's operated in single phase mode, only one phase is connected. In three phase mode is connected in a way that the three wattmeter method is applied, one wattmeter per phase and connected to neutral in the stator of the synchronous machine and in the load. The way to connect it is well shown in the back part (1∅ 2W for the single phase case, 3∅ 4W for the three phase case).

From this digital power meter, the values in RMS of phase voltage $V_{\emptyset}$, line current I_A and active power per phase are taken. The load is pure resistive so it isn't needed to take the values of reactive power and power factor.

The model of the power digital meter is Yokogawa 2533e and its NTNU identification code is E02-0003. It can be seen in the next figure:

Figure 16. Digital Power Meter.

-Oscilloscope and digital probe: I use an oscilloscope Tektronix TDS 2014C to study the waveform of the line voltage. I save this waveform from every synchronous generator. To take this waveform a digital differential probe Tektronix P5200A is used to attenuate the voltage from the source to the oscilloscope.

The NTNU identification code of the oscilloscope is G04-0360.

-Mili-ohmeter: I use this accurate device to measure the resistance at 20ºC of every phase in every stator. This has to be connected from the terminal of a phase and the neutral. The resistances in every phase use to be similar, the same number of windings per coil in each phase and the same thickness of the wire makes the value of the resistances quite similar. The differences are in little details that are negligible when building the stator. Having a similar value of the resistance per phase is a sign that the coils of the stator are well connected.

Figure 17. Mili-ohmeter.

It has a pretty high accuracy, it can measure $0.1m\Omega$. The NTNU identification code is H01-0096.

4.3 Measurements

Once everything is connected and prepared, using the speed controller, the synchronous generator is taken to the desired speed, usually highest speed 1600 rpm at first, without load. The load, in every speed, is taken from minimum to maximum and the measurements are taken in every step. Every time I change the speed of the rotor I disconnect gradually the load and then start again.

Every step of the load in every speed I measure and save in a table the values of: torque in the shaft τ_s and rotor speed ω_m, from the speed controller of the Machine Test System; phase voltage $V_\emptyset$, line current I_A and phase active power load P_{load} per phase, from the Digital Power Meter.

Next table shows an example of measured values during a round of tests of the synchronous generator S1:

n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)
1600	-0,02	15,89	0,002	0	15,76	0,0017	0	16,03	0,0013	0
1600	-0,53	14,62	1,9925	29,05	14,49	2,0072	29,04	14,71	1,9685	28,93
1600	-1,36	12,58	5,05	63,66	12,5	5,014	62,83	12,63	4,95	62,53
1600	-1,95	10,97	7,205	79,6	10,91	7,167	78,7	10,98	7,077	78,2
1600	-2,32	9,64	8,714	85,2	9,61	8,652	84,3	9,64	8,566	83,6
1600	-2,53	8,26	9,615	79,2	8,28	9,525	78,9	8,31	9,421	78,8
1400	0,01	13,68	0,002	0	13,57	0,0023	0	13,81	0,0014	0
1400	-0,44	12,54	1,7087	21,28	12,42	1,7166	21,21	12,65	1,6717	21,14
1400	-1,12	10,75	4,316	46,4	10,68	4,277	45,61	10,83	4,228	45,7
1400	-1,63	9,4	6,164	58,2	9,32	6,128	57,4	9,42	6,07	57,4
1400	-1,97	8,31	7,448	62,7	8,22	7,43	62	8,29	7,362	61,9
1400	-2,23	7,36	8,49	62,1	7,3	8,444	61,3	7,37	8,352	61,1
1200	0,03	11,67	0,0012	0	11,58	0,0005	0	11,78	0,0017	0
1200	-0,38	10,69	1,459	15,55	10,59	1,4669	15,48	10,77	1,4527	15,58
1200	-0,95	9,17	3,689	33,76	9,11	3,643	33,15	9,24	3,607	33,28
1200	-1,38	8,04	5,274	42,48	7,97	5,248	41,94	8,07	5,196	41,98
1200	-1,69	7,15	6,425	46	7,07	6,403	45,5	7,14	6,348	45,5
1200	-1,92	6,4	7,306	47	6,34	7,255	46,4	6,4	7,18	46,2
1000	0,04	9,72	0,0019	0	9,64	0,0005	0	9,82	0,0015	0
1000	-0,32	8,92	1,2203	10,85	8,84	1,2152	10,74	8,99	1,2065	10,81
1000	-0,78	7,66	3,088	23,62	7,63	3,028	23,08	7,72	3,01	23,22
1000	-1,15	6,74	4,423	29,76	6,7	4,39	29,34	6,76	4,36	29,41
1000	-1,41	6,02	5,415	32,7	5,98	5,375	32,2	6,01	5,338	32,1
1000	-1,61	5,42	6,184	33,6	5,39	6,133	33,2	5,41	6,084	33

Table 4. Data measured from PMSM S1 with wooden base and plastic brackets.

In every speed, the waveform of the phase voltage is saved from the oscilloscope when no-load and maximum load situation. So I recorded 8 times per round of measurements the waveform of the phase voltage.

4.4 Calculations

From the measurements taken in the laboratory, I make some calculations for a further study later. Every point of the measurement has calculated the input power P_{in}, output power P_{out}, power losses P_{loss}, efficiency of the machine, reactance per phase X_S, load per phase R_{load} and copper losses P_{Cu}.

As explained before in the Chapter 2 (section 2.4 Power Balance) and from the data measured in the laboratory tests, the power input, power output, power losses and efficiency can be calculated from the following formulas:

-Power input:

$$P_{in} = \tau_s \omega_m$$

-Power output:

$$P_{out} = P_{\emptyset 1} + P_{\emptyset 2} + P_{\emptyset 3}$$

-Power losses:

$$P_{loss} = \ P_{in} - P_{out}$$

-Copper losses:

$$P_{Cu} = R_{A1} I_{A1}^2 + R_{A2} I_{A2}^2 + R_{A3} I_{A3}^2$$

-Efficiency:

$$\eta = \frac{P_{out}}{P_{in}}$$

The reactance per phase can be easily calculated from the formula:

$$X_S = \sqrt{\frac{E_A^2 - (V_\phi - R_A I_A)^2}{I_A^2}}$$

The electromotive force will always be the phase voltage measured at a determined speed when there is no load in the generator. For a calculation of the inductance per phase it’s only needed to divide the reactance by the speed.

$$L_S = \frac{X_S}{\omega}$$

Next table shows an example of the calculations made in an Excel sheet from the measures taken in the laboratory tests.

Calculations											
omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1 (ohm)	Xs2 (ohm)	Xs3 (ohm)	Rload1 (ohm)	Rload2 (ohm)	Rload3 (ohm)	RA-loss (W)
167,55	5,027	0	5,027	0,000							0,000
167,55	113,935	108,81	5,125	95,502	0,964	1,023	1,371	7,353	7,170	7,431	5,750
167,55	294,891	250,1	44,791	84,811	0,659	0,700	0,886	2,488	2,488	2,537	39,024
167,55	427,257	330,1	97,157	77,260	0,602	0,643	0,753	1,522	1,515	1,541	84,782
167,55	519,410	369,5	149,910	71,138	0,598	0,628	0,707	1,109	1,101	1,118	130,965
167,55	594,808	378,6	216,208	63,651	0,630	0,655	0,713	0,878	0,872	0,888	169,894
146,61	1,466	0	1,466	0,000							0,000
146,61	80,634	79,32	1,314	98,370	1,287	1,308	1,477	7,319	7,213	7,433	4,226
146,61	212,581	183,71	28,871	86,419	0,753	0,804	0,897	2,485	2,489	2,552	28,574
146,61	312,274	244,3	67,974	78,233	0,665	0,679	0,752	1,518	1,512	1,543	62,413
146,61	391,442	277,7	113,742	70,943	0,615	0,634	0,702	1,106	1,101	1,118	97,130
146,61	448,619	292	156,619	65,089	0,603	0,622	0,683	0,873	0,873	0,887	128,908
125,66	-1,257	0	-1,257	0,000							0,000
125,66	57,805	57,57	0,235	99,593	1,202	1,242	1,414	7,309	7,227	7,488	3,066
125,66	152,053	133,62	18,433	87,877	0,749	0,781	0,881	2,478	2,494	2,552	20,827
125,66	227,451	178,7	48,751	78,566	0,630	0,649	0,734	1,516	1,521	1,542	45,687
125,66	284,000	203,8	80,200	71,761	0,593	0,600	0,671	1,105	1,105	1,119	71,441
125,66	329,239	216,4	112,839	65,727	0,573	0,584	0,646	0,869	0,875	0,889	95,743
104,72	-2,094	0	-2,094	0,000							0,000
104,72	39,794	39,82	-0,026	100,067	1,222	1,215	1,329	7,325	7,229	7,526	2,116
104,72	104,720	92,55	12,170	88,379	0,765	0,755	0,849	2,482	2,511	2,555	14,384
104,72	156,032	124,1	31,932	79,535	0,629	0,624	0,703	1,520	1,541	1,545	31,554
104,72	195,826	142,6	53,226	72,820	0,572	0,567	0,638	1,108	1,115	1,121	49,863
104,72	228,289	125,7	102,589	55,062	0,544	0,542	0,605	0,872	0,883	0,890	67,427

Table 5. Calculations from PMSM S1 with wooden base and plastic brackets.

All my measurements taken in the electric laboratory as well as the calculations made from them are shown in the Appendices of this report.

5. ANALYSIS OF DATA

In this chapter the all the data extracted from the laboratory tests and its measurements is analysed in order to get a physical explanation of how the PM synchronous machines are working and to derive this in a proper electrical model.

First of all it is briefly analysed the data measured by other students and professors before I started with this project. From this previous work it will be shown the early problematic surrounding the measurements of the PM synchronous machines and the modelling of them.

Then my measurements will be analysed focusing in the efficiency changes, calculation of the reactance and the effects of the different characteristics of every PM synchronous machine in the electric model and the power balance.

This analysis of my measurements it's extracted from the data gathered in the electric laboratory and it can be found in the Appendices.

5.1 Previous Measures

5.1.1 Professors' Measures in P1

The first previous measurements I was given were performed by professors in the stator P1. They were made in the ideal case of metal base and plastic brackets and they were tested in 1600 rpm, 1400 rpm, 1200 rpm and 1000 rpm. The main purpose of having them was to check them doing it again in the same conditions as they were made.

The calculations made from this previous measurements only take into account the phase one so the synchronous reactance of the PM synchronous machine is calculated from only one phase supposing that it is the same in the other phases because of its symmetry.

There were some results from the calculations of those measurements that seemed to be unexpected or not correct. The first thing noticed about this is that when calculating the absolute value of the reactance, in several points of the tests, it gives an imaginary value that doesn't correspond with any possible case.

The voltages, from no-load situation to maximum load, are slightly lower than expected. Also the active power measured has an ineligible difference to the active power calculated from the line current and phase voltage product (knowing that the load is pure resistive). This resulted in imaginary values for the reactance that shows that something is wrong.

When calculating the load from the line current and phase voltage, it doesn't follow the pattern that I saw from the resistor bank and it seems to have more positions than the resistor bank has. This could mean that this measurements were taken in other way or with a wrong connection at some point.

From this observations I made some theories about what could have happened to get this results because when performing my measurements I didn’t get any of this irregularities.

It is possible that there was a mistake when connecting the cables during the tests in the electric laboratory. The neutral cable from the PM synchronous machine to the Digital Power Meter and to the load wasn’t probably connected so I made some tests with and without neutral cable connected with the purpose of checking if it was the source of the problem.

METAL BASE AND PLASTIC BRACKETS													
Measured													
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1 product	P1(W)	U2 (V)	I2 (A)	P2 product	P2(W)	U3 (V)	I3 (A)	P3 product	P3 (W)
1600	-0,1	17,61	0,002	0,035	0	17,32	0,0017	0,029	0	17,53	0,002	0,035	0
1600	-0,78	16,57	2,26	37,448	37,38	16,26	2,274	36,975	36,92	16,42	2,19	35,960	35,97
1600	-1,86	14,78	5,906	87,291	87	14,48	5,853	84,751	84,5	14,54	5,692	82,762	82,5
1600	-2,71	13,33	8,727	116,331	115,5	13,04	8,617	112,366	111,6	13,02	8,416	109,576	109
1600	-3,3	12,02	10,793	129,732	128,1	11,76	10,62	124,891	123,4	11,71	10,4	121,784	120,6
1600	-3,67	10,74	12,32	132,317	133,6	10,53	12,09	127,308	128,5	10,49	11,86	124,411	125,6
METAL BASE AND PLASTIC BRACKETS (without neutral load-Digital Power Meter)													
Measured													
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1 product	P1(W)	U2 (V)	I2 (A)	P2 product	P2(W)	U3 (V)	I3 (A)	P3 product	P3 (W)
1600	-0,08	17,35	0,0014	0,024	0	17,09	0,0006	0,010	0	17,28	0,0017	0,029	0
1600	-0,73	16,28	2,197	35,767	35,38	16,01	2,176	34,838	34,47	16,14	2,175	35,105	34,73
1600	-1,7	14,58	5,732	83,573	82,3	14,32	5,635	80,693	79,5	14,31	5,646	80,794	79,6
1600	-2,38	13,17	8,434	111,076	108,8	12,9	8,3	107,070	104,9	12,81	8,319	106,566	104,3
1600	-3,05	11,89	10,4	123,656	120	11,65	10,225	119,121	115,6	11,5	10,24	117,760	114,3
1600	-3,5	10,81	11,881	128,434	126,8	10,59	11,67	123,585	122,1	10,4	11,668	121,347	119,5

Table 6. Measures with and without neutral cable in stator P1.

From this comparison we can see that the voltages are lower without neutral cable than with neutral cable. This lower voltage is seen in the previous measurements so it could be an explanation for this unexpected low voltages.

Apart from the voltages, the product between phase voltage and line current is closer to the measured active power with neutral cable than without it. This is other reason why this previous measurements could be different.

In the next table it is compared the relative error of the product referred to the measured value of the active power in the phase 1.

Relative errors (%)	
Phase 1 Neutral	Phase 1 w/o Neutral
0,182	1,082
0,333	1,523
0,714	2,049
1,258	2,957
-0,970	1,272

Table 7. Relative errors when using neutral or not.

As it can be seen the relative errors are higher without the neutral cable connected than when connected.

This difference between measured and calculated active power from the measurements, and the lower voltages in the professor’s measurements can be explained because of this error of connection in this previous measurements.

From a scope of the PM synchronous machine P1 working we can see that the waveform of the phase voltage is not completely sinusoidal, this means that there are some harmonics due to how the stator was made.

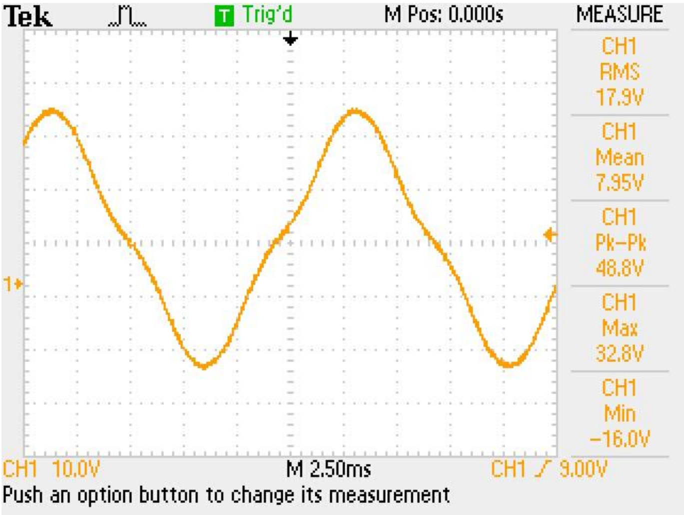


Figure 18. Waveform of PM synchronous machine P1 phase voltage.

As the load is pure resistive, the waveform of the current is the same but divided by the value of the resistance per phase. The current at the main frequency flowing through neutral cable must be zero because it is a three phase machine and by Kirchhoff's law, the current of the neutral cable is equal to the sum of the current of the three phases, so at the main frequency, the current of each phase is sinusoidal and delayed 120º, therefore the sum is zero.

As we see in the previous figure, there are harmonics in the voltage and current, predominating the 3rd harmonic.

There is a possibility that when the neutral cable is not connected, due to the harmonics in the current and the non-perfectly symmetrical generator, there is some current that usually flows through the neutral cable when connected and at this case doesn't do it and creates this irregularities when measuring the PM synchronous machine.

5.1.2 Students' Measures in own PM Synchronous Machines

The previous measurements made by students were made during the course 'TEP 4175: Energy from Environmental Flows' where they build them and made some tests. They had the freedom to build their own PM synchronous machine as they wanted so I had data from axial and radial flux machines as well as three phase and single phase machines. The PM synchronous machines that I tested had radial flux and were most of them three-phased so I focused my analysis of this data on machines with similar properties that were four. This PM synchronous machines with radial flux and three phases were made by student's group's number 3, 4, 5 and 6. None of this generators were one of the generators analysed by me.

Depending on the group of students that made the machine, the measurements were made with speeds of 1200 rpm, 1500 rpm, 1800 rpm and 2000 rpm. As my measurements, they were done from no-load to maximum load.

Some of the problems I had with this measurements is that there wasn't enough data gathered so the results are sometimes inaccurate an uncompleted. In some of the PM synchronous machines, physical characteristics of the machine were uncompleted so it was hard to know the number of windings per coil (Group 4), the thickness of the cables (Groups 3, 4, 5 and 6) and in few cases the value of the stator's resistance (Group 4).

There was also only one voltage measured and one current so the calculations and analysis from them were for only one of the phases and not for the whole PM synchronous machine. The data of the voltages were ambiguously gathered because it wasn't clear sometimes if the voltage is from line to line or phase voltage. At least with the current there is no doubt that is line current.

This also means that the modelling of each machine has been done taking into account only one of the phases and supposing the perfect symmetry of each one, something that I wouldn't suppose.

The reactance values were in some machines unusually high because the calculation was made from a line to line voltage and not from a phase voltage so this give a 'fake' reactance from line to line. Dividing this reactance by three to calculate the phase to neutral synchronous reactance I got expected values so this didn't supposed a big problem.

The biggest observation made with this previous measurements and that will be seen in my measurements too is that the synchronous reactance and therefore the inductance varies with the current, from a high value it gets lower when increasing the load.

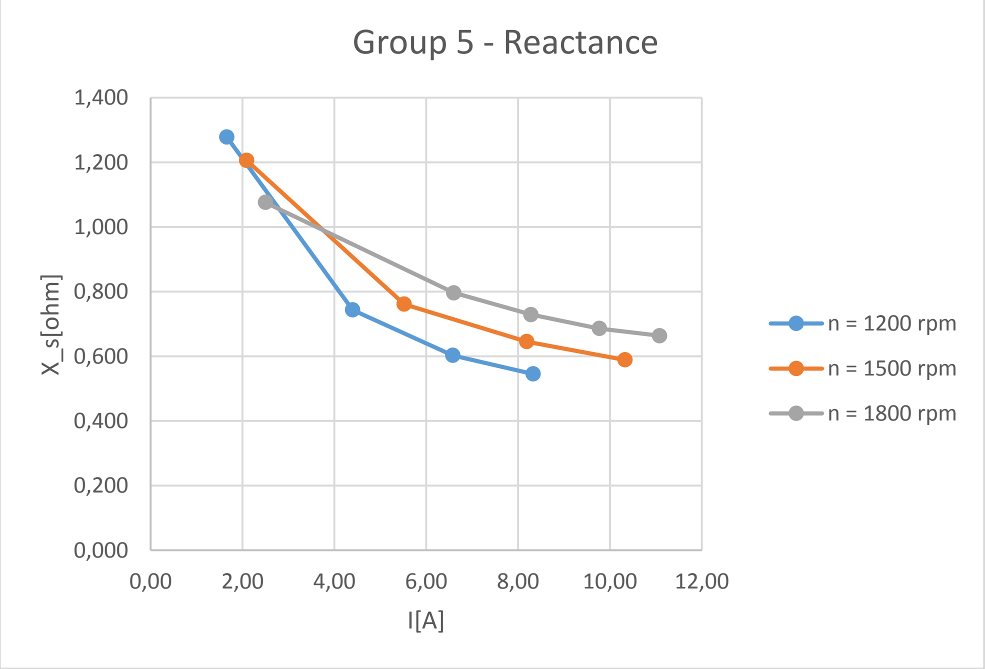


Figure 19. Reactance variation with current in Group 5.

