Politecnico di Torino

Master's degree in Electrical Engineering

Master Thesis

Frequency Response Analysis of the Tesla Model S Induction Motor

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Abstract

I performed my internship in the laboratory G2Elab, based in Grenoble. It is a research laboratory specialized on electrical engineering and its application. The main goal of this internship was to analyse the Tesla Model S motor, characterize in its frequency response, validate the 2D model created before and finally obtain the parameter of the equivalent electric circuit considering the harmonic impact. Then, all of this information will be useful to create a scientific paper to exhibit in a conference.

Acknowledgments

I wanted to write this chapter because there are people who had a fundamental role in this beautiful experience, and I think they deserve to be thanked.

First of all, I would like to thank Mr. Robin Thomas and Mr. Lauric Garbuio for believing in me since the beginning, knowing that I was with no experience in the work field and with some difficulties with the French language. Without their guidelines and their support would have been more and more difficult to work and understand what to do, always available to help me in any moment. They are for me a point of reference both from a professional and social point of view.

Thanks also to Mr. Herve Chazal, also involved in the project. He was always present to answer my questions, gave me very valuable advice, not only with regard to the project. It is thanks to you if I became able to change my point of view and look into the right direction.

Thanks to Mr. Laurent Gerbaud, professor and researcher in MAGE cluster of the lab, that even if I was not directly linked to him, he helped me to develop the CADES code, in which I got stuck several times, finding no solution.

Thanks to Mr. Sébastien Flury, technique in MDE team, who provided me with all the necessary equipment to carry out the tests and was always there to explain their correct functioning and in cases where I had any doubts or problems.

Thanks to Jean-Luc Schanen, the last but not the least, to which I should apologize for not having made him so involved in the project. It was my fault, not in purpose, but due to some misunderstanding. Anyway, everyday present for my doubt concerning the PFE, I am glad to have you as my referent of the university.

Table of contents

1. Introduction

This thesis is about the PFE (Projet de fin d'études) that I developed during my internship in G2Elab, important laboratory based on Grenoble concerning studies and research in the huge field of the electricity and his applications. I have been there since the 15th of February 2021 until the 23rd of July 2021.

The reasons why I chose this internship are several: since I was searching for an internship, I was looking for something interesting, focusing on electrics motor development and their application in the automotive. Nowadays, the request of electric vehicles is growing day-by-day and, being something relatively new, there are many problems that have not been taken into consideration in previous years which, if solved (or at least optimized), could improve the motor efficiency, help to save design time and even reduce costs.

The project in which I worked is based on the characterization of the Tesla Model S motor, bought by the company to make tests, understand how Tesla engineers designed it and why. Tesla Inc has captured the attention of the whole world in the last couple of years for his effort spent on energy conversion into the renewable one and on the production of high-performance electric vehicles. Several engineers are interested to study and discover the peculiarity of their motors, thanks to their performance and efficiency.

One in particular is the one used in Tesla Model S that is an induction motor. This is a really uncommon choice for a car application due to the fact that, even if they have a lot of advantages compared with the most common motor used in the automotive sector (permanent magnet synchronous machines), they present some flaws like, the most important, they are less efficient, with a lower power-to-weight ratio.

Then the goal is to compare the results with simulations made with Flux and FluxMotor, two software provided by Altair, where is possible to draw the motor, set the parameter and study it in several conditions using FEM (Finite Elements Method) analysis. Specifically, we have been focused into the frequency responses analysis, making the most common test, the SSFR (StandStill Frequency Response) test, and the constant ratio V/f test, an evolution of the previous one.

This report will be divided in 4 parts:

- Presentation of the lab
- Internship objectives
- Explanation of the work
- Related conclusions

2. G2Elab

As I mentioned in the previous chapter, G2Elab is the laboratory where my internship took place. From the beginning I was well received, everything was explained to me, starting from how the bureaucratic offices were organized up to the equipment that I should have used. The people were immediately friendly, always available in case I needed help, and thanks to this I immediately felt at ease. My workplace was in the MADEA + cluster, a team specialized in the study of magnetic materials, their application and the conversion of electrical energy in all its nuances.

A few more details could help to understand the importance of the laboratory, which was one of the reasons that prompted me to undertake this path.

Fig.1 Laboratory logo

In the everyday context, where electrical engineering plays a central and unifying role, in the versatility and performance that electricity provides to all the systems, the Grenoble Electrical Engineering Laboratory (G2Elab) works in several studies, starting from materials and devices to the design and management of electrical energy systems. With around 100 permanent staff, around 100 PhD students and more than 70 master students, post-docs and visiting professors, G2Elab has established itself as a significant national and international actor at the heart of the energy efficiency of electrical energy devices and systems.

2.1 Organization

Fig.2 Laboratory work fields

The laboratory has been divided in 5 research teams and 2 transversal research groups, everyone specialized in a specific field of expertise. The 5 research teams are:

- EP team
- MADEA+ team
- MAGE team
- MDE team
- SYREL team

2.1.1 EP (Power Electronics) team

Keywords: modelling, integrated power electronics, EMC, gate drivers, packing, power converters design and optimization, cooling.