In this figure it can be seen how the reactance varies with the current with the machine working at different speeds.

This effect is also seen in the inductance:

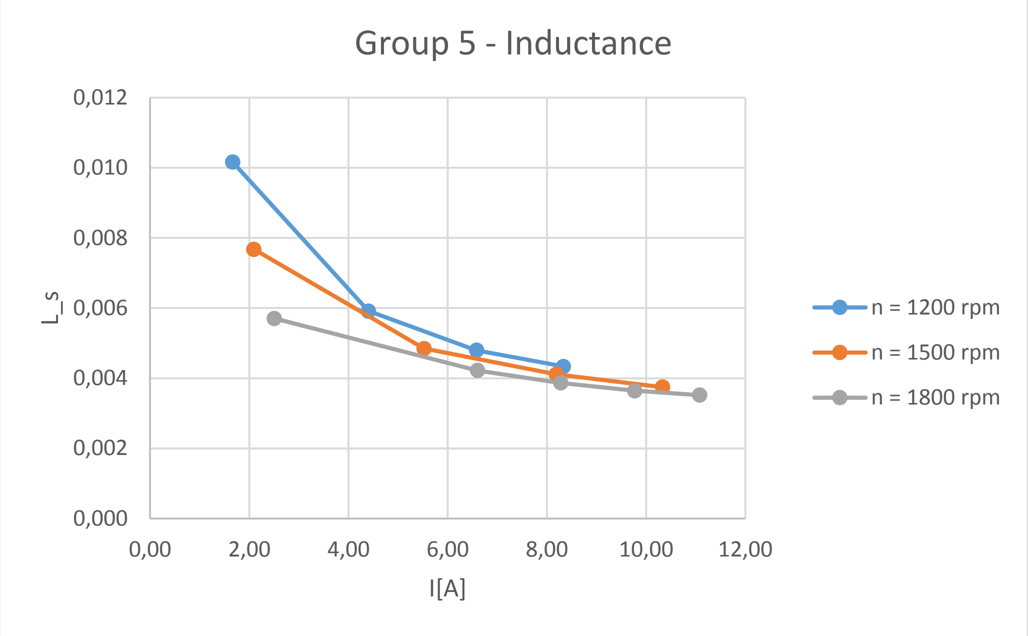


Figure 20. Inductance variation with current in Group 5.

This is furtherer studied and analysed in my measurements.

5.2 Own Measures

In this section my own measurements are fully analysed, from the behaviour of the voltages and currents depending on the generators operation and characteristics to the behaviour of the reactance, passing through an analysis of the efficiency, losses and power balance of this small generators.

5.2.1 Voltages and Currents

In every PM synchronous machine, the voltage decreases from the maximum at no-load situation to minimum when the load is maximum. This happens because there is a voltage drop that increases with the load while the electromotive force doesn't vary due to the load. A PM synchronous machine has always the same flux in the air gap, which creates the electromotive force when varying with the time, but that can't be controlled because it depends directly on the magnetic fields of the permanent magnets of the rotor.

When increasing the load, the voltage drop increases because it depends on the current and the stator impedance:

$$\Delta V_S = Z_S I_L = (R_A + jX_S) I_L$$

This voltage drop makes the phase voltage be lower when increasing the load:

$$V_\phi = E_A - \Delta V_S$$

Next figure shows how the voltage decreases while the load increases in PM synchronous machine P3 being run at 1600 rpm:

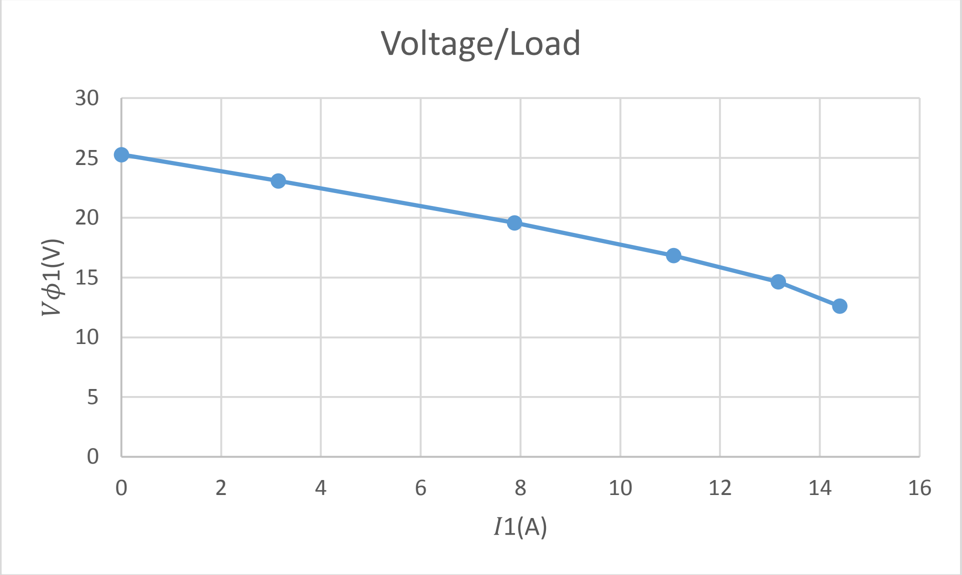


Figure 21. Phase voltage variation with load in P3 at 1600 rpm.

The phase voltages also vary with the speed of the rotor. The electromotive forces, as explained in the theory chapter of this report (Chapter 2), depend on the electric speed of the inducted currents or in the mechanical speed of the rotor. This affects directly the electromotive forces and therefore the phase voltages because they are dependent on the electromotive forces as shown before. Explained clearly: the higher is the speed of the rotor, the higher are the phase voltages.

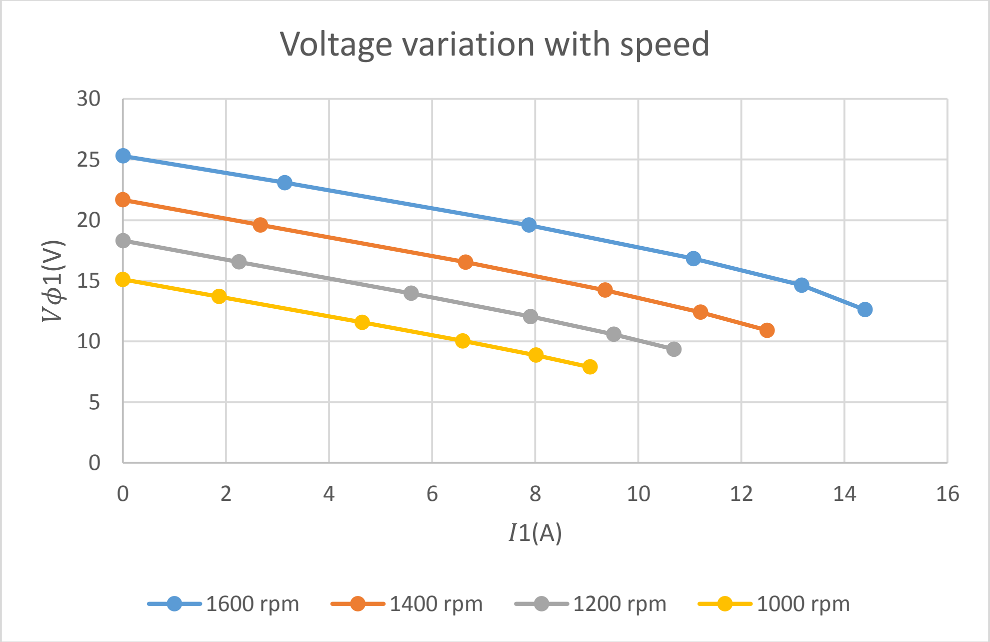


Figure 22. Phase voltage variation with rotor speed in P3.

This figure shows how the phase voltage is higher when the rotor speed increases. This phenomenon is seen not only in the example of the stator P3 but in the rest of the stators that I tested.

Depending on the material used for the base and the brackets, I have observed the phase voltages suffer a small variation that in most of the cases can be neglected but enough to be commented.

The PM synchronous generator P1 was tested with metal base and metal brackets; metal base and plastic brackets; and wooden base and plastic brackets so the analysis of how the voltages change due to the materials will be performed from the generator P1.

The biggest difference in voltages is seen between having metal brackets and plastic brackets when the base is metallic. When there are plastic brackets the voltage is slightly higher, less than half a volt. The difference between metal or wooden base when the brackets are made of plastic is negligible but in most of the synchronous generators the voltage is higher when the base is metallic.

This variations can be considered as negligible but it is interesting to see how similar they are in the next figure:

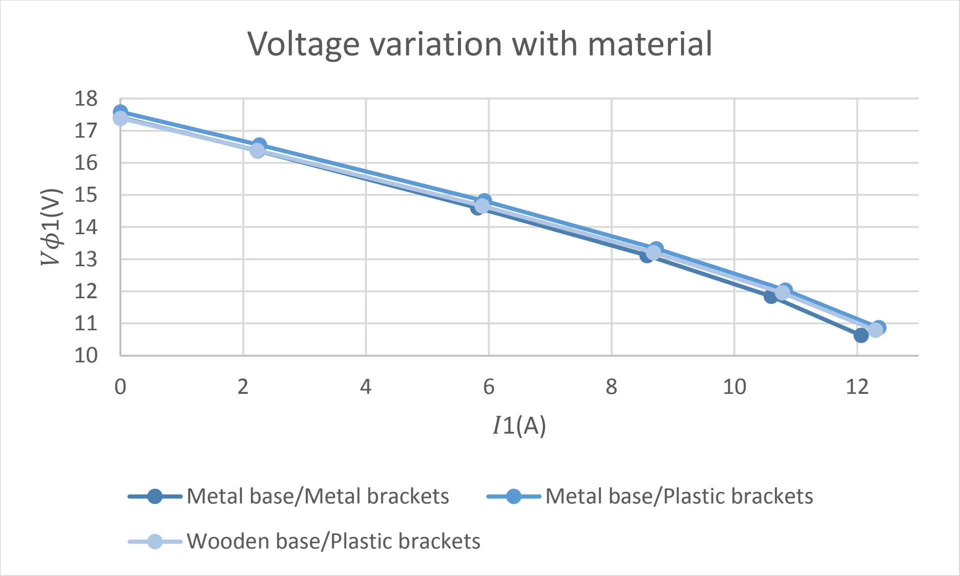


Figure 23. Phase voltage variation with material of base and brackets in P1.

In the three phase synchronous generators, the phase voltages and line currents are similar between each other. In some cases it can be small differences because of the imperfect symmetry of the load and the stator’s resistances and reactance but this differences can be neglected and the three phase synchronous generators can be considered as symmetric.

Depending on the number of windings per coil, the number of coils per phase, the cable thickness and in general the characteristics with that the PM synchronous machines’ stators were constructed, the phase voltage and line current vary in different ways due to this limitations.

The higher is the number of windings per coil and the number of coils per phase, the higher should be the phase voltage. As explained in Chapter 2, the electromotive force is dependent on the number of turns and therefore the phase voltage is dependent on that too.

$$E = -\frac{d\phi}{dt} = \mu\frac{Ni}{l}S\omega_e\sin(\omega_e t - \theta)$$

The limits that the line current can reach depend not only in the electromotive force inducted in the stator but in the thickness of the cable that is going to hold this line currents. So we can say that the thicker is the cable, the more current can flow through it.

In the next figure it’s shown how the voltage behaves in every machine at the same conditions of testing: wooden base, plastic brackets and a speed of 1600 rpm.

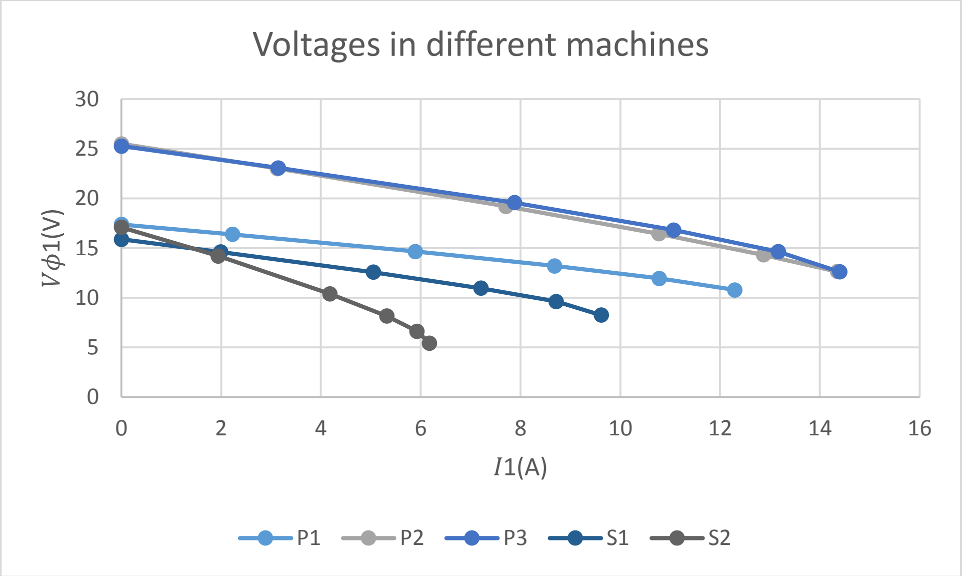


Figure 24. Voltage variation in all the machines tested.

The highest voltages are reached by the PM synchronous machines P2 and P3. This happens because P2 is single phase and has six coils in that phase (the three-phase machines have three coils per phase) with 28 windings per coil like the rest of the generators except from P3. The generator P3 reaches this voltages because the number of turns is higher than the rest having 42 windings per coil. It was interesting to see how strong the magnetic forces were during the tests of P3, I had tight harder the brackets because at my first try, the stator started to unexpectedly rotate due to this stronger magnetic forces caused by an increase of the windings per coil.

PM synchronous machines P1, S1 and S2 have 28 windings per coil and three coils per phase. For that reason their voltages are quite similar when the load is zero. When increasing the load, the phase voltages behave in different ways because of the different limitations that they have.

The thickness of the wires in P1 are the same as in generators P2 and P3 (1.4 mm) and higher than the generators S1 and S2 (0.75 mm). As we can see in the graphic, the line currents get higher levels at maximum load when the thickness is higher so that is why stator P1 has higher currents with load and therefore higher voltages when increasing the load.

In generators S1 and S2 the current is more limited because of its thinner wires and therefore the phase voltages too. Generator S1 reaches higher line current and phase voltage because in every coil it has 28 windings but with two wires in parallel so this makes a thicker equivalent wire that lets the line currents get higher levels than in generator S2.

About the waveforms of the phase voltages, it’s interesting to see that there are some harmonics in the voltages due to the possibilities of a perfect construction of this stators when they are handmade.

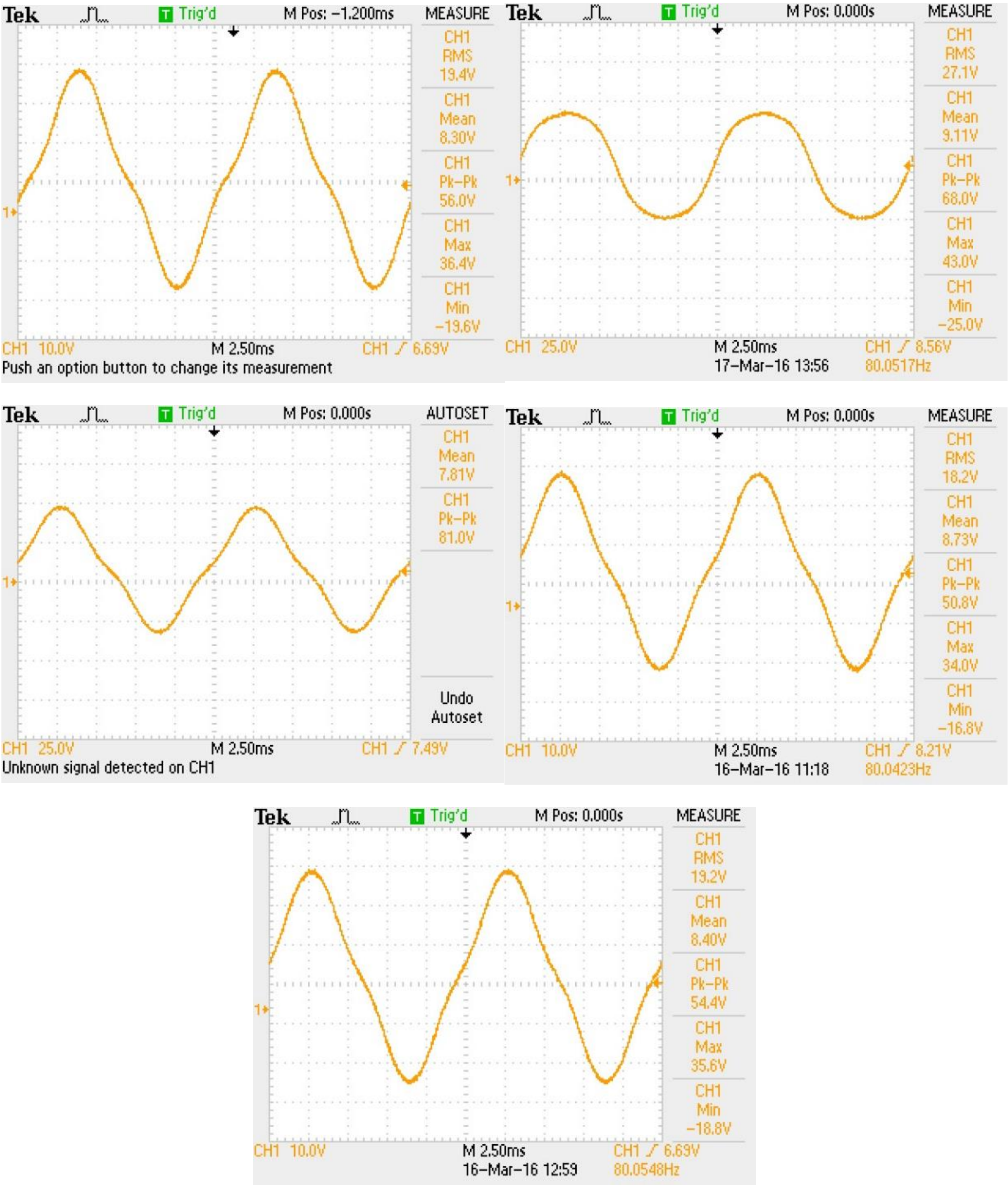


Figure 25. Scopes of phase voltages. From left to right: first row P1 and P2; second row P3 and S1; third row S2.

In PM synchronous machines with three phases (P1, P3, S1 and S2) we can see that the waveforms aren’t completely sinusoidal and they have a small harmonic component. This predominant harmonic in the voltage would be the 3rd harmonic.

In the phase voltage of P2 the waveform is perfectly sinusoidal meaning that the harmonic components are negligible.

To end this section about voltages I leave a table with the values of the electromotive forces of each phase in every PM synchronous machine when tested with wooden base and plastic brackets.

		E1(V)	E2(V)	E3(V)
P1	1600 rpm	17,39	17,12	17,31
	1400 rpm	14,98	14,76	14,92
	1200 rpm	12,77	12,58	12,72
	1000 rpm	10,63	10,47	10,58
P2	1600 rpm	25,5	-	-
	1400 rpm	22,15	-	-
	1200 rpm	18,91	-	-
	1000 rpm	15,72	-	-
P3	1600 rpm	25,28	25,48	25,56
	1400 rpm	21,67	21,84	21,93
	1200 rpm	18,31	18,45	18,52
	1000 rpm	15,11	15,24	15,29
S1	1600 rpm	15,89	15,76	16,03
	1400 rpm	13,68	13,57	13,81
	1200 rpm	11,67	11,58	11,78
	1000 rpm	9,72	9,64	9,82
S2	1600 rpm	17,1	16,5	16,84
	1400 rpm	14,77	14,24	14,54
	1200 rpm	12,62	12,17	12,42
	1000 rpm	10,51	10,14	10,35

Table 8. Electromotive forces measured in all PM synchronous machines.