Objective: Design and create increasingly high-performance power converters and supply devices targeting compactness; Performance and compatibility with the environment.

Action involved: new semiconductor devices (GaN, diamond, SiC) characterization, power integration (packing concepts, EMI, cooling...), converter design, innovative design methods and tools.

2.1.2 MADEA+ (Materials and Advanced Electromagnetic Devices) team

Keywords: Magnetic materials, superconductors, innovative converter devices, multiphysics couplings

Objective: Conception and design of innovative electromagnetic devices going beyond the limits of existing systems; Multidisciplinary approach from materials to applications

Action involved: Functional materials for Electrical Engineering, Conversion and processing of energy, Information conversion and processing.

2.1.3 MAGE (Models, methods and methodologies Applied to Electrical Engineering) team

Keywords: knowledge modelling, electromagnetic formulations, numerical methods, meshing techniques, optimisation techniques

Objective: Extending the computing capabilities; Helping the expertise and the design of devices addressing the themes of innovation; Sizing and capitalization and management of knowledge

Action involved: Computational Electromagnetics; System Modelling; Design; Optimisation and inverse problems; Engineering of knowledge and capitalisation of know-how.

2.1.4 MDE (Electrostatic and Dielectric Materials) team

Keywords: dielectrics, layers, electrostatics, microgaps, insulation

Objective: Studying physical mechanisms resulting from the application of electrical field to dielectrics; Studying the materials used for electrical insulation of electric/electronic devices; Developing processes using electrostatic forces

Action involved: Characterization of dielectrics; pre-disruptive phenomena studies; Development of electrostatic processes and of specific techniques.

2.1.5 SYREL (System and Electrical Networks) team

Keywords: production, transmission, distribution, non-conventional load, electric plant, private and embedded networks

Objective: Optimisation of Electricity chain; Network architectures and integration of producer, storage and costumers; Control of energy flows; Economic

Action involved: Unconventional connected systems; Analysis and optimization of advanced power systems; Advanced methods in understanding and securing complex infrastructures.

All of those teams are well combined, they work together, and this is a strong point of the laboratory.

3. Internship objectives

At the beginning, the purpose of this internship was to create a scientific paper to present at the ELMA conference in July. In one of the first meeting with my supervisors we defined all the steps that I should follow, and they gave me different papers to have a general idea about the work we were developing, what it was concerning about and some tutorial to understand the software I was going to use.

In the paper the goal was to characterize the motor in his frequency response, then simulate the 2D Model and check if it has been created accurately or if there are some leaks in the software that in our specific application has an important weight. Moreover, this model needs to be precise enough in a large frequency range to represent the machine behaviour at the operating frequency but also at the PWM frequency. Once reached this point, the idea was to develop an equivalent electric circuit that takes in account also the harmonic component of the motor. So different kind of harmonic equivalent circuits were analysed, and their analytic impedance module and phase computed. At the end, these parameters should have been implemented in an optimization software in order to decide which one of the circuits presented fit better with the test and simulation results, and from that, extrapolate the values of its parameters.

Summarizing what we will speak about, this chapter starts with an explanation of the kind of tests chosen to identify the motor. Then, a short presentation of the software used for the simulation has been made with the model of the motor and the results of the simulation. After that, we will pass to the physical test sub-chapter, and so: explication of the test bench, description of how the tests are made and finally the results obtained. Afterwards, the experimental results are compared to the simulation ones in order to validate this FE model. Finally, these results should have been used to identify the parameters of the equivalent frequency electrical model of the machine, so the last sub-chapter focuses on the different kind of circuits and the flowchart of the code implemented to obtain the parameter of the circuits.

3.1 Tests Methodology

First of all, it was necessary to understand which kind of test we were looking for, and why. So, the first move was to search as much information as possible about the different kind of tests that could have been done to characterize the machine in his frequency response. Those tests are important because with the introduction and the development of power converters, which, however, have significantly improved the efficiency of power systems, the quality of the signals gets worse, with a greater percentage of harmonics present on it. In fact, this problem calls the necessity to study the behaviour of the components of those systems, in order to see if some of those harmonics could be dangerous for the machine and his supplementary elements. Anyhow, this study has been focused just on the motors.

Different testing procedures exist for the frequency response analysis of electrical machines. Among these tests, two different are selected. The first test consists of supply two phases of the motor with a defined sinusoidal voltage, measuring the resulting current and compute the equivalent impedance at different frequencies. This test is described in the IEEE standard procedure as StandStill Frequency Response (SSFR) test and is usually easier to implement. The second test is similar to the first one with the only difference that is imposed the voltage over frequency ratio, i.e. V/f ratio, so the rms value of the supplied voltage is no longer imposed but it depends on the frequency. For simplicity, in this report, this test will be called V/f test.

The downside of the first test is that, imposing just the voltage and changing the frequency, the flux flowing through the machine will change and, hence, the general environment in which the motor is working. On the other hand, in the second test, the same magnetic state is imposed through the machine for all the tested frequencies. Therefore, the problem of the permeability variability is overcome.

Originally written for industrial synchronous motors, these procedures were afterwards adapted for the induction machine, with the following assumptions:

- Thanks to its symmetrical rotor, from the electric characteristics point of view, no particular rotor position is required. Moreover, no separate measurement of the direct and quadrature axis operational impedance is required.
- The rotor has no field winding or rotor terminals; thus, the direct measurement of field quantities is not possible and not required.

The simulations (and experimental tests) are always done with locked rotor. The frequency is varied from a few hundreds of mHz to a few tens of kHz for the simulation, and from dozens of Hz to some kHz for the real tests, due to limitation on the experimental setup. It enables to study the machine behaviour at the operating frequency but also at the PWM frequency. According to the procedure recommendations, the stator voltage and, therefore, the V/f ratio have to remain very low, in order to remain in a very weak magnetic state, far from saturation levels.

3.2 Simulation Test

After having some knowledge about what I was searching, I decide to move on the simulation test using the two-software provided by the same company, Altair, to the laboratory. Before going deeply to the implementation of the test I spent a few days getting familiar with the software, new to me, in order to be ready to face any hypothetic problem during the implementation and manipulation of the data.

3.2.1 Altair Flux™ & Altair FluxMotor™

Altair Engineering Inc. is an American multinational information technology company headquartered in Troy, Michigan. It provides software and cloud solutions for simulation, IoT, high performance computing (HPC), data analytics, and artificial intelligence (AI). Altair Engineering is the creator of the HyperWorks CAE software product, among numerous other software packages and suites. The company was founded in 1985 and went public in 2017.

Flux and FluxMotor are the two-software used in this experience. Flux application is extended in multiple industries such as transportation, electrical equipment, and consumer goods to develop more efficient electrical systems with higher levels of connectivity. FluxMotor is more specific for motor simulations, for their prestation and equivalent circuit parameters, always using FE method to solve them.

3.2.2 Flux™ 2D FE Model of the Tesla Model S Induction Motor

A 2D FE model of the induction motor of the Tesla Model S60 is presented in [1]. This model has been created from a synthesis of the main information available in literature about this machine and validated by comparing simulation results with expected performances. This model is made with Altair Flux2D™ software and it is shown in Fig. 4.

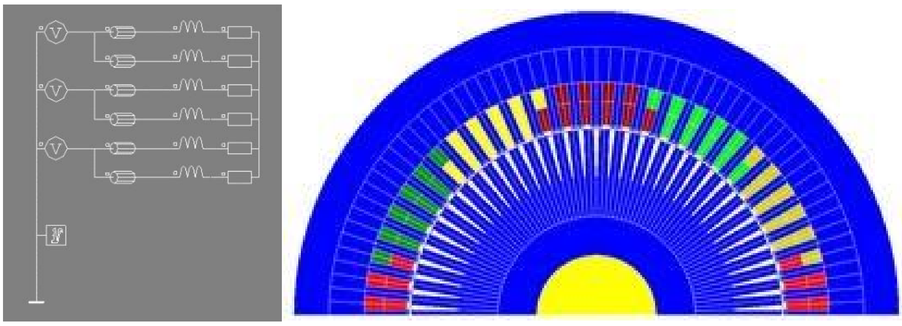


Fig.4 Equivalent circuit (on the left) and 2D model (on the right) implemented on the software

3.2.3 Simulation Results

3.2.3.1 V/f simulation

The presented 2D FE model is simulated using the described methodology for the two different frequency response tests. For each simulated point, the module and the phase of the equivalent impedance are computed and then plotted according to frequency. These tests are also carried out for different values of voltage of V/f ratios, to see how the motor act at different magnetic levels considering 10 points per decade of frequency.

As it is clear, seeing the two graphs below, there is a small pit between 0.1 Hz and 10 Hz that gets less deep with the decreasing of the V/f ratio. The module, in the same interval, has a lower growth rate until it starts to increase almost linearly. What it has been supposed is that probably this is due to the saturation of the teeth, because there the flux density is the highest and that range could represent the interval in which the permeability is not linear. Indeed, at the lowest value there is no more this particular shape. By the way, this phenomenon was not taken in consideration because all the studies have been done at the lowest V/f value for technical limits during the test.