This values of electromotive forces can be used when working with the electric model in the same conditions as in the table.

5.2.2 Efficiency

The efficiency of the PM synchronous machines tell us how does the generators take advantage of the input mechanical power got from the spin of the rotor. The output power is electrical power that is transferred from the terminals of the stator in the synchronous generator.

This power transmission between mechanical power input and electrical power output can be more or less efficient depending on the materials of the base and brackets, the speed of the machine, the load of the synchronous generator and the characteristics of the machine.

There is a clear difference in efficiency when the base and brackets are metallic; the base is metallic and the brackets made of plastic; and the base is made of wood while the brackets are made of plastic.

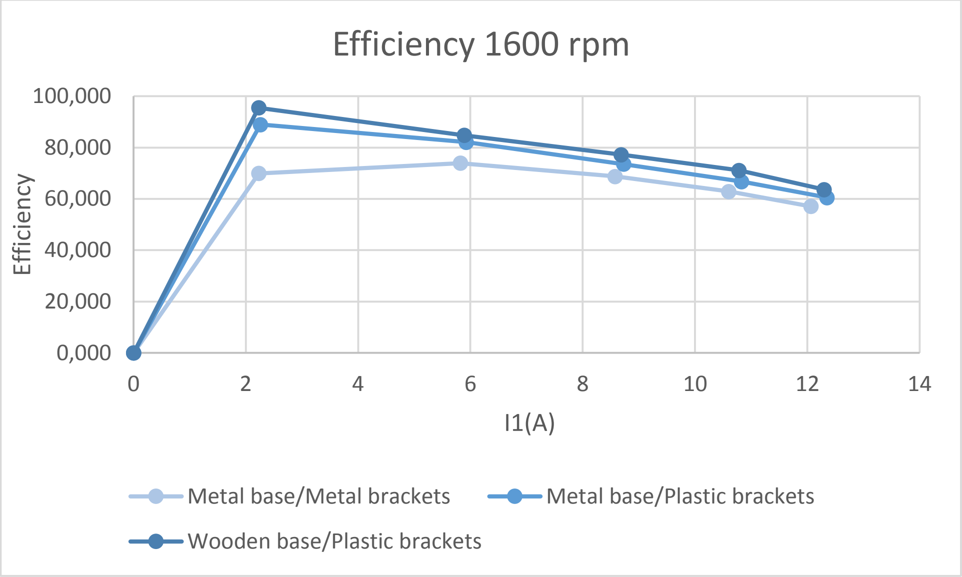


Figure 26. Efficiency of generator P1 running at 1600 rpm.

The previous figure shows this difference in the PM synchronous machine P1 that is tested in the three cases. The highest efficiency is reached with wooden base and plastic brackets, then with metal base and plastic brackets and the worst with metal base and metal brackets.

As we can see, the efficiency is lower when the more metal parts are surrounding the PM synchronous machine. This happens because the magnetic flux, which rotates because of the rotor spin, creates eddy currents or Foucault currents in the metal near the stator. This eddy currents flow only through the metal because of its high conductivity and, as they aren't used to generate electric power, they are power losses that take the form of heat.

During the testing of the PM synchronous machines I could experience this heat losses produced by eddy currents in the metallic brackets and in the metal base. This doesn't happen in the plastic brackets or in the wooden base because they have a really low conductivity.

The difference between having metal brackets or plastic brackets is higher than the difference between having metal base or wooden base because the brackets are surrounding the stator and they hold more eddy currents due to the rotating magnetic flux. The metal base holds eddy currents too but in a smaller proportion as the graphic shows.

So from this graphic we can see that the ideal case with the highest efficiency would be with wooden base and plastic brackets. Also we can deduce that we get higher efficiencies from lower load currents because the copper losses increase with the current.

Depending on the speed in every PM synchronous machine, the efficiency changes with the load current in different ways. This will be analysed in all the machines when run with wooden base and plastic brackets.

The next figure shows how does the efficiency changes with the load in different speeds in the generator P1:

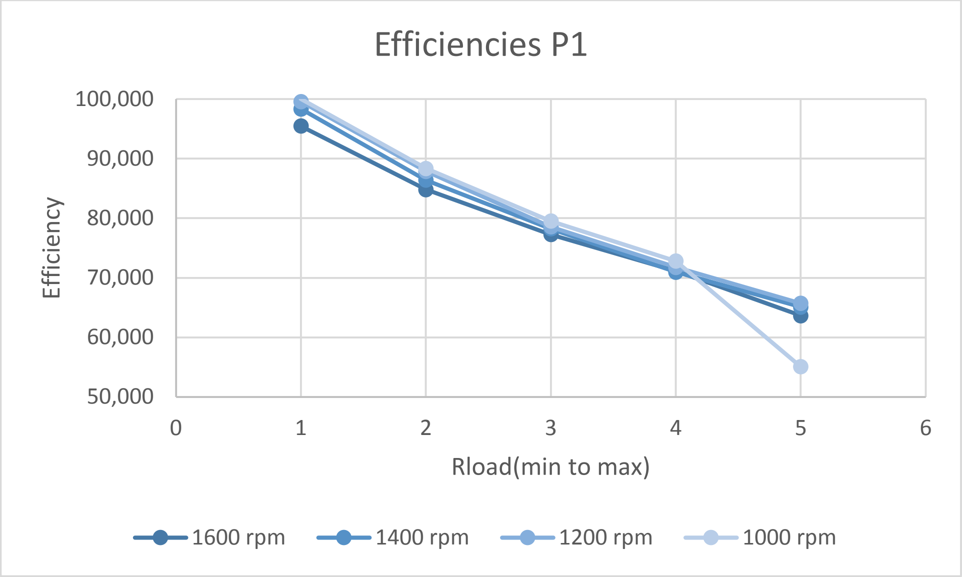


Figure 27. Efficiencies in generator P1.

In generator P1 the efficiency is higher at 1000 rpm and gets lower until reaching the lowest time when the speed is 1600 rpm. At maximum load point this changes having the lowest efficiency with 1000 rpm.

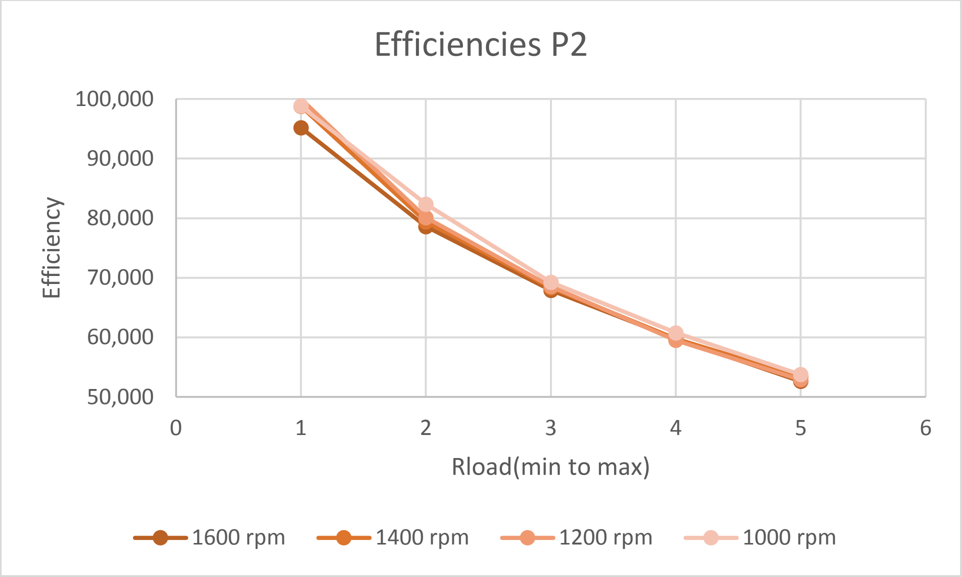


Figure 28. Efficiencies in generator P2.

In this generator P2 the efficiencies are so similar in different speeds but the efficiency is slightly higher at 1000 rpm and slightly lower at 1600 rpm when he load is minimum.

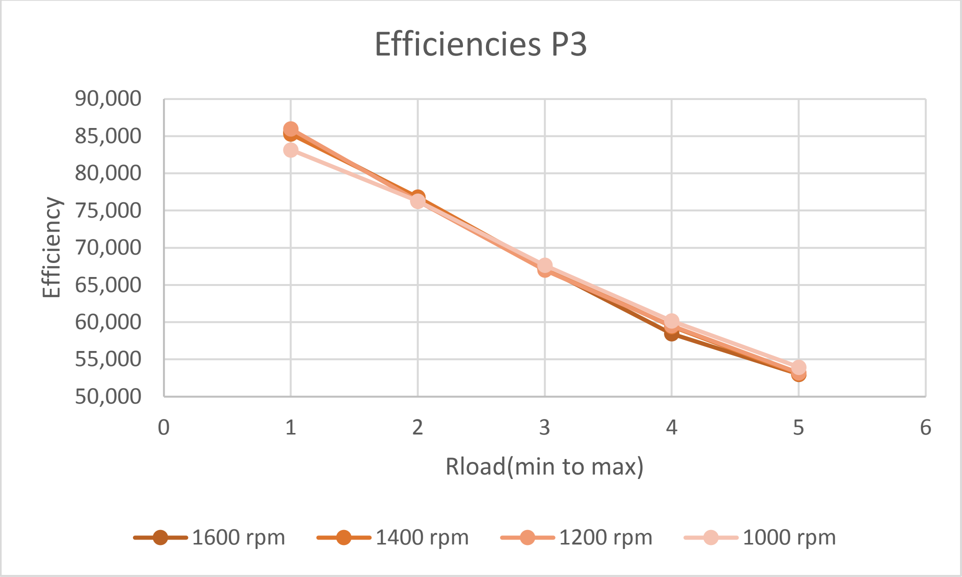


Figure 29. Efficiencies in generator P3.

Generator P3 seems to be the less dependent on the speed of the rotor in terms of efficiency, which is almost the same in the different levels of load.

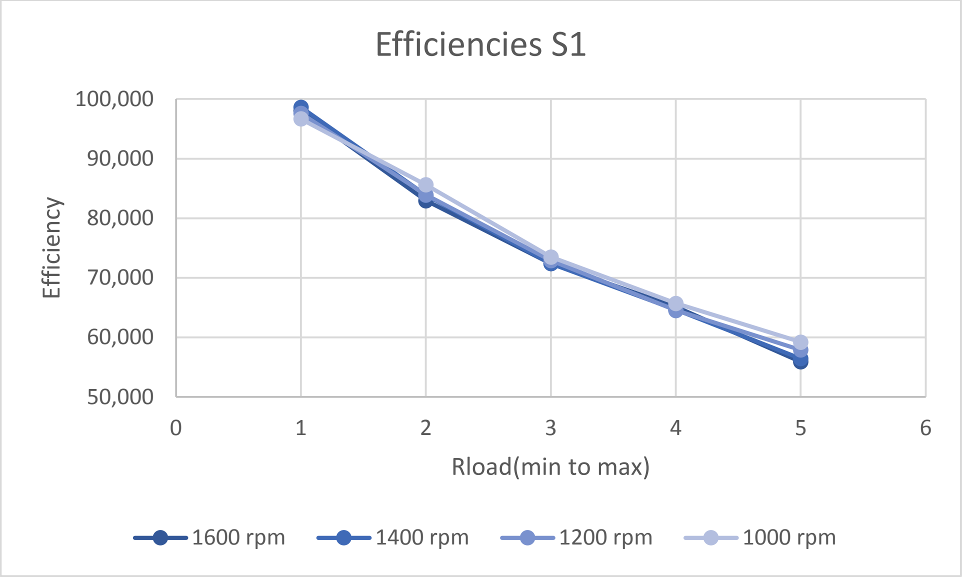


Figure 30. Efficiencies in generator S1.

This PM synchronous machine S1 has pretty similar efficiencies in all of the tested speeds. When running it at 1000 rpm the efficiency seems to be slightly higher but still similar to the other speeds.

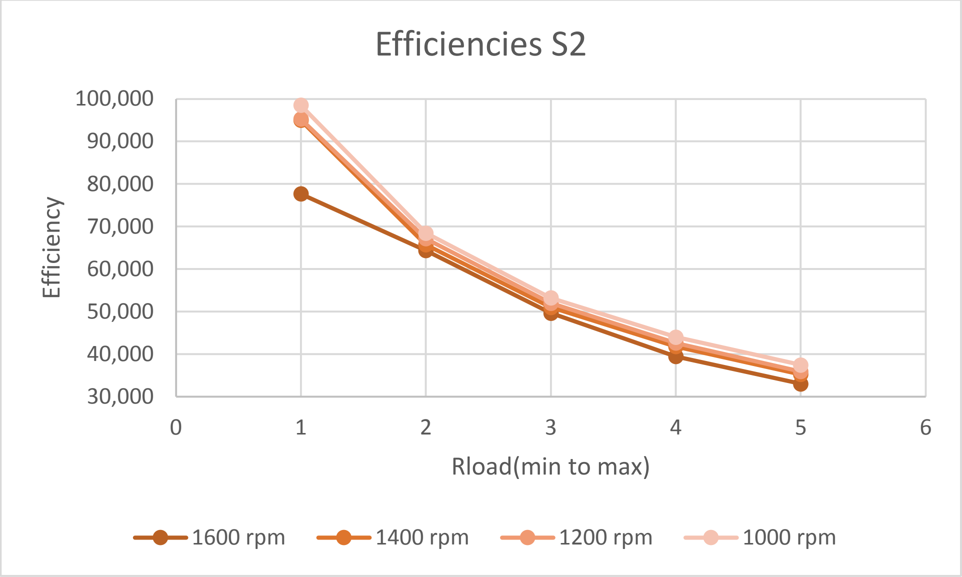


Figure 31. Efficiencies in generator S2.

PM synchronous machine S2 has similar efficiency levels depending on the speed. The most efficient speed is at 1000 rpm and the less efficient one is 1600 rpm having a bigger difference when the load is minimum.

From this observations of the efficiency depending on the speeds in every PM synchronous generator we conclude that the speed has some effect on the efficiency of the machine. Depending on the machine, some speeds are better than other ones in order to get a better efficiency.

In most of them, the speed of 1000 rpm has the most efficient results so in order to have a profitable use of them I would recommend to use them at this speed. Sometimes a little increase of the efficiency means a high save of money.

Once having the efficiencies of all the PM synchronous machines in the ideal conditions of wooden base and plastic brackets, we can make a comparison between the generators.

With low loads, the efficiency gets higher levels in generators P1, P2 and S1, between 95% and 99%. Generator S2 gets also high levels at low load but not when the speed of the rotor is 1600 rpm. P3 reaches maximum levels of efficiency about 85%.

The efficiencies decrease when increasing the load. The highest efficiencies at high loads are reached by generator P1, between 60% and 70%. Generators P2, P3 and S1 reach efficiencies between 50% and 60% at higher loads. Then the worst efficiency levels at high loads are reached by the PM synchronous generator S2, between 30% and 40%.

From this we can deduce that the best generator in terms of efficiency and the most recommended to use is the PM synchronous machine P1.

The power losses that we can observe in this synchronous generators can come from the copper of the wires and eddy currents (in the metallic brackets or base), from the iron of the rotor and from the mechanical process of the PM synchronous machine.

The copper losses are strongly dependent on the line current of the generator and also in the electric resistance of the wires in the stator. They are calculated in my measurements from the formula:

$$P_{Cu} = R_{A1}I_{A1}^2 + R_{A2}I_{A2}^2 + R_{A3}I_{A3}^2$$

From this we deduce and also see from the measurements that the synchronous machines have higher losses when the load current is higher and therefore, as seen before, when the speed of the machine increases.

Next figure shows the copper losses when increasing the current at different speeds in generator P2 with wooden base and plastic brackets.

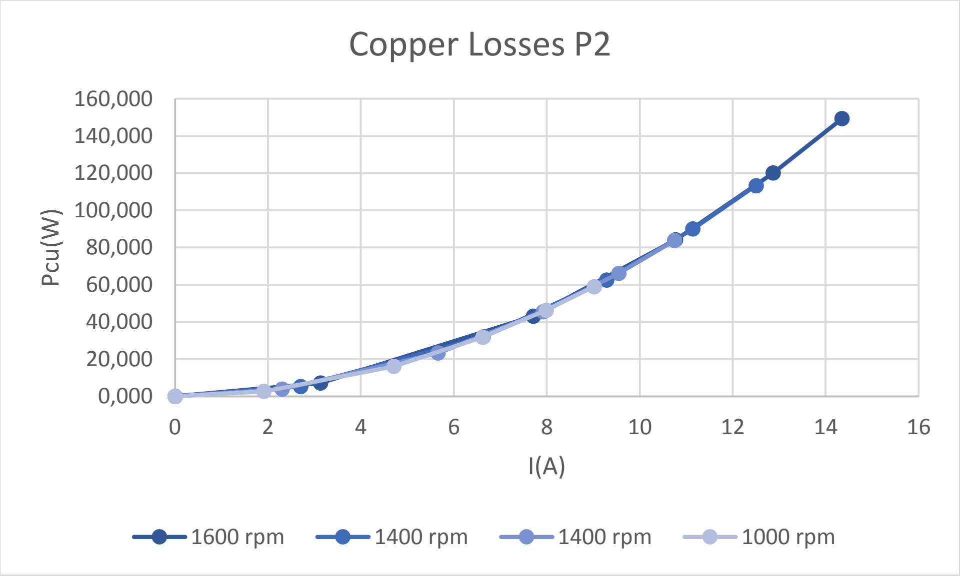


Figure 32. Copper losses in generator P2.

As we can see, when the speed is higher and therefore the load current is higher, the copper losses are higher too. They increase in a parabolic way.

Generators with higher currents tend to rise more the copper losses because the can hold more current but this also depend on the resistance. The highest is the stator resistance, the higher the copper losses will rise with the current. We can see it in the next figure where it is compared the copper losses of all the generators with wooden base, plastic brackets and running at 1000 rpm.

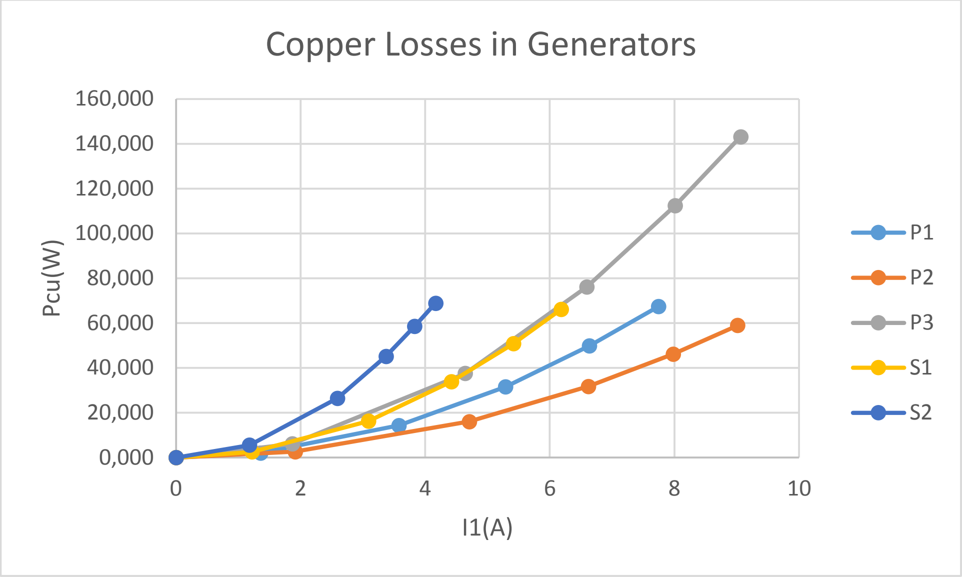


Figure 33. Copper losses in generators.

The generator that rises the copper losses with the biggest slope is S2 due to the higher copper resistance that it has. The copper losses are larger in generator P3 because of the high currents it reaches and the value of its stator resistance.

In my measurements, the calculation of the copper losses neglects the effect that the increment of the temperature has in the value of the resistances. My analysis is focused on how the copper losses behave depending on the machine and the speed but not in getting an exact value.

If we want to go further on this we only need to measure the temperature when the machine is working and follow the formula to get the new value of the resistance, where R_0 is the resistance at 20ºC and α is the thermic coefficient of the copper:

$$R = R_0(1 + \alpha\Delta T)$$

The generators wires should be between 50ºC and 70ºC, so the true resistance at this point is about a 15% higher than at 20ºC and therefore, the copper losses are about a 15% higher too.

The rest of the losses can be calculated from the difference between the total losses and the copper losses. To be more exact, when the current is zero, the total power losses will be equal to the mechanical losses and they will be constant at the same speed and characteristic of the test.

The iron losses can be calculated from the difference between total losses and copper and mechanical losses when the machine is being tested with wooden base and plastic brackets.

$$P_{Fe} = P_{loss} - (P_{mech} + P_{Cu})$$

If we want to go further we can calculate the losses produced by eddy currents in the metal brackets or metal base just subtracting the rest of the losses at a determined current load.

My analysis won't go further on this calculations of iron losses, mechanical losses and Eddy currents losses in base and brackets due to some errors of accuracy that the measuring instruments had.

There are some cases in my measurements that the power input when no load is negative and therefore the power losses are negative too and the efficiencies at low loads were slightly higher than 100% (something that is physically impossible). This happens because in situation of no-load, the torque that the speed controller gives was oscillating around zero so the measurement taken has some inaccuracy that gives this physically unfeasible results.

5.2.3 Reactance/Inductance

The biggest unknown when modelling a PM synchronous machine is always the synchronous reactance. It's important to know because most of the times is the main value of the synchronous impedance, due to the fact that the synchronous reactance is usually larger than the wire resistance.

The way I used to estimate the value of the synchronous reactance is making calculations from measured values like electromotive forces, phase voltages, line currents and wire resistances. This measured values can be considered accurate and true values because they come from direct measurements.

$$X_S = \sqrt{\frac{E_A^2 - (V_\phi - R_A I_A)^2}{I_A^2}}$$

The problem with the synchronous reactance is that it comes from a calculation. This means that when estimating the value of the synchronous reactance and therefore its inductance, we are including in it more phenomenon unexplained than in the usual electric model.

A change in the position of the stator, the saturation of the magnetic metals and materials, they way to test the PM synchronous machines as well as other variables, can make the calculation of synchronous reactance to change in order to representing all the phenomenon that can't be directly measured. This will be studied further in this section.

The first observation made when calculating the synchronous reactance from the data measured is that it isn't constant with the load. At low current loads, the reactance reaches its highest value and it starts decreasing until get stabilised at higher load currents.

This doesn't make so much sense because the synchronous reactance is a parameter that depends on the speed and the inductance, which depends on physical parameters as number of turns, section of the coil, etc. The load current shouldn't affect in the value of the inductance neither in the synchronous reactance.

$$X_S = \omega L_S$$

Next figure shows an example of this variation of the synchronous reactance with the current in the phase 3 of the PM synchronous machine P1 when it is tested with metal base and plastic brackets.

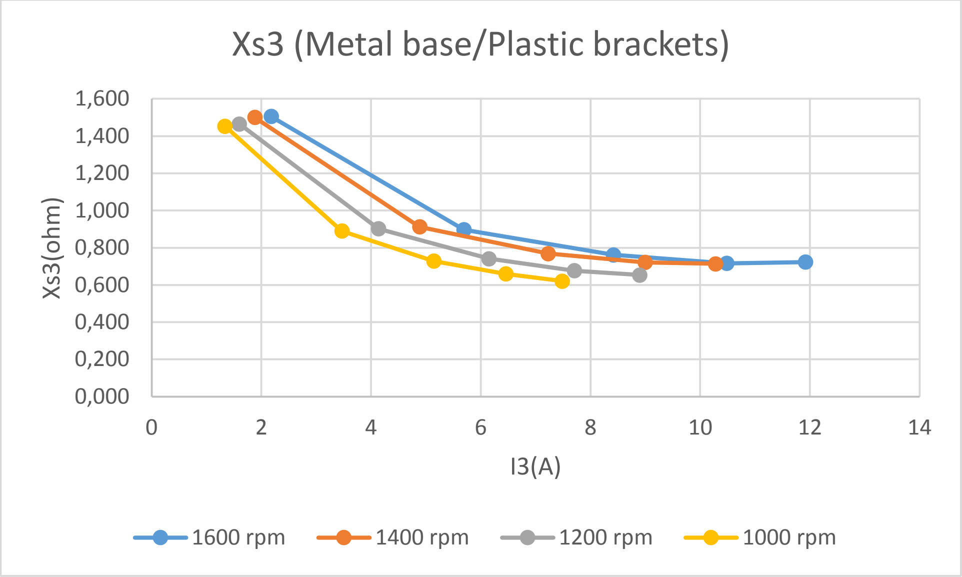


Figure 34. Synchronous reactance in phase 3 in generator P1 with different speeds.

This variation of the synchronous reactance with the load current appears in all the PM synchronous machines and with all the possible combinations of brackets and base. The higher is the load current, the less variation appears in the synchronous reactance. We could say that it gets stabilised when increasing the load current to certain levels. In the case from generator P1 shown in the figure, the synchronous reactance could be stabilised at high currents in a value between 0.6Ω and 0.8Ω.

The speed of the rotor doesn’t make a big change in the synchronous reactance, even though it directly depends on the speed of the PM synchronous machine. The higher is the speed, the higher should be the synchronous reactance. This reactance increase with speed is shown in all the synchronous generators (also shown in the previous figure) but it doesn’t make the change as expected because in some machines the reactance is lower than expected at 1600 rpm and also the difference between speeds is not as large as it should be.

It is also quite interesting to see how the synchronous inductance is depending on the load current and speed because it is supposed to not have any variation with current or speed (not like the synchronous reactance that is speed dependent).

The synchronous inductance is considered to be the sum of the auto inductances of the coils in series in each phase and the mutual inductances between coils. Neither the value of the auto inductance L of a coil or the mutual inductance M of some coils are dependent on other thing than the magnetic permeability, number of turns, section of the coil, length of the coil, etc.

$$L = \mu \frac{N^2 A}{l}; \ \varepsilon_{11} = -L_1 \frac{dI_1}{dt}; \ \varepsilon_{21} = -M_{21} \frac{dI_1}{dt}$$

The next figure shows the variation of the synchronous inductance with load currents in different speeds in stator P2 when tested with metal base and plastic brackets.

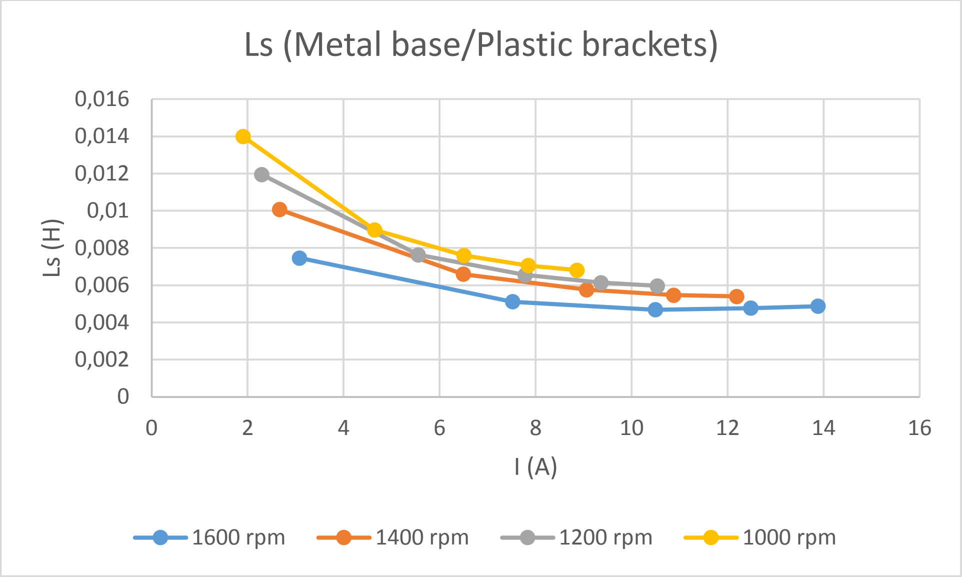


Figure 35. Synchronous inductance in generator P2 with different speeds.

In a similar way to the synchronous reactance, the inductances are higher when the load current is low and get stabilised when increasing the current. The main difference with the synchronous reactance is that the inductances calculated reach higher values with lower speeds. That is how the inductance at 1000 rpm is the highest and the inductance at 1600 rpm is the lowest.

The inductance should be the same in every speed because it isn't a parameter dependent on the speed as the synchronous reactance.

There is also an interesting observation made in all the machines inductances. The highest is the speed, the lowest is the value of the inductance and the less variation it suffers with the load current. With this I mean that when the generator is being run at a speed of 1600 rpm, the inductance will be almost stable from low to high load currents. This doesn't happen at lower speeds like 1000 rpm. This can be seen in the previous picture where the inductance at 1600 rpm goes between 5mH and 8mH and when the speed is 1000 rpm, the inductance goes from 7mH to 14mH.

In all the three phase PM synchronous generators, the reactance in each phase can be considered similar when the current is high and it gets stabilised. When the load current is lower, the synchronous reactance is in some cases not as symmetric as when the load current is high. Anyways I could consider that the synchronous generators are three phased symmetrical even though when there is low load current, the reactance and inductances doesn't follow in some cases the same pattern.

From the values of the synchronous reactance and inductances with different currents and with different material in the base and the brackets it is easy to see that there isn't any notable variation when changing the material of the base and the brackets. Of course the values aren't exactly the same in the calculations, in some times with a bigger difference at low currents and with a slight tendency to be lower when the materials aren't metal, but they are so similar that we can conclude that the influence in the synchronous reactance or inductances from the material of the base and the brackets is negligible.

In the next figures we can see how similar the synchronous reactance values are with different materials in the phase 3 of the PM synchronous machine P1.

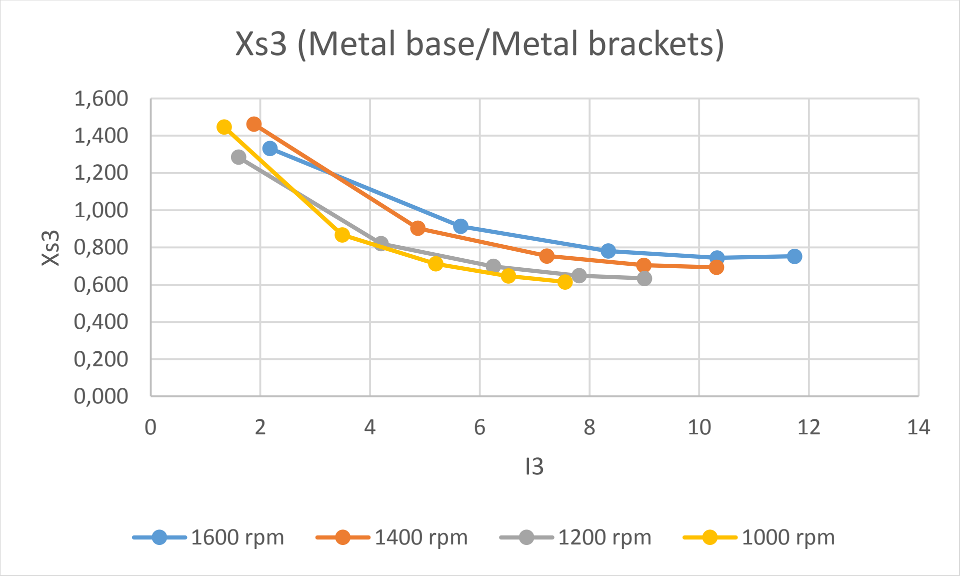


Figure 36. Synchronous reactance in phase 3 with metal base and metal brackets in P1.

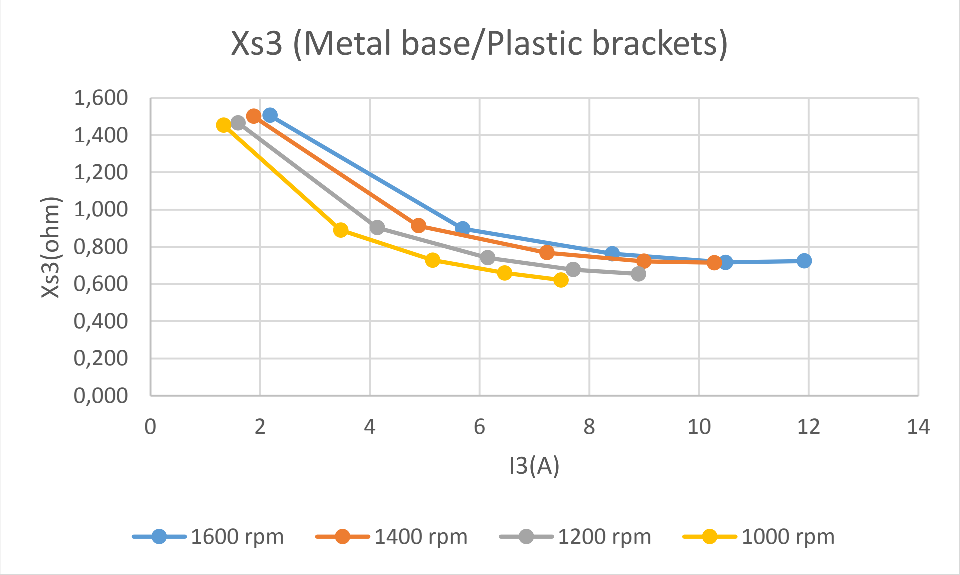


Figure 37. Synchronous reactance in phase 3 with metal base and plastic brackets in P1.

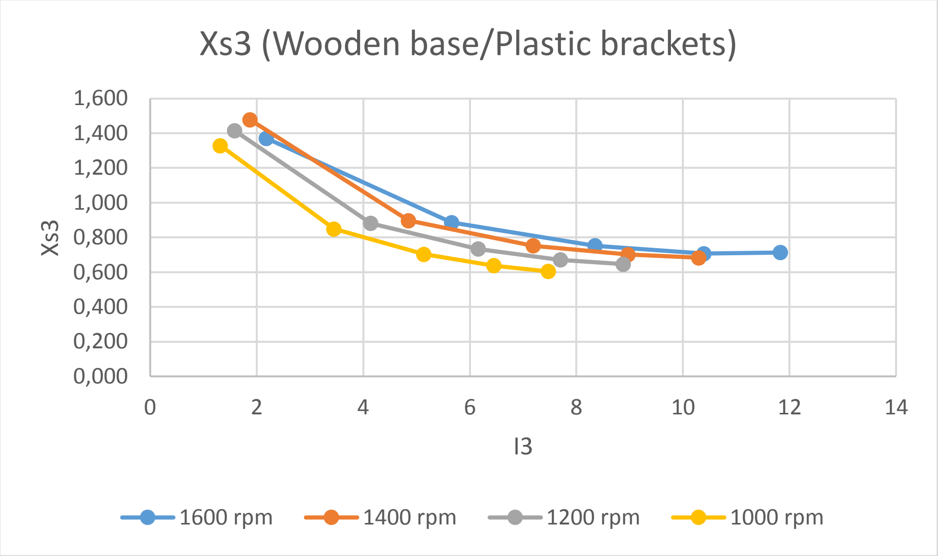


Figure 38. Synchronous reactance in phase 3 with wooden base and plastic brackets in P1.

As we can see the values of the synchronous reactance at high load currents oscillates between 0.6Ω and 0.8Ω. At low currents they have similar values between 1.3Ω and 1.5Ω. With the inductances we have the same phenomenon as in the previous figures.

In all the synchronous reactance calculations made I haven't taken into account the increase of the resistance because of the temperature. As I couldn't get the temperature of the copper wires when the PM synchronous machines were working, I estimated that the temperature could change the resistance and make it between a 5% and a 15% higher than at 20ºC.

When checking the change that the temperature makes in the reactance, I see that the values of the synchronous reactance when high load current decrease between 0.1Ω and 0.2Ω, even more when the load current is low. There isn't as much variation with the current when taking into account the temperature of the resistance but is still higher at low loads and in some cases, when I suppose a high temperature, it increases at high loads, being the lower levels of the synchronous reactance at middle current load.

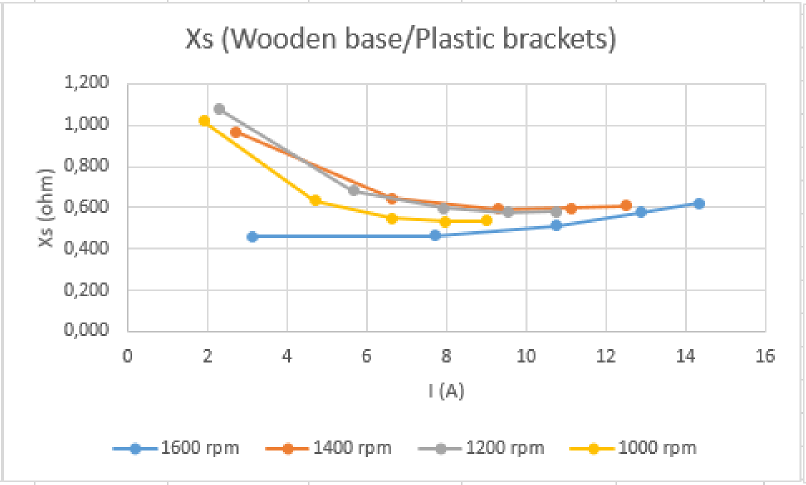


Figure 39. Synchronous reactance in P2 when resistance value 8% higher.

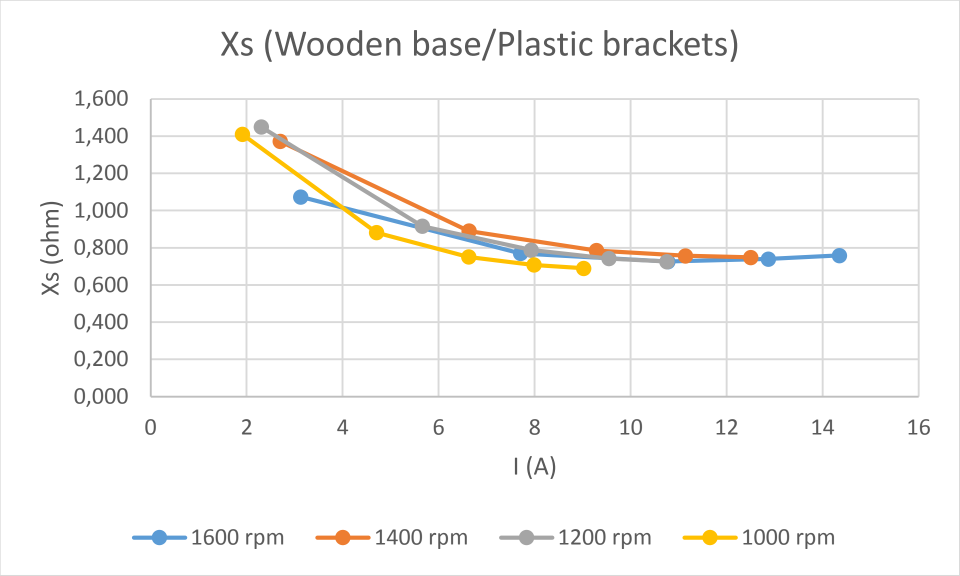


Figure 40. Synchronous reactance in P2 when resistance with resistance at 20ºC.

As we see in the last two figures, the synchronous reactance decreases at higher temperatures (making an 8% higher the resistance in the example) when the load current is high and low. The variation is less than measured at 20ºC and in some cases, like at 1600 rpm in the example, the synchronous reactance slightly increases at high load currents.

From this point, the most challenging part to explain is why the synchronous reactance does behave in that way with the load current because the material of the brackets and base or the increment of the temperature from the stator resistance doesn’t explain any of this changes.

There isn’t proven reason for the variation of the synchronous reactance and the inductances with the current. The first source of the problem could be an inaccuracy in the measuring instruments that depends on the load current in a way that alters the results and for instance the synchronous reactance calculations.