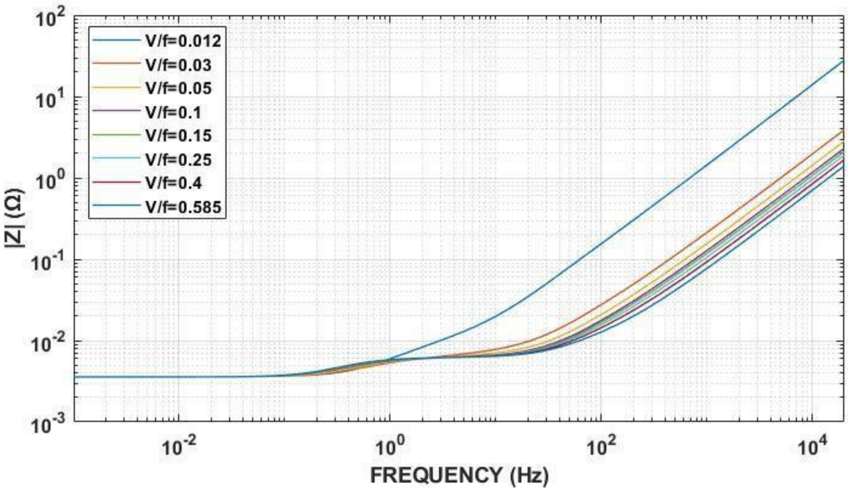


Fig.5 Impedance module obtained with Flux2D at different V/f values

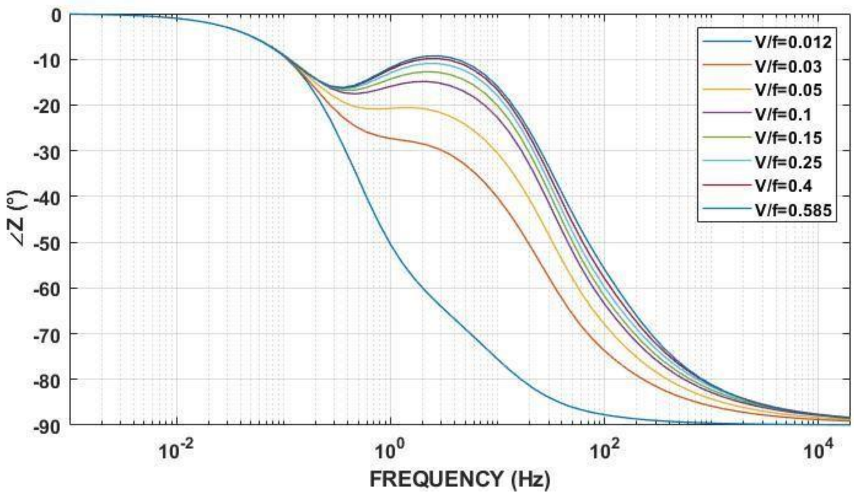


Fig.6 Impedance phase obtained with Flux2D at different V/f values

Then the graphs below (Fig.7) show the behaviour at the V/f ratio used for the test (V/f=0.012) to focus on it.

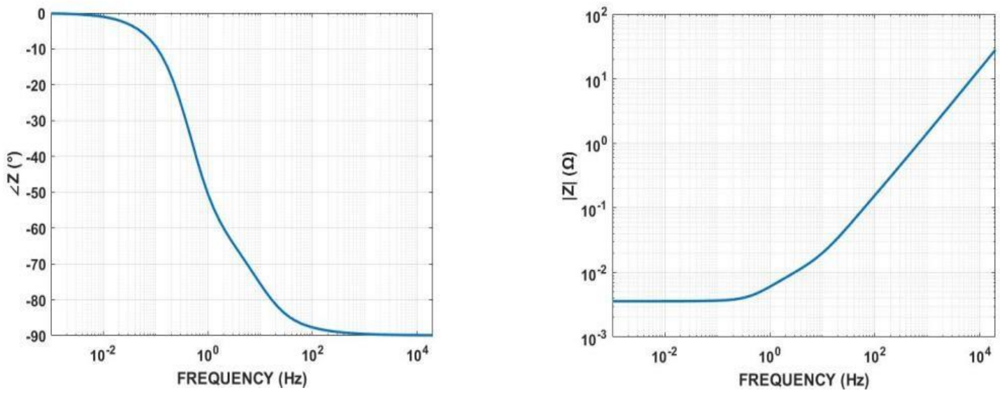


Fig.7 Impedance module (left) and phase (right) obtained with Flux2D with V/f ratio=0.012

3.2.3.2 SSFR simulation

The SSFR simulation is made drawing the motor in the software FluxMotor, in which we could directly have the simulations of the main tests, used to be done in the reality to identify all the parameter of the equivalent circuit. The SSFR is one of them, that has been carried out since a lot of time before the proposition of other tests.

The simulation has been done with a supply voltage of 0.4 V, the one that was used on the test too, chosen thinking about BOP limits and noise that could impact on the measurement.