But something that seems interesting and that can be a true possibility is that the magnets and metal from the rotor suffer a magnetic saturation at some point that makes the magnetic permeability µ change and therefore the inductance and the synchronous reactance.

First of all, the no linearity of the synchronous reactance and inductances occurs when the load currents are low. Having low currents goes directly related to have a low inducted torque between the PM rotor and the stator of the PM synchronous generator.

When the inducted torque is low, there are two main reasons that produce this: a low load current that makes the stator magnetic field to be weak, or a low charge angle that makes the vector product between the magnetic fields of the stator and the rotor to be small.

$$\tau_{ind} = kB_R B_S \sin\gamma$$

The magnetic field of the rotor is constant because is produced by the permanent magnets but the stator magnetic field depends on the load current.

The charge angle doesn’t suffer any change with increase or decrease of the load current, the load is pure resistive and this doesn’t change during the tests. It will be supposed that it is the load current the main reason why the torque is low or high because of the direct dependency that the stator magnetic field has on it.

Something that is unknown is where in the B-H curve, the magnets and metallic materials of the rotor are working when the PM synchronous machines aren’t being run.

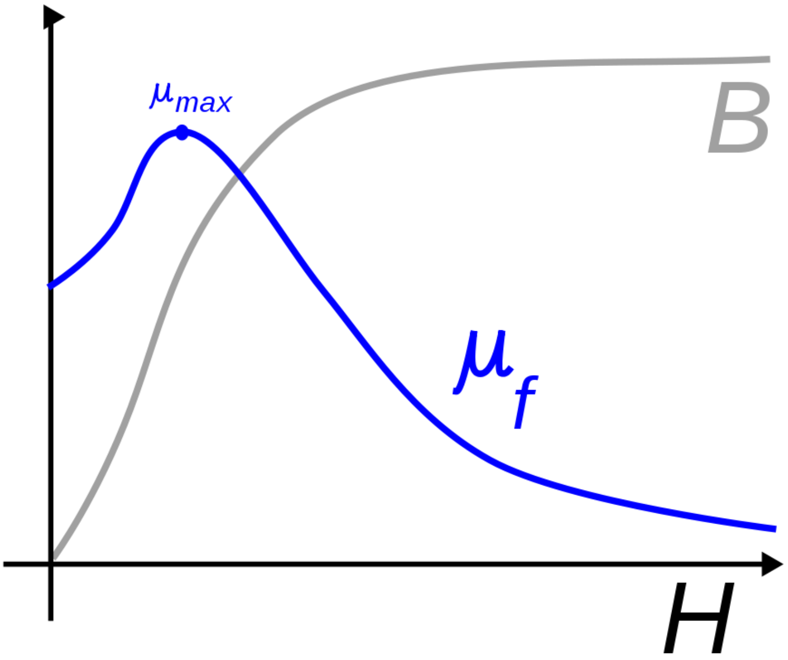


Figure 41. B-H curve with magnetic permeability curve.

There is a high probability that when there isn’t current load, the magnetic field of the rotor is between the linear part of the curve B-H and the saturated part. At this point, a small change in the magnetic field intensity H can end in a large variation of the magnetic permeability. This change in magnetic field can be produced adding the magnetic field of the stator when the synchronous generator is loaded.

The inducted torque always increases with the load current so if this theory is correct, at low load currents, the total magnetic field (sum of rotor and stator magnetic fields) will be between the linear part and the saturation in the B-H curve and the magnetic permeability is likely to suffer high variations; and at high currents, the total magnetic field will suffer a magnetic saturation and low variations of the magnetic permeability.

The higher synchronous reactance and inductances when the load current is low can be related to a higher magnetic permeability when the magnets aren’t saturated yet. When increasing the current load and therefore the total magnetic field, the synchronous reactance and inductances decrease and gets stabilised due to a magnetic saturation of the rotor, which makes the magnetic permeability get stabilised.

$$L = \mu \frac{N^2 A}{l}\,;\, X_S = \omega L_S$$

This also explains why the inductance always decreases when increasing the speed. As analysed before, the values of the inductances were always the lowest at 1600 rpm and always the highest at 1000 rpm. From the current analysis we know that the higher is the speed, the higher will be the load current. Knowing this we can deduce that with higher load currents, the magnetic field of the stator increases and therefore the rotor will be more saturated. This saturation makes the magnetic permeability be lower and then the inductance too.

Also the values of the inductances suffer less variation at higher speeds because the load current is higher in every point of the load. This makes the lowest currents being higher than at low speed and therefore having the inductance saturated earlier in a way that doesn’t suffer as much variation as it could be in lower speeds.

When comparing the synchronous reactance, this is not easily seen because the speed of the synchronous generator makes a big change on it.

Once we know that the values of the synchronous reactance belong to a saturated synchronous reactance, its values when it gets stabilised, or in other words saturated, and the load current is high are shown in the next table.

	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)
P1	0,54-0,63	0,54-0,65	0,605-0,713
P2	0,68-0,76	-	-
P3	0,82-0,98	0,81-0,98	0,85-1,01
S1	0,58-1,01	0,53-0,77	0,67-0,87
S2	1,13-2,35	1,1-1,56	1,25-1,6

Table 9. Values of the synchronous reactance in every PM synchronous machine.

The table shows the limit values that have in between the saturated synchronous reactance of every generator tested with wooden base and plastic brackets. In this synchronous reactance the effect of the temperature on the resistance isn’t taken into account. Also the speed isn’t shown in the table due to the similar values that the synchronous reactance have with the different speeds of the laboratory tests because of the magnetic saturation.

From the table it can be seen how symmetric are the generators P1 and P3 compared with the generators S1 and S2. The highest synchronous reactance is in the synchronous generator S2 while the lowest is in P1.

In all the PM synchronous generators modelled we can observe that the stator resistance and the synchronous reactance have similar values. Usually, in big PM synchronous machines, the stator resistance is a negligible value so when the calculations are made, the synchronous impedance is completely inductive. But this is not the case.

As the PM synchronous machines tested are small with a power between 500W and 600W at the highest limit, the inductances and synchronous reactance aren’t that big that can turn the resistance of the wires of the stator into a negligible value.

6. COMSOL SIMULATIONS ANALYSIS

This chapter analyses the data provided by Christian Svihus from the simulations of his model of the PM synchronous machine P1 in the software COMSOL. The generator P1 is modelled in a way that there are ideal efficient conditions, like the case of wooden base and plastic brackets. The data received from this simulations were an Excel sheet with the values of the three phase voltages and the three line currents with different speeds and loads, simulated during a period of 0.02 seconds. This phase voltages and line currents were simulated in the same speeds as I made my measurements (1600 rpm, 1400 rpm, 1200 rpm and 1000 rpm) and with approximately the same resistive loads (from no load to maximum load in the resistor bank) as in my laboratory tests.

With the purpose of getting waveforms, root mean square values of the phase voltages and line currents and values of the reactance, I used Matlab to make this task easier because of the amount of data that I had to analyse.

COMSOL also provides an approximated schematic of the magnetic field distribution of the permanent magnets rotor and how does it influences the stator.

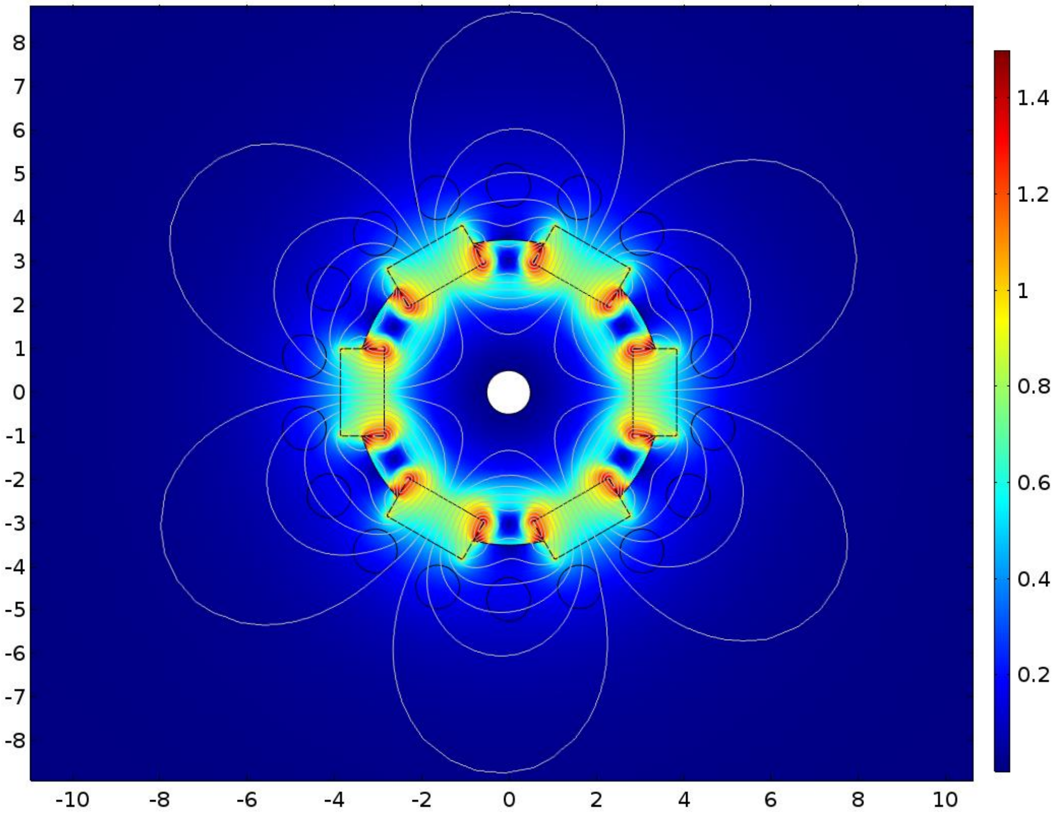


Figure 42. Magnetic field distribution in the PM synchronous machine.

In the figure we can see the magnetic field lines and also the strength of the field in the magnets, especially where they join the metallic cylinder of the rotor. The smaller is the air gap, the higher is the magnetic flux that goes through the windings of the stator and the higher is the electromotive force induced.

This is easily seen in the next figure:

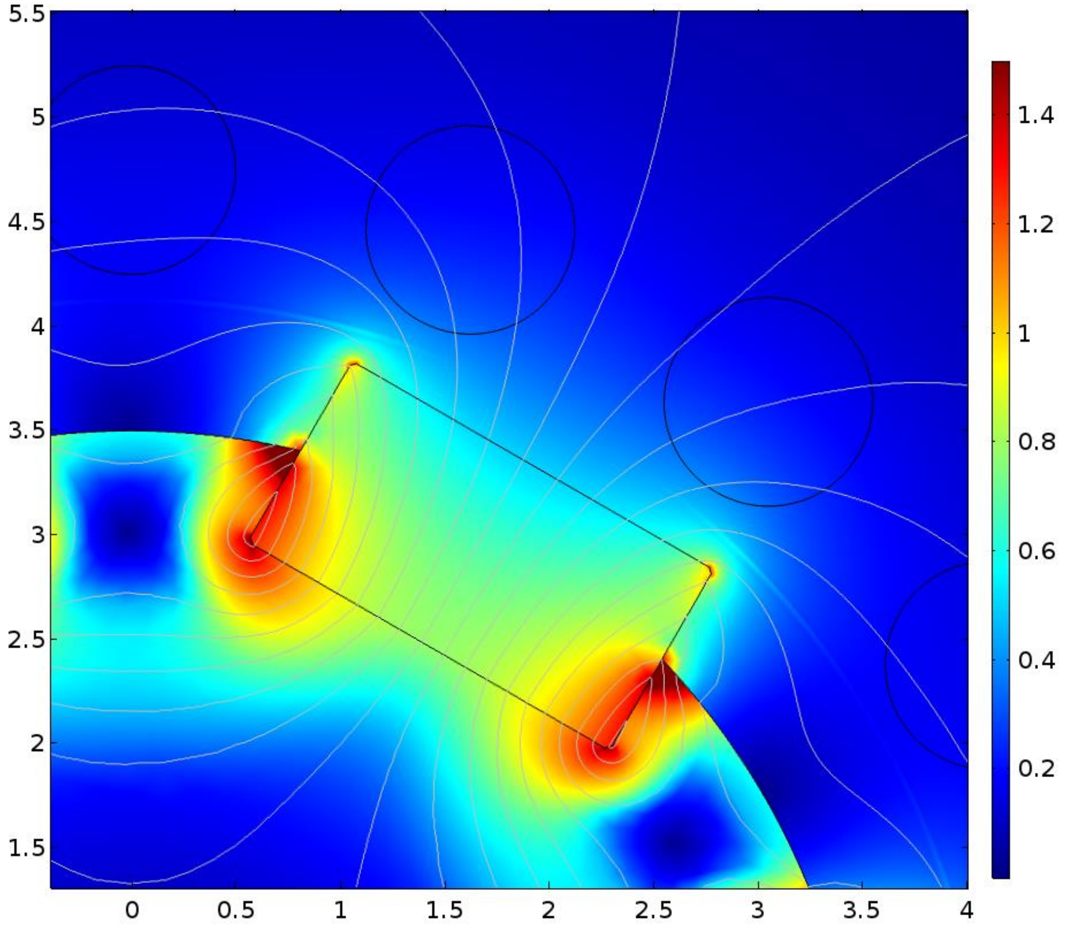


Figure 43. Detail of the magnetic field in one of the permanent magnets of the rotor.

6.1 Voltages and Currents

The three phase voltages and the three line currents I got were in an Excel file where every voltage and current was measured over the time and during 0.02 seconds.

The model of the PM synchronous generator built in COMSOL supposes that the machine is perfectly symmetric, the stator resistances and synchronous reactance of each phase is the same as in the other phases as well as the electromotive forces induced by the rotor magnetic flux.

As the model is made for a perfectly symmetric PM synchronous machine, I only analysed the Phase 1 due to the results are the same in each phase.

The first thing I do with the phase voltages and line currents simulated is to get the root mean square value of them, to compare with the measured data and to make easier later calculations.

To get the RMS values is as easy as introduce the next code in Matlab, where ‘yrms’ is the RMS value we want to calculate and ‘x’ is the vector with all the values of the voltage or the current simulated.

$$yrms = rms(x)$$

The next table shows all RMS values of the phase voltages and line currents calculated:

n (rpm)	Rload (ohm)	U1 (V)	I1 (A)	P1(W)
1600	no load	21,6788	0	0
1600	7,5	21,0546	2,7327	57,535905
1600	2,5	19,1742	7,3024	140,01768
1600	1,54	18,6049	10,892	202,64457
1600	1,12	17,8894	13,9095	248,83261
1600	0,88	17,2835	16,5	285,17775
1400	no load	18,9701	0	0
1400	7,5	18,4492	2,4046	44,362946
1400	2,5	18,146	6,7875	123,16598
1400	1,54	17,3425	10,1431	175,90671
1400	1,12	16,6828	12,9486	216,0189
1400	0,88	16,1094	15,3622	247,47582
1200	no load	16,2614	0	0
1200	7,5	15,8178	2,0623	32,621049
1200	2,5	14,6403	5,5046	80,588995
1200	1,54	14,0052	8,1981	114,81603
1200	1,12	13,472	10,4485	140,76219
1200	0,88	12,9885	12,4132	161,22885
1000	no load	13,5531	0	0
1000	7,5	13,1801	1,7181	22,64473
1000	2,5	12,5396	4,7007	58,944898
1000	1,54	12,0125	7,0257	84,396221
1000	1,12	11,5832	8,9781	103,99513
1000	0,88	11,188	10,7016	119,7295

Table 10. RMS values extracted from COMSOL simulation.

The input power is calculated from the RMS values of the voltages and the currents.

The phase voltages in each speed are higher from no load situation to maximum load than voltages measured in the laboratory tests. Also the variation between the highest phase voltage when no load situation to the lowest voltage in maximum load is less than the measured in the laboratory tests which is significantly higher.

The same happens with the line currents, in the simulation results we see that the currents measured reach higher values. This is seen better at maximum loads.

As we can see in the next figure, the phase voltages are higher in the simulation than in the measurements performed in the laboratory.

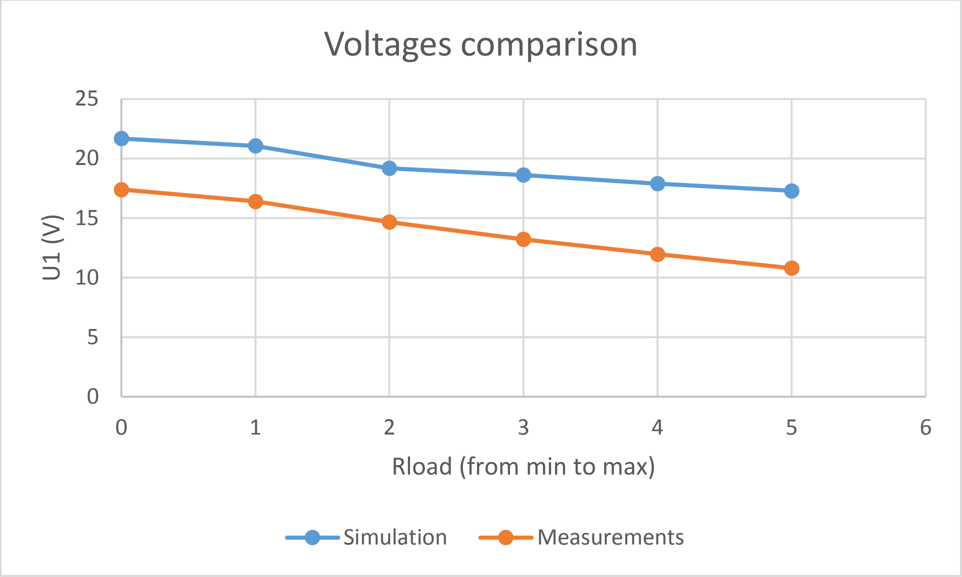


Figure 44. Voltages comparison at 1600 rpm.

This is also seen with the line currents:

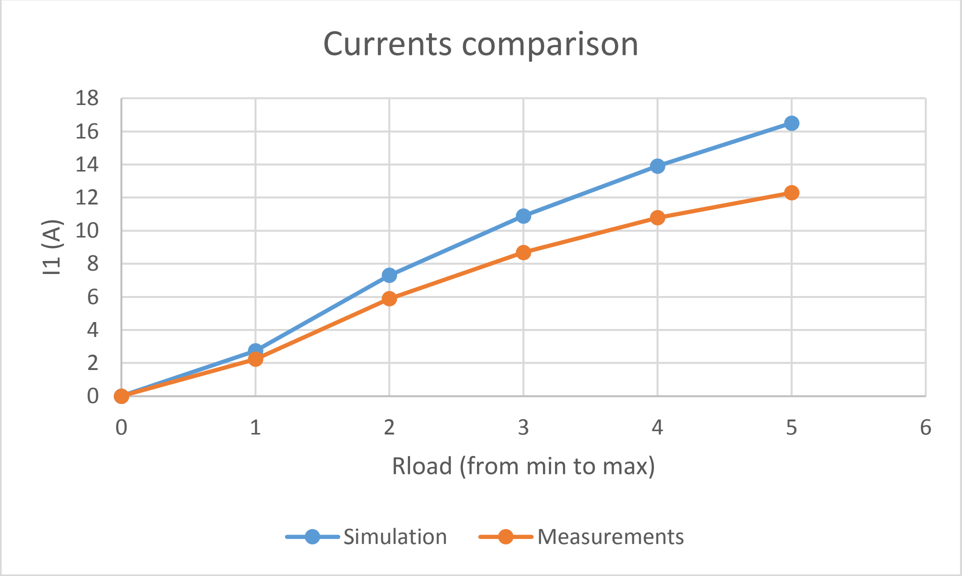


Figure 45. Currents comparison at 1600 rpm.

Once seen this effects we can deduce that the same happens with the input power, there will be a difference too and even higher due to it depends both on the line current and phase voltage.

This difference between phase voltages and line currents simulated and measured in the tests may have its origin in the model used in the simulations in COMSOL. This model of the synchronous generator only studies the part of the stator that directly cover the PM rotor .Only the length of the rotor is taken into account so as we have described and seen before, there will be some parts of the windings that aren’t included in the model because the stator isn’t perfectly made. With this I mean that there are some end effect that may have something to do with this results from the simulation.