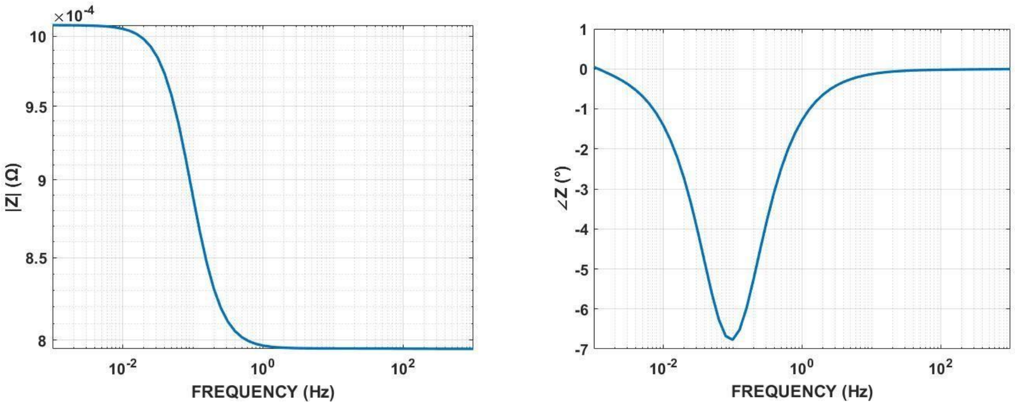


Fig.8 Impedance module (left) and phase (right) obtained with FluxMotor with V=0.4 V

3.3 Experimental Tests

This part of the work was the hardest so, in general, was the one which took me more time.
Started reading the DSpace manuals, afterwards I implemented the Simulink block diagram (Fig.9), in order to send correctly the three signals and to supply the relatives three phases of the machine, and to read the 6 signals, 3 voltage and 3 current signals,

to correctly compute module of the impedance with their ratio, and its phase with the phase shift. Specially at low frequencies, was harder to set up the DSpace values because there were phase shift problems between the voltages, that was supposed to be 120°, and between the voltage values in itself, that was different from the value set in the diagram. This needs a double check of the phase with the oscilloscope for the phase shift and with a precise multimeter for the voltages.

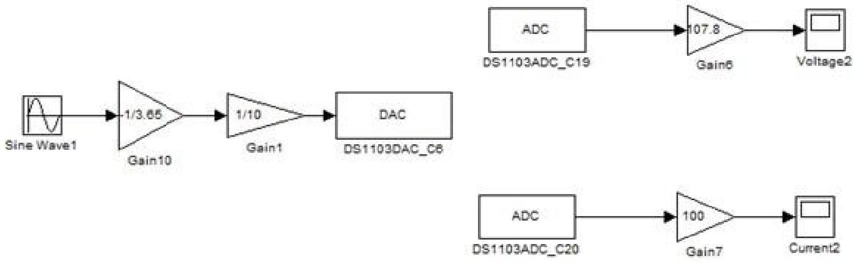


Fig.9 DSpace diagram block for just 1 phase

3.3.1 Experimental Setup

The experimental tests are carried out on the rear induction motor of one of the 2012-2015 period Tesla Model S, which corresponds to the modelled machine.

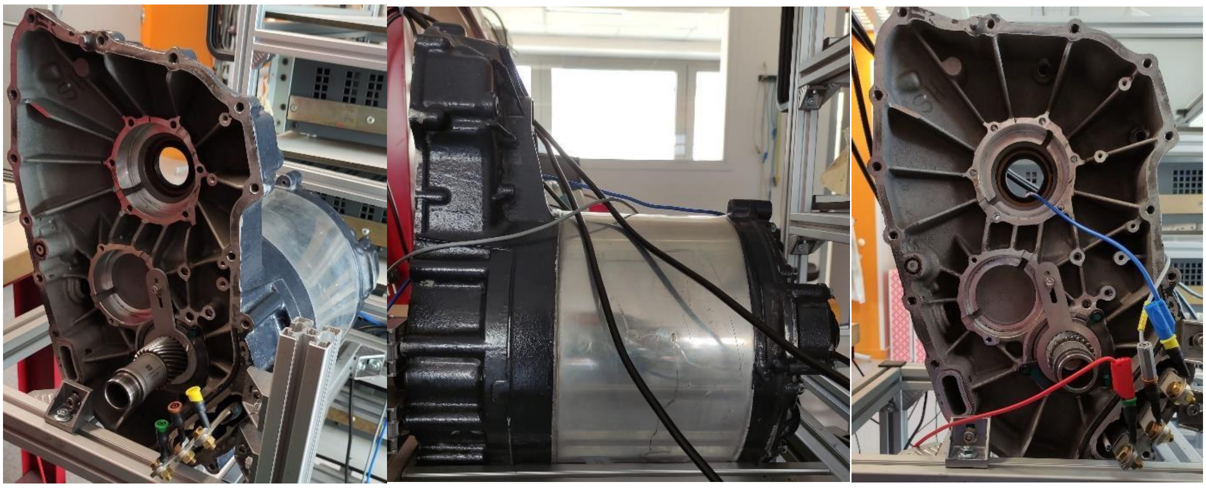


Fig.10 Tesla Model S motor in different perspectives

For the <u>*V/f test*</u>, the motor is fed by three Bipolar Operational Power supply (BOP) that are linear voltage amplifiers controlled with a desired input signal that has to be reproduced. This control signal is generated thanks to a DSpace Controller Board that is processing a Matlab/Simulink block diagram through which the frequency and amplitude are tuned to the desired values. However, since the three-power supply have low voltage and, above all, low current physical limits (±36.5 V and ±12 A) compared to the machine limitations, the desired applied voltage has to be limited to very low values due to the low impedance of the motor.