Also the model could be inaccurate because the mechanical dimensions of the stator were hard to measure and some of them are estimated from other measures. Once the stator is made, measuring the dimensions of the winding thickness, inner diameter and similar can be a demanding task.

For that inaccuracy in the dimensions measurements, the length of the air gap could have been inaccurately measured and this means a big difference in the induced voltages of the stator and therefore in the currents.

Something interesting about this simulations in COMSOL is getting the waveform of the voltages and currents. In the next figure we can see the waveform of the voltage when the PM synchronous machine is run at 1600 rpm with medium load.

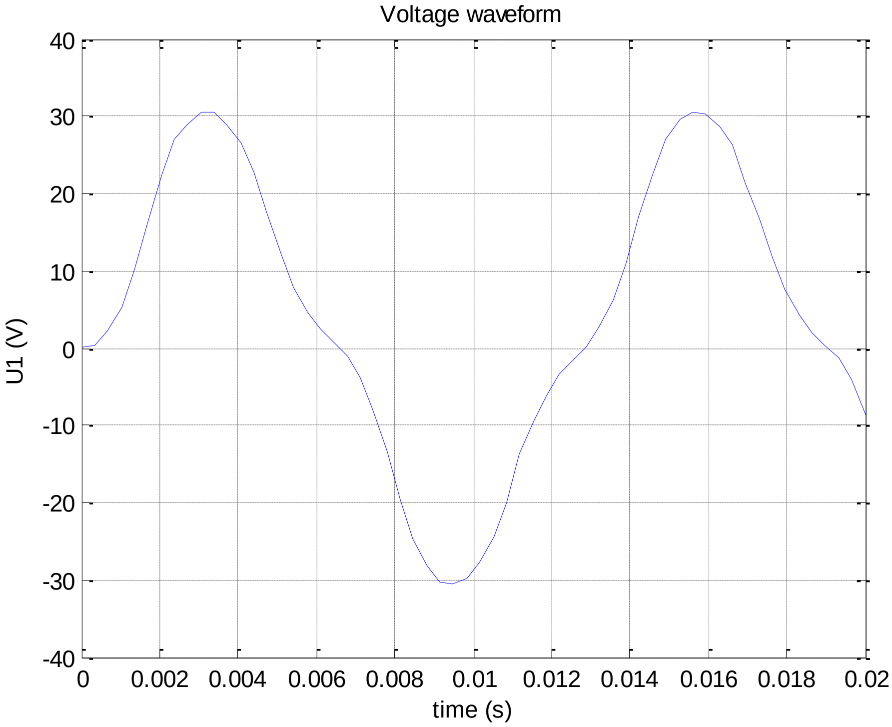
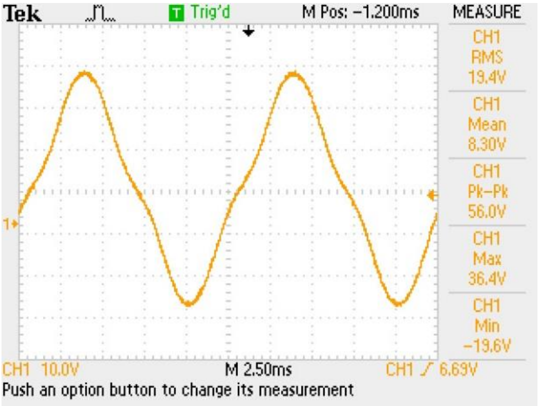


Figure 46. Voltage waveform.

The waveform is pretty similar to the waveform recorded from the oscilloscope.



M Pos: -1.200ms
MEASURE
CH1 RMS 19.4V
CH1 Mean 8.30V
CH1 Pk-Pk 56.0V
CH1 Max 36.4V
CH1 Min -19.6V
CH1 10.0V
M 2.50ms
CH1 ⁄ 6.69V
Push an option button to change its measurement

Figure 47. Voltage waveform of recorded from oscilloscope.

The waveform presents a strong component of the third harmonic because of it mechanical properties. The simulation gets a good approximation of this voltage waveform.

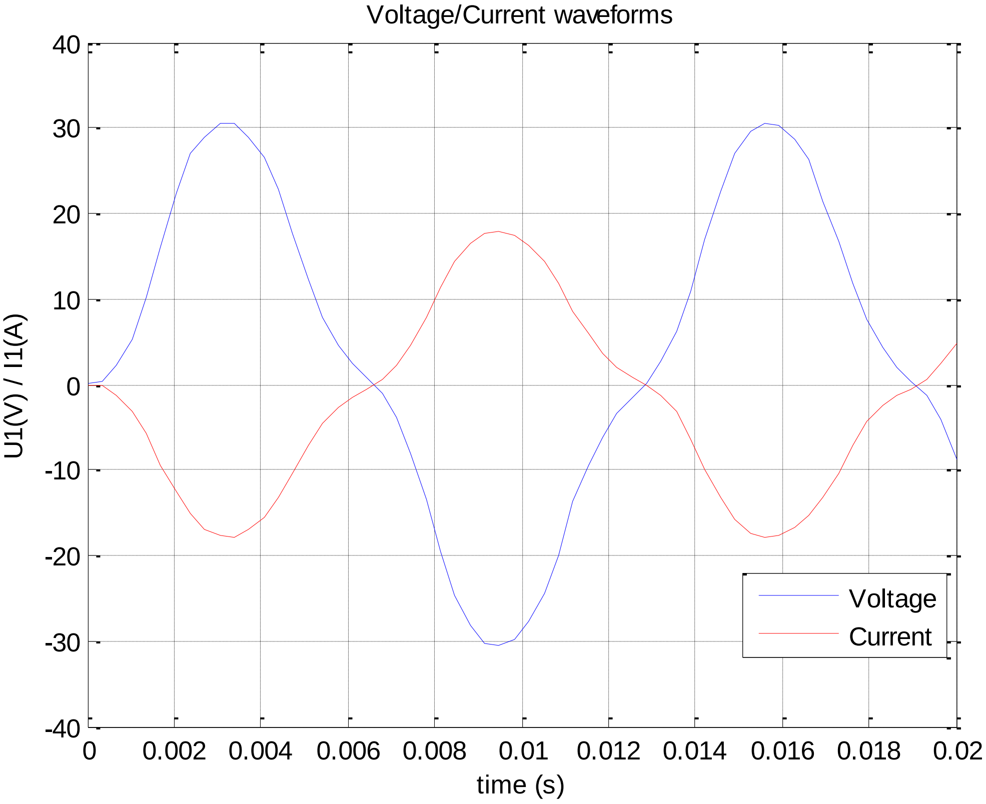


Figure 48. Voltage and current waveforms.

In this figure we can see compared the waveforms of the voltage and the current in the same case as before. The waveforms are similar and they are delayed 180º because the power input is generated and therefore negative.

6.2 Synchronous Reactance

The calculation of the synchronous reactance is made from the RMS values calculated in the currents and voltages. At first, when calculating, the results obtained were imaginary numbers so it didn’t make so much sense.

Due to the inaccuracies of the model explained before, the calculations can have this unexpected imaginary results. Even though there is this problem, the absolute values of the synchronous reactance obtained are analysed.

The next table shows this values with the currents, voltages and power input.

n (rpm)	Rload (ohm)	U1 (V)	I1 (A)	P1(W)	Xs (ohm)
1600	no load	21,6788	0	0	
1600	7,5	21,0546	2,7327	57,535905	1,603
1600	2,5	19,1742	7,3024	140,01768	0,524
1600	1,54	18,6049	10,892	202,64457	0,660
1600	1,12	17,8894	13,9095	248,83261	0,613
1600	0,88	17,2835	16,5	285,17775	0,580
1400	no load	18,9701	0	0	
1400	7,5	18,4492	2,4046	44,362946	1,657
1400	2,5	18,146	6,7875	123,16598	1,251
1400	1,54	17,3425	10,1431	175,90671	0,952
1400	1,12	16,6828	12,9486	216,0189	0,816
1400	0,88	16,1094	15,3622	247,47582	0,736
1200	no load	16,2614	0	0	
1200	7,5	15,8178	2,0623	32,621049	1,664
1200	2,5	14,6403	5,5046	80,588995	0,752
1200	1,54	14,0052	8,1981	114,81603	0,681
1200	1,12	13,472	10,4485	140,76219	0,628
1200	0,88	12,9885	12,4132	161,22885	0,586
1000	no load	13,5531	0	0	
1000	7,5	13,1801	1,7181	22,64473	1,655
1000	2,5	12,5396	4,7007	58,944898	1,014
1000	1,54	12,0125	7,0257	84,396221	0,826
1000	1,12	11,5832	8,9781	103,99513	0,735
1000	0,88	11,188	10,7016	119,7295	0,673

Table 11. Values of the synchronous reactance.

As seen in the measurements and in the analysis of the reactance, the values of the synchronous reactance vary from higher values when no load situation to lower and stabilised values when increasing the load.

The values when the load increases and the synchronous reactance gets stabilised are quite similar to the values obtained in my calculations from the laboratory tests. The synchronous reactance is between 0.5Ω and 0.7Ω when increasing the current.

This shows that the model is more similar to reality when simulating the reactance than when simulating currents and voltages.

Also we can deduce that the theories made about the behaviour of the inductances in the stator are maintained by this results that show the same effects of the saturation of the permanent magnets and metal in the rotor and the variation of the inductance and synchronous reactance with the load current.

7. CONCLUSIONS AND FURTHER WORK

7.1 Conclusions of the Project

Modelling a handmade PM synchronous machines, without any standard in its dimensions and electric values, is a demanding task that requires several measurements and application of electromagnetic laws.

From this written report about my specialisation project we can see how, applying electric engineering and electromagnetic concepts, a PM synchronous machine behaviour can be explained. Making certain and detailed measurements help us to deduce the behaviour of other internal parameters of a synchronous generator and therefore to explain how it works and why.

Voltages and currents aren’t only dependent on the load but on the strength of the magnetic flux, length of the air gap and different mechanical characteristics. We have already proved that the number of turns per coil, the thickness of the wire, the speed of the PM rotor can be significant for the limits of the currents, voltages and electromotive forces.

The efficiency of a PM synchronous generator can be altered depending on the materials that have the base and the brackets of the stator. Non-metallic materials are considered as ideal to get a high efficiency because they don’t hold eddy currents that produce losses. The study of the efficiency has also shown how it can change depending on the different mechanical characteristics of a synchronous machine. Power losses in the copper show also a dependency on the speed of the rotor, apart from the load current and resistance.

The main challenge of this project work was the modelling of the synchronous reactance. The variation of the reactance with the load current was something that was unexplained. Several measurements and calculations made me realise that the inductance was variable with the load current too. This made me think about a saturation of the magnetic field that could cause the variation of the inductance with the current. This could happen because of the variation of the magnetic permeability with the saturation of the rotor.

Finally, using COMSOL as a modelling tool can help to get a further analysis on the magnetic flux distribution as well as the values of the currents and voltages to reach a proper electric model of the synchronous machine.

7.2 Further Work

Even though this report gathers a large analysis of the behaviour of small PM synchronous machines, there are several things that could be interesting to furtherly analyse to have a better description of the generators.

If my work is going to be continued by other students in NTNU, I suggest them to take into account the following issues.

First of all, a further study of the magnetic properties of the rotor could be really helpful to verify that the inductances vary with the current due to the magnetic saturation of the rotor and the decrease of the magnetic permeability. It also could be a good idea to test the synchronous generators with other rotors with different magnetic properties and then study how this change of the rotor affects the inductances of the stator.

The relation of the length of the air gap with the value of the electromotive forces is also an interesting issue. I would suggest to make some laboratory tests with different size stators to see how the air gap length influences the induced voltages. In order to have closer results with the voltages in a COMSOL model, more accurate measures of the dimensions of the stators will be needed.

About the efficiencies of the different PM synchronous machines, it would be worthy to analyse exactly which levels of load are acceptable in terms of the efficiency and power losses. Also in which cases can be this PM synchronous generators used in a profitable way. To reach good results in this task it will be needed to study how to minimise the power losses of the generators, mainly in the copper.

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APPENDICES

This final section includes all the tables I used in the electric laboratory to gather the data from my measurements as well as the calculations made from this measures.

This data belong to all the PM synchronous machines that I have tested so it will show measurements from P1, P2, P3, S1 and S2 synchronous generators.

P1

METAL BASE AND METAL BRACKETS																					
Measured											Calculations										
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss(W)
1600	-0,28	17,41	0,0028	0	17,16	0,0012	0	17,4	0,0019	0	167,55	46,914	0	46,914	0,000							0,000
1600	-0,92	16,38	2,23	36,47	16,08	2,243	36,02	16,31	2,173	35,35	167,55	154,147	107,84	46,307	69,959	1,066	1,179	1,332	7,345	7,169	7,506	5,738
1600	-2	14,6	5,819	84,6	14,26	5,764	81,9	14,41	5,654	81,2	167,55	335,103	247,7	87,403	73,918	0,744	0,813	0,914	2,509	2,474	2,549	38,593
1600	-2,82	13,12	8,575	111,4	12,78	8,441	106,9	12,88	8,344	106,6	167,55	472,496	324,9	147,596	68,763	0,664	0,712	0,781	1,530	1,514	1,544	83,536
1600	-3,41	11,85	10,6	123,2	11,49	10,416	117,9	11,58	10,328	118,2	167,55	571,351	359,3	212,051	62,886	0,654	0,696	0,745	1,118	1,103	1,121	127,609
1600	-3,82	10,63	12,065	125,5	10,36	11,827	119,8	10,41	11,739	120,1	167,55	640,047	365,4	274,647	57,090	0,685	0,709	0,753	0,881	0,876	0,887	164,905
1400	-0,28	15	0,0025	0	14,79	0,0008	0	15	0,0006	0	146,61	41,050	0	41,050	0,000							0,000
1400	-0,82	14,04	1,9145	26,89	13,8	1,9327	26,67	14,01	1,8843	26,38	146,61	120,218	79,94	40,278	66,496	1,324	1,362	1,462	7,334	7,140	7,435	4,267
1400	-1,7	12,51	5	62,46	12,26	4,962	60,76	12,44	4,871	60,52	146,61	249,233	183,74	65,493	73,722	0,802	0,836	0,904	2,502	2,471	2,554	28,578
1400	-2,4	11,28	7,378	82,8	11,03	7,295	80,1	11,16	7,22	80,2	146,61	351,858	243,1	108,758	69,090	0,675	0,702	0,755	1,529	1,512	1,546	62,254
1400	-2,91	10,26	9,191	93,2	10,01	9,055	89,7	10,09	8,99	89,9	146,61	426,628	272,8	153,828	63,943	0,631	0,657	0,705	1,116	1,105	1,122	96,349
1400	-3,32	9,3	10,577	96,8	9,07	10,388	92,7	9,16	10,315	93	146,61	486,737	282,5	204,237	58,040	0,635	0,657	0,694	0,879	0,873	0,888	127,088
1200	-0,23	12,82	0,0021	0	12,64	0,0013	0	12,82	0,0014	0	125,66	28,903	0	28,903	0,000							0,000
1200	-0,7	12,06	1,643	19,81	11,85	1,657	19,63	12,03	1,6	19,24	125,66	87,965	58,68	29,285	66,709	1,070	1,147	1,285	7,340	7,151	7,519	3,119
1200	-1,47	1078	4,3	46,28	10,57	4,262	44,96	10,71	4,2	44,87	125,66	184,726	136,11	48,616	73,682	#¡NUM!	0,747	0,821	250,698	2,480	2,550	21,155
1200	-2,08	9,74	6,373	61,8	9,53	6,285	59,7	9,62	6,245	59,8	125,66	261,381	181,3	80,081	69,362	0,609	0,641	0,698	1,528	1,516	1,540	46,411
1200	-2,56	8,88	7,981	70,4	8,67	7,85	67,7	8,73	7,811	67,8	125,66	321,699	205,9	115,799	64,004	0,571	0,599	0,649	1,113	1,104	1,118	72,599
1200	-2,93	8,1	9,237	74,2	7,92	9,05	71,1	7,97	9	71,2	125,66	368,195	216,5	151,695	58,800	0,569	0,592	0,634	0,877	0,875	0,886	96,713
1000	-0,23	10,7	0,002	0	10,54	0,0004	0	10,68	0,0018	0	104,72	24,086	0	24,086	0,000							0,000
1000	-0,61	10,1	1,3657	13,66	9,84	1,3753	13,53	9,98	1,34	13,31	104,72	63,879	40,5	23,379	63,401	0,888	1,345	1,447	7,395	7,155	7,448	2,163
1000	-1,23	8,95	3,552	31,76	8,77	3,52	30,88	8,88	3,49	30,95	104,72	128,805	93,59	35,215	72,660	0,784	0,814	0,868	2,520	2,491	2,544	14,489
1000	-1,77	8,09	5,28	42,64	7,92	5,213	41,2	7,99	5,197	41,44	104,72	185,354	125,28	60,074	67,590	0,645	0,665	0,713	1,532	1,519	1,537	31,974
1000	-2,15	7,39	6,642	48,9	7,22	6,537	47,1	7,27	6,518	47,2	104,72	225,147	143,2	81,947	63,603	0,584	0,605	0,647	1,113	1,104	1,115	50,391
1000	-2,48	6,79	7,74	52,3	6,64	7,583	50,1	6,67	7,553	50,2	104,72	259,705	152,6	107,105	58,759	0,555	0,574	0,615	0,877	0,876	0,883	67,972

METAL BASE AND PLASTIC BRACKETS																						
Measured											Calculations											
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss (W)
1600	-0,06	17,59	0,0019	0	17,3	0,0016	0	17,51	0,0012	0	167,55	10,053	0	10,053	0,000							0,000
1600	-0,73	16,56	2,261	37,36	16,08	2,233	35,9	16,35	2,179	35,54	167,55	122,313	108,8	13,513	88,952	1,017	1,548	1,506	7,324	7,201	7,503	5,784
1600	-1,83	14,82	5,926	87,4	14,33	5,758	82	14,53	5,692	82,4	167,55	306,619	251,8	54,819	82,121	0,679	0,860	0,897	2,501	2,489	2,553	39,223
1600	-2,67	13,33	8,728	114,9	12,7	8,35	105,6	13,01	8,417	108,6	167,55	447,363	329,1	118,263	73,564	0,625	0,800	0,762	1,527	1,521	1,546	84,447
1600	-3,3	12,04	10,826	128,8	11,57	10,43	118,9	11,73	10,483	121,6	167,55	552,920	369,3	183,620	66,791	0,622	0,709	0,716	1,112	1,109	1,119	130,864
1600	-3,7	10,87	12,35	131,6	10,42	11,83	119,7	10,59	11,92	124,1	167,55	619,941	375,4	244,541	60,554	0,647	0,723	0,724	0,880	0,881	0,888	169,309
1400	-0,05	15,1	0,002	0	14,87	0,0016	0	15,05	0,0013	0	146,61	7,330	0	7,330	0,000							0,000
1400	-0,6	14,14	1,9322	27,31	13,86	1,9244	26,66	14,05	1,88	26,39	146,61	87,965	80,36	7,605	91,355	1,295	1,437	1,501	7,318	7,202	7,473	4,275
1400	-1,52	12,6	5,06	63,69	12,29	4,93	60,52	12,47	4,884	60,82	146,61	222,844	185,03	37,814	83,031	0,786	0,887	0,913	2,490	2,493	2,553	28,739
1400	-2,23	11,37	7,47	84,5	11,03	7,252	79,6	11,17	7,226	80,4	146,61	326,935	244,5	82,435	74,785	0,659	0,743	0,768	1,522	1,521	1,546	62,575
1400	-2,76	10,3	9,28	94,9	9,93	8,995	88,5	10,07	8,996	90	146,61	404,637	273,4	131,237	67,567	0,634	0,708	0,722	1,110	1,104	1,119	96,608
1400	-3,17	9,35	10,67	100,3	8,91	10,06	91,4	9,13	10,28	94,4	146,61	464,746	286,1	178,646	61,560	0,634	0,746	0,714	0,876	0,886	0,888	124,959
1200	-0,04	12,81	0,002	0	12,62	0,0007	0	12,76	0,0014	0	125,66	5,027	0	5,027	0,000							0,000
1200	-0,5	12	1,636	19,63	11,75	1,643	19,32	11,92	1,598	19,03	125,66	62,832	57,98	4,852	92,278	1,286	1,457	1,466	7,335	7,152	7,459	3,090
1200	-1,26	10,71	4,271	45,68	10,44	4,178	43,7	10,59	4,135	43,78	125,66	158,336	133,16	25,176	84,099	0,779	0,882	0,902	2,508	2,499	2,561	20,570
1200	-1,85	9,68	6,332	61,1	9,37	6,196	58	9,52	6,15	58,4	125,66	232,478	177,5	54,978	76,351	0,645	0,728	0,741	1,529	1,512	1,548	45,316
1200	-2,33	8,83	7,94	69,8	8,52	7,74	65,6	8,64	7,706	66,3	125,66	292,796	201,7	91,096	68,887	0,592	0,660	0,677	1,112	1,101	1,121	71,040
1200	-2,7	8,08	9,203	74,6	7,77	8,926	69,6	7,89	8,894	70,4	125,66	339,292	214,6	124,692	63,249	0,577	0,640	0,654	0,878	0,870	0,887	94,860
1000	-0,03	10,65	0,002	0	10,49	0,0004	0	10,61	0,0019	0	104,72	3,142	0	3,142	0,000							0,000
1000	-0,41	9,98	1,364	13,61	9,79	1,348	13,19	9,91	1,3358	13,23	104,72	42,935	40,03	2,905	93,234	1,260	1,412	1,453	7,317	7,263	7,419	2,128
1000	-1,03	8,91	3,565	31,64	8,7	3,462	30	8,8	3,466	30,42	104,72	107,861	92,06	15,801	85,350	0,764	0,868	0,890	2,499	2,513	2,539	14,302
1000	-1,54	8,05	5,287	42,5	7,82	5,126	40	7,92	5,145	40,66	104,72	161,268	123,16	38,108	76,370	0,636	0,720	0,728	1,523	1,526	1,539	31,442
1000	-1,93	7,37	6,625	48,8	7,13	6,413	45,7	7,2	6,458	46,5	104,72	202,109	141	61,109	69,764	0,575	0,648	0,659	1,112	1,112	1,115	49,373
1000	-2,25	6,77	7,73	52	6,54	7,456	48,5	6,62	7,482	49,3	104,72	235,619	149,8	85,819	63,577	0,547	0,611	0,621	0,876	0,877	0,885	66,751

WOODEN BASE AND PLASTIC BRACKETS																						
Measured											Calculations											
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss (W)
1600	-0,03	17,39	0,0016	0	17,12	0,0012	0	17,31	0,001	0	167,55	5,027	0	5,027	0,000							0,000
1600	-0,68	16,39	2,229	36,49	16,09	2,244	36,05	16,2	2,18	36,27	167,55	113,935	108,81	5,125	95,502	0,964	1,023	1,371	7,353	7,170	7,431	5,750
1600	-1,76	14,66	5,892	86,2	14,38	5,78	82,9	14,36	5,66	81	167,55	294,891	250,1	44,791	84,811	0,659	0,700	0,886	2,488	2,488	2,537	39,024
1600	-2,55	13,21	8,681	114	12,9	8,513	109,2	12,87	8,353	106,9	167,55	427,257	330,1	97,157	77,260	0,602	0,643	0,753	1,522	1,515	1,541	84,782
1600	-3,1	11,96	10,78	127,6	11,65	10,578	122,1	11,62	10,394	119,8	167,55	519,410	369,5	149,910	71,138	0,598	0,628	0,707	1,109	1,101	1,118	130,965
1600	-3,55	10,79	12,296	130,9	10,5	12,038	124,9	10,5	11,83	122,8	167,55	594,808	378,6	216,208	63,651	0,630	0,655	0,713	0,878	0,872	0,888	169,894
1400	-0,01	14,98	0,0025	0	14,76	0,0008	0	14,92	0,0015	0	146,61	1,466	0	1,466	0,000							0,000
1400	-0,55	14,03	1,917	26,86	13,8	1,9133	26,37	13,93	1,874	26,09	146,61	80,634	79,32	1,314	98,370	1,287	1,308	1,477	7,319	7,213	7,433	4,226
1400	-1,45	12,53	5,042	63,02	12,29	4,938	60,64	12,38	4,851	60,05	146,61	212,581	183,71	28,871	86,419	0,753	0,804	0,897	2,485	2,489	2,552	28,574
1400	-2,13	11,26	7,418	83,6	11,05	7,31	80,8	11,1	7,192	79,9	146,61	312,274	244,3	67,974	78,233	0,665	0,679	0,752	1,518	1,512	1,543	62,413
1400	-2,67	10,25	9,267	95,5	10,03	9,11	91,8	10,03	8,968	90,4	146,61	391,442	277,7	113,742	70,943	0,615	0,634	0,702	1,106	1,101	1,118	97,130
1400	-3,06	9,35	10,716	100,9	9,15	10,485	96,5	9,14	10,3	94,6	146,61	448,619	292	156,619	65,089	0,603	0,622	0,683	0,873	0,873	0,887	128,908
1200	0,01	12,77	0,0011	0	12,58	0,0017	0	12,72	0,0016	0	125,66	-1,257	0	-1,257	0,000							0,000
1200	-0,46	11,98	1,639	19,57	11,78	1,6301	19,15	11,9	1,5893	18,85	125,66	57,805	57,57	0,235	99,593	1,202	1,242	1,414	7,309	7,227	7,488	3,066
1200	-1,21	10,68	4,31	45,88	10,5	4,21	44,14	10,57	4,142	43,6	125,66	152,053	133,62	18,433	87,877	0,749	0,781	0,881	2,478	2,494	2,552	20,827
1200	-1,81	9,65	6,365	61,3	9,48	6,233	59	9,49	6,156	58,4	125,66	227,451	178,7	48,751	78,566	0,630	0,649	0,734	1,516	1,521	1,542	45,687
1200	-2,26	8,78	7,943	69,8	8,63	7,807	67,5	8,62	7,702	66,5	125,66	284,000	203,8	80,200	71,761	0,593	0,600	0,671	1,105	1,105	1,119	71,441
1200	-2,62	8,03	9,24	74,4	7,9	9,03	71,7	7,89	8,878	70,3	125,66	329,239	216,4	112,839	65,727	0,573	0,584	0,646	0,869	0,875	0,889	95,743
1000	0,02	10,63	0,0014	0	10,47	0,0013	0	10,58	0,0021	0	104,72	-2,094	0	-2,094	0,000							0,000
1000	-0,38	9,97	1,361	13,52	9,81	1,3571	13,27	9,92	1,3181	13,03	104,72	39,794	39,82	-0,026	100,067	1,222	1,215	1,329	7,325	7,229	7,526	2,116
1000	-1	8,88	3,578	31,69	8,77	3,493	30,58	8,82	3,452	30,28	104,72	104,720	92,55	12,170	88,379	0,765	0,755	0,849	2,482	2,511	2,555	14,384
1000	-1,49	8,04	5,288	42,43	7,95	5,16	40,93	7,94	5,138	40,74	104,72	156,032	124,1	31,932	79,535	0,629	0,624	0,703	1,520	1,541	1,545	31,554
1000	-1,87	7,35	6,633	48,8	7,26	6,509	47,2	7,23	6,451	46,6	104,72	195,826	142,6	53,226	72,820	0,572	0,567	0,638	1,108	1,115	1,121	49,863
1000	-2,18	6,75	7,743	25,4	6,68	7,567	50,6	6,65	7,473	49,7	104,72	228,289	125,7	102,589	55,062	0,544	0,542	0,605	0,872	0,883	0,890	67,427

P2

METAL BASE AND PLASTIC BRACKETS												
Measured					Calculations							
n (rpm)	Torque (Nm)	U (V)	I (A)	P (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs (ohm)	Rload (ohm)	RA-loss (W)
1600	-0,07	25,22	0,0027	0	167,55	11,729	0	11,729	0,000			0,000
1600	-0,56	22,69	3,08	69,76	167,55	93,829	69,76	24,069	74,348	1,251	7,367	6,880
1600	-1,2	18,93	7,518	141,9	167,55	201,062	141,9	59,162	70,575	0,857	2,518	40,994
1600	-1,64	16,23	10,49	169	167,55	274,785	169	105,785	61,503	0,785	1,547	79,812
1600	-1,9	14,11	12,48	175	167,55	318,348	175	143,348	54,971	0,800	1,131	112,966
1600	-2,1	12,46	13,88	170,4	167,55	351,858	170,4	181,458	48,429	0,817	0,898	139,732
1400	0,02	21,92	0,0023	0	146,61	-2,932	0	-2,932	0,000		9530,435	0,000
1400	-0,38	19,63	2,666	52,24	146,61	55,711	52,24	3,471	93,770	1,477	7,363	5,155
1400	-0,9	16,29	6,495	105,5	146,61	131,947	105,5	26,447	79,956	0,967	2,508	30,597
1400	-1,27	13,97	9,06	126,1	146,61	186,192	126,1	60,092	67,726	0,845	1,542	59,535
1400	-1,54	12,23	10,87	132,4	146,61	225,776	132,4	93,376	58,642	0,802	1,125	85,699
1400	-1,71	10,84	12,19	131,5	146,61	250,699	131,5	119,199	52,453	0,792	0,889	107,777
1200	0,03	18,76	0,0023	0	125,66	-3,770	0	-3,770	0,000		8156,522	0,000
1200	-0,32	16,78	2,291	38,38	125,66	40,212	38,38	1,832	95,443	1,502	7,324	3,807
1200	-0,77	13,96	5,553	77,4	125,66	96,761	77,4	19,361	79,991	0,959	2,514	22,365
1200	-1,08	11,99	7,779	93	125,66	135,717	93	42,717	68,525	0,824	1,541	43,890
1200	-1,31	10,53	9,357	98,2	125,66	164,619	98,2	66,419	59,653	0,771	1,125	63,503
1200	-1,48	9,38	10,53	98,4	125,66	185,982	98,4	87,582	52,908	0,750	0,891	80,422
1000	0,04	15,62	0,0025	0	104,72	-4,189	0	-4,189	0,000		6248,000	0,000
1000	-0,27	13,99	1,9015	26,56	104,72	28,274	26,56	1,714	93,937	1,466	7,357	2,622
1000	-0,63	11,63	4,643	53,93	104,72	65,973	53,93	12,043	81,745	0,940	2,505	15,636
1000	-0,9	10,02	6,505	65	104,72	94,248	65	29,248	68,967	0,795	1,540	30,691
1000	-1,1	8,81	7,848	69	104,72	115,192	69	46,192	59,900	0,739	1,123	44,672
1000	-1,23	7,86	8,86	69,4	104,72	128,805	69,4	59,405	53,880	0,713	0,887	56,936

WOODEN BASE AND PLASTIC BRACKETS

Measured					Calculations							
n (rpm)	Torque (Nm)	U (V)	I (A)	P (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs (ohm)	Rload (ohm)	RA-loss (W)
1600	-0,03	25,5	0,0017	0	167,55	5,027	0	5,027	0,000			0,000
1600	-0,45	23,01	3,127	71,77	167,55	75,398	71,77	3,628	95,188	1,074	7,358	7,092
1600	-1,12	19,21	7,707	147,5	167,55	187,658	147,5	40,158	78,601	0,770	2,493	43,081
1600	-1,55	16,46	10,77	176,3	167,55	259,705	176,3	83,405	67,885	0,726	1,528	84,130
1600	-1,83	14,32	12,87	183,2	167,55	306,619	183,2	123,419	59,748	0,740	1,113	120,136
1600	-2,04	12,65	14,351	179,8	167,55	341,805	179,8	162,005	52,603	0,759	0,881	149,376
1400	0,01	22,15	0,0025	0	146,61	-1,466	0	-1,466	0,000		8860,000	0,000
1400	-0,37	19,88	2,7	53,59	146,61	54,245	53,59	0,655	98,793	1,371	7,363	5,287
1400	-0,94	16,54	6,63	109,4	146,61	137,811	109,4	28,411	79,384	0,890	2,495	31,882
1400	-1,31	14,18	9,287	131,2	146,61	192,056	131,2	60,856	68,313	0,785	1,527	62,556
1400	-1,57	12,4	11,141	137,5	146,61	230,174	137,5	92,674	59,737	0,757	1,113	90,026
1400	-1,75	11,01	12,5	137	146,61	256,563	137	119,563	53,398	0,749	0,881	113,328
1200	0,02	18,91	0,0021	0	125,66	-2,513	0	-2,513	0,000		9004,762	0,000
1200	-0,31	16,94	2,306	38,97	125,66	38,956	38,97	-0,014	100,037	1,449	7,346	3,857
1200	-0,79	14,08	5,66	79,5	125,66	99,274	79,5	19,774	80,081	0,916	2,488	23,235
1200	-1,11	12,1	7,926	95,6	125,66	139,487	95,6	43,887	68,537	0,788	1,527	45,564
1200	-1,35	10,61	9,546	100,9	125,66	169,646	100,9	68,746	59,477	0,742	1,111	66,094
1200	-1,52	9,43	10,75	101	125,66	191,009	101	90,009	52,877	0,725	0,877	83,817
1000	0,04	15,72	0,0025	0	104,72	-4,189	0	-4,189	0,000		6288,000	0,000
1000	-0,26	14,1	1,9125	26,91	104,72	27,227	26,91	0,317	98,835	1,410	7,373	2,653
1000	-0,64	11,75	4,706	55,2	104,72	67,021	55,2	11,821	82,363	0,881	2,497	16,063
1000	-0,92	10,11	6,622	66,7	104,72	96,342	66,7	29,642	69,232	0,751	1,527	31,805
1000	-1,11	8,88	7,983	70,6	104,72	116,239	70,6	45,639	60,737	0,708	1,112	46,222
1000	-1,26	7,9	9,016	70,9	104,72	131,947	70,9	61,047	53,734	0,689	0,876	58,958

P3

WOODEN BASE AND PLASTIC BRACKETS																						
Measured											Calculations											
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss (W)
1600	-0,1	25,28	0,0016	0	25,48	0,0016	0	25,56	0,0012	0	167,55	16,755	0	16,755	0,000							0,000
1600	-1,54	23,08	3,143	72,4	23,24	3,233	75	23,32	3,152	73,3	167,55	258,029	220,7	37,329	85,533	1,391	1,325	1,454	7,343	7,188	7,398	17,542
1600	-3,61	19,58	7,877	153,3	19,78	7,955	156,4	19,78	7,847	154,4	167,55	604,861	464,1	140,761	76,728	0,953	0,923	1,000	2,486	2,486	2,521	108,325
1600	-4,95	16,83	11,071	184	17,04	11,183	188,2	16,94	11,081	185,5	167,55	829,380	557,7	271,680	67,243	0,899	0,874	0,936	1,520	1,524	1,529	214,683
1600	-5,82	14,64	13,168	188,2	14,81	13,262	192,5	14,65	13,165	189,2	167,55	975,150	569,9	405,250	58,442	0,910	0,900	0,952	1,112	1,117	1,113	302,881
1600	-6,3	12,61	14,4	185	12,79	14,5	189,4	12,63	14,408	185,2	167,55	1055,575	559,6	495,975	53,014	0,983	0,974	1,014	0,876	0,882	0,877	362,348
1400	-0,11	21,67	0,0015	0	21,84	0,0009	0	21,93	0,0021	0	146,61	16,127	0	16,127	0,000							0,000
1400	-1,27	19,6	2,667	52,1	19,72	2,742	53,9	19,82	2,67	52,8	146,61	186,192	158,8	27,392	85,288	1,780	1,741	1,850	7,349	7,192	7,423	12,612
1400	-2,95	16,53	6,647	109,7	16,7	6,705	111,9	16,73	6,623	110,6	146,61	432,493	332,2	100,293	76,811	1,109	1,085	1,149	2,487	2,491	2,526	77,085
1400	-4,1	14,22	9,355	133,5	14,38	9,44	136,3	14,36	9,364	135	146,61	601,091	404,8	196,291	67,344	0,980	0,962	1,010	1,520	1,523	1,534	153,189
1400	-4,87	12,4	11,209	140	12,55	11,305	143,1	12,48	11,23	141,2	146,61	713,979	424,3	289,679	59,427	0,948	0,935	0,977	1,106	1,110	1,111	219,981
1400	-5,38	10,91	12,5	138	11,09	12,557	141,2	10,98	12,507	139,1	146,61	788,749	418,3	370,449	53,033	1,189	0,939	0,975	0,873	0,883	0,878	272,603
1200	-0,1	18,31	0,0018	0	18,45	0,0016	0	18,52	0,0016	0	125,66	12,566	0	12,566	0,000							0,000
1200	-1,05	16,55	2,255	37,22	16,67	2,315	38,45	16,74	2,262	37,76	125,66	131,947	113,43	18,517	85,966	1,799	1,722	1,832	7,339	7,201	7,401	9,019
1200	-2,46	13,96	5,596	77,9	14,08	5,666	79,5	14,14	5,569	78,4	125,66	309,133	235,8	73,333	76,278	1,122	1,098	1,155	2,495	2,485	2,539	54,731
1200	-3,44	12,05	7,911	95,5	12,17	8	97,6	12,16	7,931	96,6	125,66	432,283	289,7	142,583	67,016	0,969	0,949	0,995	1,523	1,521	1,533	109,820
1200	-4,11	10,59	9,528	101,4	10,69	9,624	103,5	10,65	9,562	102,5	125,66	516,478	307,4	209,078	59,519	0,914	0,902	0,941	1,111	1,111	1,114	159,288
1200	-4,57	9,35	10,692	100,9	9,48	10,76	103	9,42	10,7	101,6	125,66	574,283	305,5	268,783	53,197	0,906	0,897	0,930	0,874	0,881	0,880	199,712
1000	-0,1	15,11	0,0008	0	15,24	0,0008	0	15,29	0,0021	0	104,72	10,472	0	10,472	0,000							0,000
1000	-0,89	13,7	1,866	25,5	13,79	1,914	26,32	13,87	1,852	25,68	104,72	93,201	77,5	15,701	83,154	1,683	1,669	1,749	7,342	7,205	7,489	6,129
1000	-2,03	11,57	4,642	53,57	11,69	4,679	54,52	11,73	4,623	54,04	104,72	212,581	162,13	50,451	76,267	1,078	1,062	1,107	2,492	2,498	2,537	37,564
1000	-2,83	10,04	6,596	66,1	10,15	6,644	67,4	10,14	6,613	67	104,72	296,357	200,5	95,857	67,655	0,913	0,904	0,939	1,522	1,528	1,533	76,145
1000	-3,42	8,87	8,014	71,1	8,99	8,061	72,5	8,93	8,048	71,9	104,72	358,142	215,5	142,642	60,172	0,845	0,836	0,870	1,107	1,115	1,110	112,422
1000	-3,85	7,89	9,063	71,8	8,03	9,087	73,3	7,96	9,071	72,4	104,72	403,171	217,5	185,671	53,947	0,824	0,818	0,848	0,871	0,884	0,878	143,150