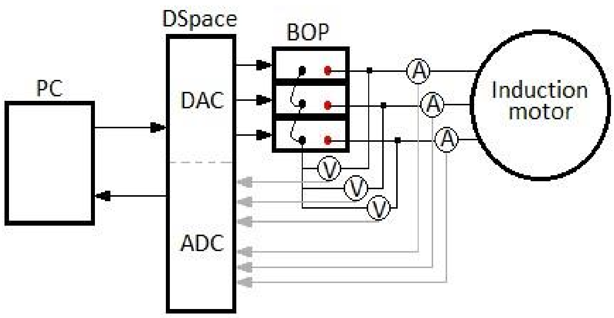


Fig.11 Experimental setup

The second main task of the DSpace is to receive the output current and voltage signals from the three phases. They are processed with Matlab to compute the equivalent impedance of the motor. The experimental setup is summarized in Fig. 11.

For the *SSFR test*, the configuration is basically the same, but the motor is powered just between two phases, so only one BOP is needed.

3.3.2 Experimental Results

For each tested operating point, i.e., for each frequency value, the voltage and the current are measured in order to compute the module and phase of the equivalent impedance of the machine, as it is done in simulation.

3.3.2.1 V/f test

V/f tests are done implementing a value of V/f=0,012. For each operative point, the DC component was checked both with a precise multimeter and in the value obtained with the DSpace. This double check was done also with the voltage value because there were some troubles with the Op-amp (operational amplifiers) inside the BOP, which their gain is a function of the frequency. This just to be sure about the validity of the test that has to be done with a specific maximum value of uncertain.

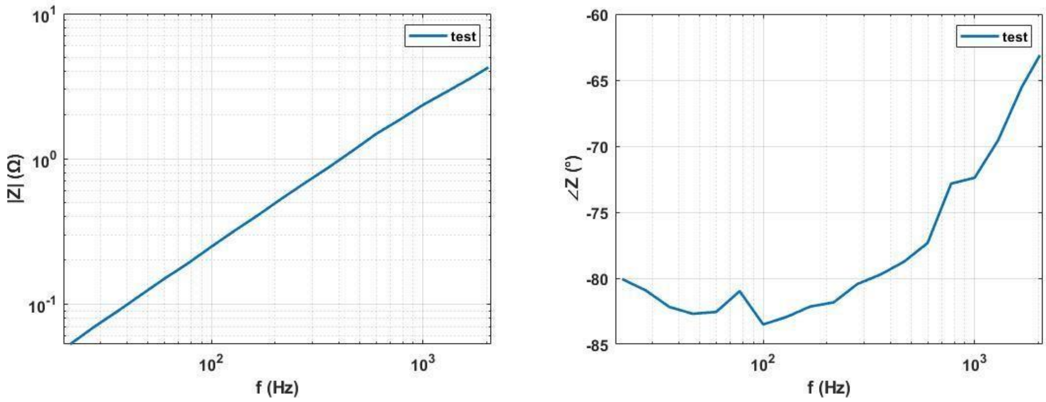


Fig.12 Impedance module (left) and phase (right) of the tested motor

Since the sample frequency cannot be bigger than 100kHz, for DSpace limitation, and since at least 40 sample per period are needed, the high limit of the test is 2.5 kHz. On the other hand, the last point analysed is at 2.035 kHz due to BOP's limitations (peak voltage lower than 36.5V means rms voltage lower than 25.8V, so f < 2.1 kHz). Unfortunately, was not possible to investigate point at frequency lower than 21.54 Hz because of signal noises that make impracticable to handle the data.

Impedance module and phase are shown in the figure above (Fig.12). Instead, below (Fig.13), it is possible to see the respective weight of resistance and reactance in the impedance, and the relative inductance, necessary to analyse and compare the results between test and simulation.