S1

METAL BASE AND PLASTIC BRACKETS																						
Measured											Calculations											
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss(W)
1600	-0,1	15,87	0,0021	0	15,74	0,0014	0	16,03	0,0014	0	167,55	16,755	0	16,755	0,000							0,000
1600	-0,6	14,59	1,983	28,88	14,44	2,0035	28,89	14,67	1,959	28,7	167,55	100,531	86,47	14,061	86,013	1,006	0,889	1,369	7,358	7,207	7,489	6,912
1600	-1,4	12,54	5,02	62,6	12,43	4,984	61,63	12,57	4,9	61,33	167,55	234,572	185,56	49,012	79,106	0,713	0,641	0,903	2,498	2,494	2,565	43,430
1600	-1,95	10,88	7,116	76,6	10,78	7,07	75,4	10,88	6,98	75,3	167,55	326,726	227,3	99,426	69,569	0,719	0,670	0,839	1,529	1,525	1,559	87,586
1600	-2,38	9,46	8,507	82	9,37	8,445	80,6	9,47	8,369	80,5	167,55	398,773	243,1	155,673	60,962	0,781	0,746	0,862	1,112	1,110	1,132	125,342
1600	-2,66	8,38	9,526	78,7	8,3	9,443	77,3	8,41	9,344	77,5	167,55	445,687	233,5	212,187	52,391	0,799	0,772	0,869	0,880	0,879	0,900	156,717
1400	0,03	13,69	0,0027	0	13,57	0,0008	0	13,83	0,0018	0	146,61	-4,398	0	-4,398	0,000							0,000
1400	-0,46	12,53	1,712	21,4	12,4	1,7168	21,27	12,62	1,6961	21,38	146,61	67,440	64,05	3,390	94,974	1,233	1,143	1,475	7,319	7,223	7,441	5,135
1400	-1,12	10,78	4,326	46,69	10,69	4,275	45,73	10,83	4,243	46	146,61	164,201	138,42	25,781	84,299	0,752	0,687	0,905	2,492	2,501	2,552	32,250
1400	-1,63	9,44	6,18	57,9	9,36	6,113	56,8	9,44	6,082	57	146,61	238,970	171,7	67,270	71,850	0,676	0,627	0,793	1,528	1,531	1,552	66,003
1400	-1,98	8,35	7,512	62	8,29	7,424	60,8	8,34	7,377	60,8	146,61	290,283	183,6	106,683	63,249	0,673	0,632	0,770	1,112	1,117	1,131	97,327
1400	-2,22	7,4	8,424	62,9	7,36	8,323	61,7	7,42	8,252	61,7	146,61	325,469	186,3	139,169	57,240	0,713	0,678	0,790	0,878	0,884	0,899	122,174
1200	0,05	11,7	0,0016	0	11,59	0,0017	0	11,82	0,0021	0	125,66	-6,283	0	-6,283	0,000							0,000
1200	-0,4	10,68	1,46	15,6	10,57	1,4593	15,42	10,78	1,4358	15,47	125,66	50,265	46,49	3,775	92,489	1,362	1,260	1,541	7,315	7,243	7,508	3,708
1200	-0,95	9,18	3,68	33,75	9,1	3,648	33,16	9,23	3,62	33,37	125,66	119,381	100,28	19,101	84,000	0,802	0,726	0,934	2,495	2,495	2,550	23,431
1200	-1,37	8,06	5,27	42,23	7,97	5,23	41,5	8,05	5,2	41,65	125,66	172,159	125,38	46,779	72,828	0,686	0,638	0,802	1,529	1,524	1,548	48,185
1200	-1,68	7,14	6,427	46,1	7,07	6,373	45,2	7,12	6,33	45,2	125,66	211,115	136,5	74,615	64,657	0,669	0,625	0,764	1,111	1,109	1,125	71,540
1200	-1,9	6,42	7,313	46,5	6,36	7,24	45,6	6,41	7,161	45,5	125,66	238,761	137,6	101,161	57,631	0,655	0,618	0,743	0,878	0,878	0,895	92,178
1000	0,05	9,73	0,0016	0	9,64	0,0008	0	9,87	0,002	0	104,72	-5,236	0	-5,236	0,000							0,000
1000	-0,34	8,9	1,216	10,82	8,8	1,2238	10,77	8,97	1,2	10,77	104,72	35,605	32,36	3,245	90,887	1,265	1,174	1,669	7,319	7,191	7,475	2,590
1000	-0,78	7,64	3,06	23,35	7,57	3,026	22,9	7,7	2,984	22,91	104,72	81,681	69,16	12,521	84,670	0,795	0,734	0,979	2,497	2,502	2,580	16,084
1000	-1,11	6,72	4,39	29,41	6,66	4,356	28,87	6,73	4,314	28,95	104,72	116,239	87,23	29,009	75,044	0,670	0,610	0,812	1,531	1,529	1,560	33,345
1000	-1,4	6	5,378	32,1	5,92	5,346	31,5	5,98	5,297	31,5	104,72	146,608	95,1	51,508	64,867	0,625	0,585	0,745	1,116	1,107	1,129	50,178
1000	-1,6	5,4	6,13	32,9	5,34	6,086	32,3	5,39	6,013	32,2	104,72	167,552	97,4	70,152	58,131	0,616	0,575	0,720	0,881	0,877	0,896	64,965

WOODEN BASE AND PLASTIC BRACKETS																						
Measured											Calculations											
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss(W)
1600	-0,02	15,89	0,002	0	15,76	0,0017	0	16,03	0,0013	0	167,55	3,351	0	3,351	0,000							0,000
1600	-0,53	14,62	1,9925	29,05	14,49	2,0072	29,04	14,71	1,9685	28,93	167,55	88,802	87,02	1,782	97,993	0,938	0,733	1,218	7,338	7,219	7,473	6,965
1600	-1,36	12,58	5,05	63,66	12,5	5,014	62,83	12,63	4,95	62,53	167,55	227,870	189,02	38,850	82,951	0,676	0,568	0,829	2,491	2,493	2,552	44,071
1600	-1,95	10,97	7,205	79,6	10,91	7,167	78,7	10,98	7,077	78,2	167,55	326,726	236,5	90,226	72,385	0,659	0,582	0,769	1,523	1,522	1,552	89,944
1600	-2,32	9,64	8,714	85,2	9,61	8,652	84,3	9,64	8,566	83,6	167,55	388,720	253,1	135,620	65,111	0,689	0,630	0,773	1,106	1,111	1,125	131,466
1600	-2,53	8,26	9,615	79,2	8,28	9,525	78,9	8,31	9,421	78,8	167,55	423,906	236,9	187,006	55,885	0,809	0,764	0,872	0,859	0,869	0,882	159,475
1400	0,01	13,68	0,002	0	13,57	0,0023	0	13,81	0,0014	0	146,61	-1,466	0	-1,466	0,000							0,000
1400	-0,44	12,54	1,7087	21,28	12,42	1,7166	21,21	12,65	1,6717	21,14	146,61	64,507	63,63	0,877	98,640	1,165	1,061	1,374	7,339	7,235	7,567	5,080
1400	-1,12	10,75	4,316	46,4	10,68	4,277	45,61	10,83	4,228	45,7	146,61	164,201	137,71	26,491	83,867	0,778	0,696	0,898	2,491	2,497	2,561	32,136
1400	-1,63	9,4	6,164	58,2	9,32	6,128	57,4	9,42	6,07	57,4	146,61	238,970	173	65,970	72,394	0,697	0,642	0,797	1,525	1,521	1,552	65,914
1400	-1,97	8,31	7,448	62,7	8,22	7,43	62	8,29	7,362	61,9	146,61	288,817	186,6	102,217	64,608	0,701	0,655	0,782	1,116	1,106	1,126	96,696
1400	-2,23	7,36	8,49	62,1	7,3	8,444	61,3	7,37	8,352	61,1	146,61	326,935	184,5	142,435	56,433	1,010	0,665	0,774	0,867	0,865	0,882	124,999
1200	0,03	11,67	0,0012	0	11,58	0,0005	0	11,78	0,0017	0	125,66	-3,770	0	-3,770	0,000							0,000
1200	-0,38	10,69	1,459	15,55	10,59	1,4669	15,48	10,77	1,4527	15,58	125,66	47,752	46,61	1,142	97,608	1,194	1,096	1,369	7,327	7,219	7,414	3,748
1200	-0,95	9,17	3,689	33,76	9,11	3,643	33,15	9,24	3,607	33,28	125,66	119,381	100,19	19,191	83,925	0,772	0,707	0,896	2,486	2,501	2,562	23,394
1200	-1,38	8,04	5,274	42,48	7,97	5,248	41,94	8,07	5,196	41,98	125,66	173,416	126,4	47,016	72,888	0,678	0,622	0,771	1,524	1,519	1,553	48,299
1200	-1,69	7,15	6,425	46	7,07	6,403	45,5	7,14	6,348	45,5	125,66	212,372	137	75,372	64,510	0,653	0,610	0,736	1,113	1,104	1,125	71,887
1200	-1,92	6,4	7,306	47	6,34	7,255	46,4	6,4	7,18	46,2	125,66	241,274	139,6	101,674	57,859	0,652	0,616	0,728	0,876	0,874	0,891	92,406
1000	0,04	9,72	0,0019	0	9,64	0,0005	0	9,82	0,0015	0	104,72	-4,189	0	-4,189	0,000							0,000
1000	-0,32	8,92	1,2203	10,85	8,84	1,2152	10,74	8,99	1,2065	10,81	104,72	33,510	32,4	1,110	96,687	1,080	0,973	1,328	7,310	7,275	7,451	2,593
1000	-0,78	7,66	3,088	23,62	7,63	3,028	23,08	7,72	3,01	23,22	104,72	81,681	69,92	11,761	85,601	0,727	0,642	0,872	2,481	2,520	2,565	16,281
1000	-1,15	6,74	4,423	29,76	6,7	4,39	29,34	6,76	4,36	29,41	104,72	120,428	88,51	31,918	73,496	0,628	0,555	0,734	1,524	1,526	1,550	33,923
1000	-1,41	6,02	5,415	32,7	5,98	5,375	32,2	6,01	5,338	32,1	104,72	147,655	97	50,655	65,694	0,594	0,538	0,691	1,112	1,113	1,126	50,849
1000	-1,61	5,42	6,184	33,6	5,39	6,133	33,2	5,41	6,084	33	104,72	168,599	99,8	68,799	59,194	0,586	0,537	0,671	0,876	0,879	0,889	66,193

S2

METAL BASE AND PLASTIC BRACKETS																					
Measured											Calculations										
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss(W)
1600	-0,02	17,21	0,0016	0	16,72	0,0013	0	17,1	0,0009	0	167,55	3,351	0	3,351	0,000							0,000
1600	-0,63	14,39	1,9584	28,06	13,93	1,9308	26,78	14,26	1,9113	27,16	167,55	105,558	82	23,558	77,683	0,966	1,080	1,433	7,348	7,215	7,461	15,460
1600	-1,2	10,47	4,2	44,4	10,2	4,081	42,04	10,43	4,077	42,92	167,55	201,062	129,36	71,702	64,338	1,319	1,325	1,469	2,493	2,499	2,558	70,180
1600	-1,52	8,18	5,4	43,2	7,98	5,25	41,1	8,12	5,285	42,1	167,55	254,678	126,4	128,278	49,631	1,318	1,322	1,421	1,515	1,520	1,536	116,678
1600	-1,71	6,62	5,944	38,5	6,5	5,78	36,8	6,59	5,83	37,7	167,55	286,513	113	173,513	39,440	1,460	1,452	1,533	1,114	1,125	1,130	141,589
1600	-1,8	5,5	6,26	33,8	5,43	6,1	32,5	5,53	6,148	33,3	167,55	301,593	99,6	201,993	33,025	1,558	1,540	1,607	0,879	0,890	0,899	157,393
1400	0,02	14,79	0,0019	0	14,36	0,0022	0	14,7	0,0019	0	146,61	-2,932	0	-2,932	0,000							0,000
1400	-0,43	12,24	1,675	20,5	11,86	1,6465	19,53	12,19	1,6288	19,85	146,61	63,041	59,88	3,161	94,985	1,542	1,562	1,747	7,307	7,203	7,484	11,260
1400	-1	9,15	3,654	33,04	8,9	3,54	31,22	9,13	3,544	32,05	146,61	146,608	96,31	50,298	65,692	1,116	1,145	1,276	2,504	2,514	2,576	52,988
1400	-1,3	7,22	4,695	33,25	7,02	4,565	31,54	7,17	4,597	32,41	146,61	190,590	97,2	93,390	51,000	1,171	1,182	1,281	1,538	1,538	1,560	88,231
1400	-1,45	5,91	5,253	30,37	5,75	5,115	28,85	5,84	5,165	29,59	146,61	212,581	88,81	123,771	41,777	1,272	1,274	1,358	1,125	1,124	1,131	110,860
1400	-1,53	4,94	5,565	26,9	4,82	5,432	25,7	4,93	5,471	26,4	146,61	224,310	79	145,310	35,219	2,331	1,364	1,435	0,888	0,887	0,901	124,606
1200	0,03	12,6	0,002	0	12,23	0,0013	0	12,52	0,0011	0	125,66	-3,770	0	-3,770	0,000							0,000
1200	-0,36	10,4	1,4115	14,71	10,07	1,394	14,05	10,34	1,386	14,34	125,66	45,239	43,1	2,139	95,272	1,744	1,729	1,902	7,368	7,224	7,460	8,072
1200	-0,83	7,77	3,112	24,04	7,57	3,009	22,68	7,78	3,009	23,3	125,66	104,301	70,02	34,281	67,133	1,145	1,167	1,290	2,497	2,516	2,586	38,308
1200	-1,1	6,19	4,026	24,58	6,02	3,912	23,29	6,15	3,945	23,95	125,66	138,230	71,82	66,410	51,957	1,115	1,127	1,221	1,538	1,539	1,559	64,884
1200	-1,25	5,12	4,556	22,89	4,98	4,441	21,72	5,06	4,483	22,29	125,66	157,080	66,9	90,180	42,590	1,160	1,158	1,247	1,124	1,121	1,129	83,491
1200	-1,34	4,31	4,878	20,65	4,22	4,743	19,66	4,3	4,782	20,18	125,66	168,389	60,49	107,899	35,923	1,232	1,228	1,305	0,884	0,890	0,899	95,320
1000	0,04	10,48	0,0021	0	10,18	0,0019	0	10,42	0,0018	0	104,72	-4,189	0	-4,189	0,000							0,000
1000	-0,29	8,65	1,1831	10,24	8,39	1,1575	9,72	8,61	1,1566	9,96	104,72	30,369	29,92	0,449	98,522	1,676	1,716	1,862	7,311	7,248	7,444	5,620
1000	-0,68	6,48	2,594	16,73	6,34	2,51	15,79	6,48	2,513	16,23	104,72	71,209	48,75	22,459	68,460	1,109	1,102	1,264	2,498	2,526	2,579	26,663
1000	-0,91	5,17	3,385	17,37	5,06	3,27	16,44	5,16	3,309	16,91	104,72	95,295	50,72	44,575	53,224	1,046	1,066	1,154	1,527	1,547	1,559	45,623
1000	-1,04	4,31	3,856	16,39	4,22	3,732	15,57	4,27	3,781	15,97	104,72	108,909	47,93	60,979	44,009	1,056	1,072	1,160	1,118	1,131	1,129	59,394
1000	-1,12	3,65	4,157	14,98	3,61	4,024	14,3	3,65	4,066	14,65	104,72	117,286	43,93	73,356	37,455	1,108	1,108	1,193	0,878	0,897	0,898	68,923

WOODEN BASE AND PLASTIC BRACKETS																					
Measured											Calculations										
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	omega (rad/s)	Pin (W)	Pload (W)	Ploss (W)	efficiency (%)	Xs1(ohm)	Xs2(ohm)	Xs3(ohm)	Rload1(ohm)	Rload2(ohm)	Rload3(ohm)	RA-loss(W)
1600	-0,01	17,1	0,0017	0	16,5	0,001	0	16,84	0,0012	0	167,55	1,676	0	1,676	0,000							0,000
1600	-0,53	14,22	1,941	27,62	13,69	1,896	25,97	14,03	1,8753	26,43	167,55	88,802	80,02	8,782	90,110	1,304	1,346	1,511	7,326	7,220	7,481	14,995
1600	-1,16	10,41	4,177	43,93	10,08	4,036	41,02	10,35	4,045	42,19	167,55	194,360	127,14	67,220	65,415	1,309	1,303	1,376	2,492	2,498	2,559	69,054
1600	-1,53	8,17	5,32	44,2	7,92	5,162	41,5	8,08	5,203	42,7	167,55	256,354	128,4	127,954	50,087	1,338	1,319	1,389	1,536	1,534	1,553	113,048
1600	-1,65	6,63	5,925	40,1	6,42	5,766	37,8	6,54	5,818	38,8	167,55	276,460	116,7	159,760	42,212	1,432	1,409	1,468	1,119	1,113	1,124	140,862
1600	-1,75	5,44	6,175	34,5	5,3	6,009	32,7	5,42	6,068	33,7	167,55	293,215	100,9	192,315	34,412	1,589	1,560	1,606	0,881	0,882	0,893	153,070
1400	0,02	14,77	0,0022	0	14,24	0,0013	0	14,54	0,0014	0	146,61	-2,932	0	-2,932	0,000				6713,636	10953,846	10385,714	0,000
1400	-0,42	12,16	1,6545	20,04	11,7	1,6223	18,9	12	1,6057	19,18	146,61	61,575	58,12	3,455	94,389	1,836	1,808	1,946	7,350	7,212	7,473	10,954
1400	-0,96	9,01	3,607	32,71	8,72	3,476	30,53	8,95	3,483	31,36	146,61	140,743	94,6	46,143	67,215	1,295	1,297	1,380	2,498	2,509	2,570	51,309
1400	-1,27	7,08	4,618	33,09	6,84	4,488	31,06	7,01	4,51	31,97	146,61	186,192	96,12	90,072	51,624	1,305	1,284	1,356	1,533	1,524	1,554	85,191
1400	-1,44	5,79	5,18	30,57	5,59	5,044	28,71	5,72	5,076	29,53	146,61	211,115	88,81	122,305	42,067	1,363	1,339	1,403	1,118	1,108	1,127	107,562
1400	-1,53	4,85	5,52	27,1	4,72	5,368	25,7	4,82	5,407	26,4	146,61	224,310	79,2	145,110	35,308	2,357	1,394	1,454	0,879	0,879	0,891	122,008
1200	0,03	12,62	0,0023	0	12,17	0,0017	0	12,42	0,0019	0	125,66	-3,770	0	-3,770	0,000				5486,957	7158,824	6536,842	0,000
1200	-0,34	10,42	1,4197	14,59	10,04	1,3875	13,83	10,28	1,3804	14,05	125,66	42,726	42,47	0,256	99,402	1,694	1,656	1,790	7,340	7,236	7,447	8,058
1200	-0,82	7,74	3,105	24,1	7,49	2,993	22,48	7,7	2,992	23,07	125,66	103,044	69,65	33,394	67,592	1,212	1,217	1,295	2,493	2,503	2,574	37,976
1200	-1,08	6,14	4,005	24,83	5,94	3,875	23,21	6,07	3,907	23,91	125,66	135,717	71,95	63,767	53,015	1,185	1,181	1,247	1,533	1,533	1,554	63,844
1200	-1,23	5,07	4,529	23,24	4,89	4,402	21,78	4,99	4,442	22,42	125,66	154,566	67,44	87,126	43,632	1,218	1,205	1,264	1,119	1,111	1,123	82,174
1200	-1,33	4,26	4,856	20,95	4,16	4,706	19,75	4,22	4,758	20,23	125,66	167,133	60,93	106,203	36,456	1,276	1,255	1,311	0,877	0,884	0,887	94,228
1000	0,05	10,51	0,0021	0	10,14	0,0017	0	10,35	0,002	0	104,72	-5,236	0	-5,236	0,000				5004,762	5964,706	5175,000	0,000
1000	-0,29	8,66	1,179	10,23	8,34	1,152	9,63	8,54	1,1515	9,84	104,72	30,369	29,7	0,669	97,798	1,794	1,796	1,892	7,345	7,240	7,416	5,573
1000	-0,67	6,47	2,594	16,81	6,28	2,484	15,64	6,42	2,51	19,09	104,72	70,162	51,54	18,622	73,458	1,164	1,188	1,254	2,494	2,528	2,558	26,463
1000	-0,89	5,16	3,37	17,5	4,99	3,261	16,34	5,1	3,286	16,82	104,72	93,201	50,66	42,541	54,356	1,101	1,102	1,175	1,531	1,530	1,552	45,193
1000	-1,03	4,27	3,83	16,53	4,13	3,714	15,48	4,21	3,748	15,88	104,72	107,861	47,89	59,971	44,400	1,128	1,121	1,186	1,115	1,112	1,123	58,592
1000	-1,11	3,61	4,168	14,89	3,52	4,026	14,08	3,6	4,047	14,53	104,72	116,239	43,5	72,739	37,423	1,133	1,128	1,197	0,866	0,874	0,890	68,861

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LABORATORY TEST AND MODELLING OF SMALL PM SYNCHRONOUS MACHINES