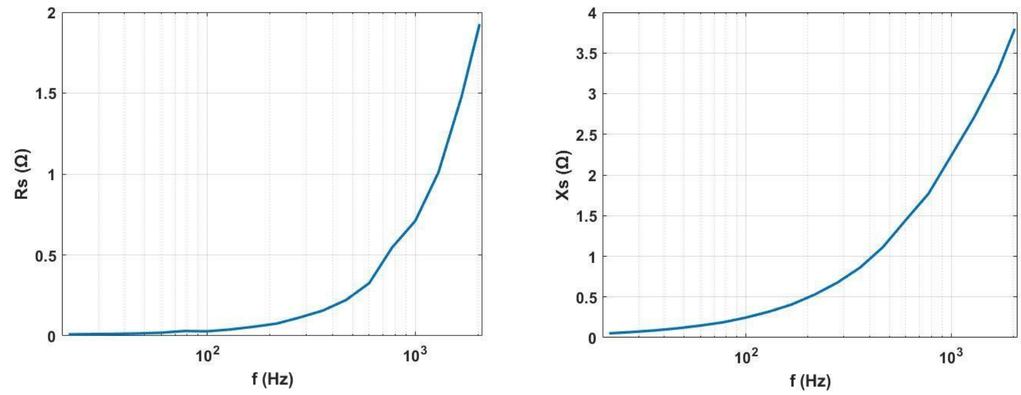


Fig.13 Real (left) and imaginary (right) part of the impedance

3.3.2.2 SSFR test

SSFR are carried with V=0.4 V. This value has been chosen because of the necessity to have low voltages. At the same time it has to be not that small because with the increase of the frequency, the magnetic flux, and so also the current, become lower and lower.

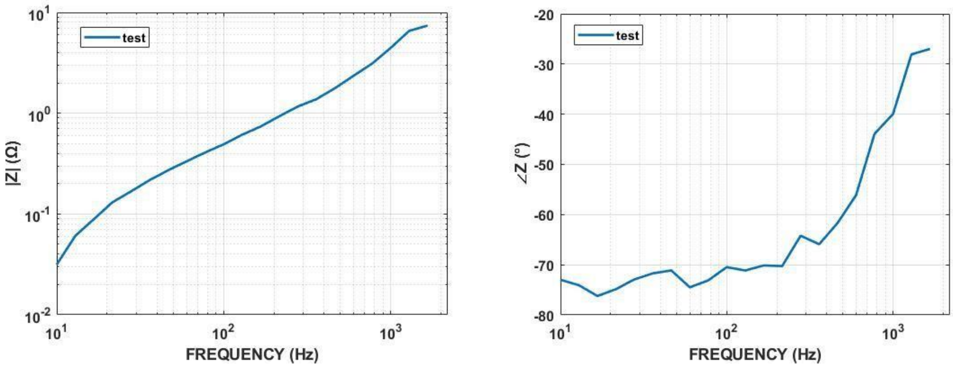


Fig.14 Impedance module (left) and phase (right) with SSFR test

3.4 Results Analysis

The experimental results are then used in order, firstly, to validate the FE model of the machine. Indeed, this model has been created from all the available information on this motor. However, several information are still uncertain and the comparison between experimental and simulation results can help to validate the model and remove these uncertainties.

On the other hand, these results enable to analyse the potential characteristic of the machine design. Indeed, the evolution of the equivalent impedance according to frequency can highlight the impact of some design choices, e.g., the rotor bridges saturation. Unluckily, like the graphs will show, the simulation results are far from the test ones so different changes had to be applied in the simulation parameters.

3.4.1 V/f test and simulation results comparation

As said, the test and the simulation are quite different. Even if the shape of the module is the same, the test values are almost 1.5 times the simulation ones.

The greatest difference is on the phase where, after 100 Hz it starts to grow, instead of continuing decreasing, until the value of -63°. As expected from the phase, plotting both the resistance and the reactance, it is easily understandable that there is a huge and unexpectable increase of the resistance with the frequency. Indeed, with increasing frequency should be the reactance to prevail over the resistance, due to its direct proportionality with frequency. So more precise and deep studies have been done.

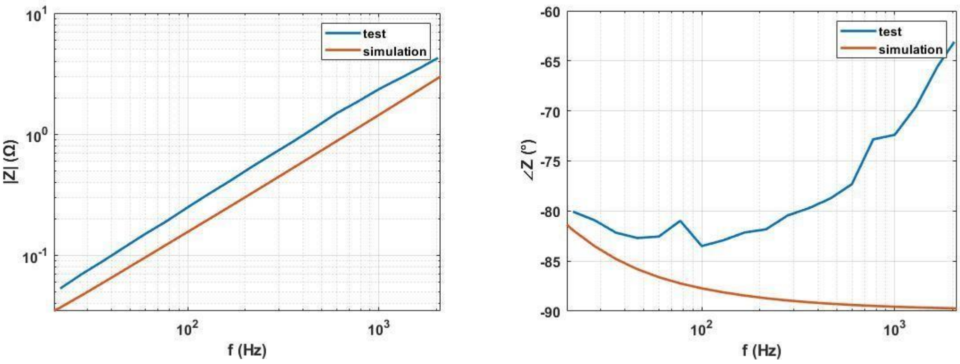


Fig.13 Comparation of module (left) and phase (right) between simulation and test results

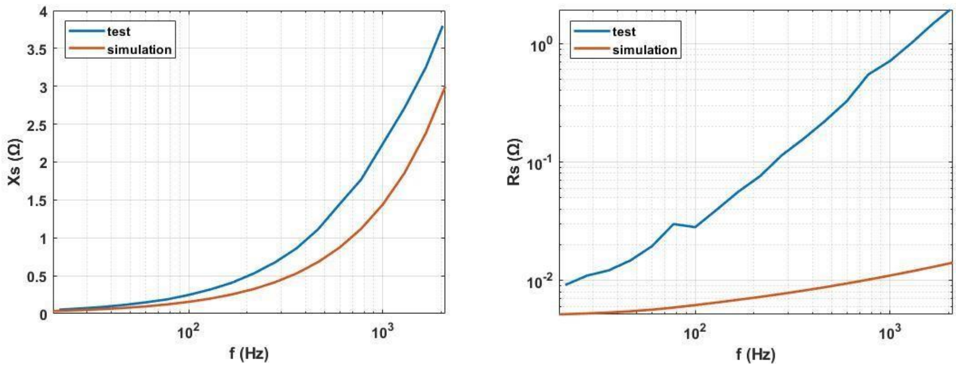


Fig.14 Comparation of resistance (left) and reactance (right) between simulation and test results

3.4.1.1 Adjustment Flux 2D parameters

Usually, the software takes in consideration also all the phenomena that impact on the resistance changing the frequency, but since the motor model is not validated yet, so it is not sure that all the parameters, even the one used to define the equivalent circuit, are the ones hypothesized. The simulation model has been analysed more deeply to see if there are some simplifications that could influence the parameters analysed. The effects that have been taken in consideration are:

- Different value of the DC stator resistance, skin effect and proximity effect that could impact his behaviour with the frequency.
- Cage inductance and resistance behaviour with the frequency.

3.4.1.1.1 DC test

First of all, the DC test was conducted to check if the theoretical stator resistance is the same as the test ones. It is done supplying the motor with different voltages, and, paying attention to be quick recording the data and turning off the BOP, in order to not warm up the resistance and have wrong values. Then, the linear interpolation of V(I) is useful to find out the coefficient of that is 2 times the stator resistance value.

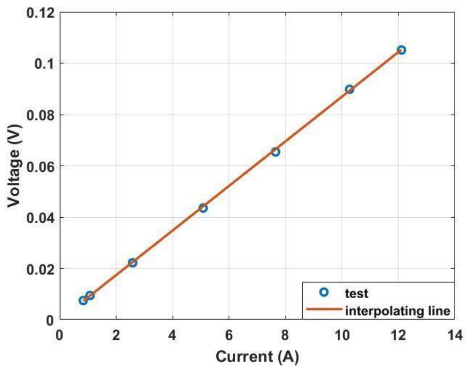


Fig.14 DC test results and their interpolating function

The value obtained is 4.35 mOhm, a bit bigger than the one computed (3.32 mOhm) so this should not change drastically the simulation's values.

3.4.1.1.2 Slot Analysis

The model of the motor has been created with the slot made by two coil conductors with each 26 wires inside, as the literature says. The problem is that Flux does not compute the resistance with FE method in the case of coil conductor because it depends on different parameters such as: distance of the cable, if they are twisted or not, etc. This means that both proximity and skin effects are not taken in consideration as we can see in the current density shape on the slot (Fig.15)

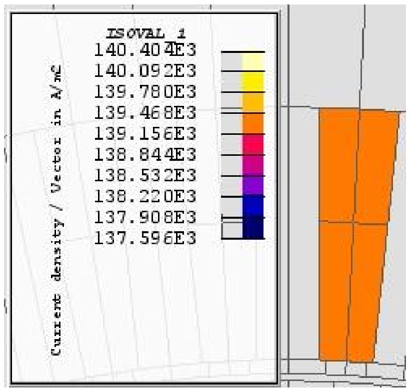


Fig.15 Slot current density

Creating a new Flux2D model with just one slot, with 52 wires (2x26 of each cable), with the precise parameters of the motor and his symmetric to have the return of the cables, it is possible to simulate and obtain the resistance behaviour, supplying the motor with a current generator.

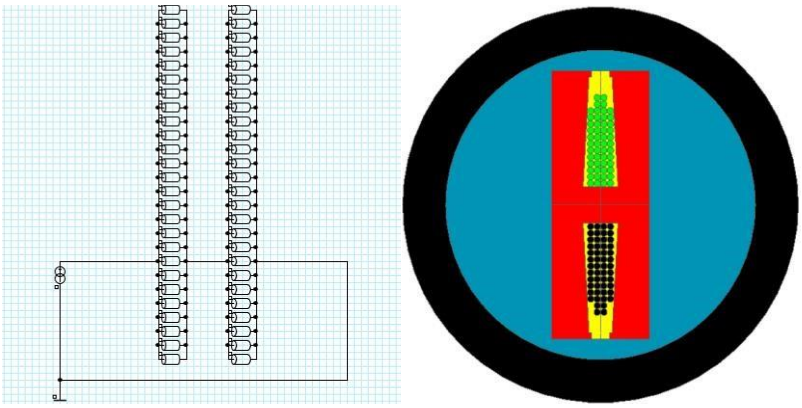


Fig.16 Equivalent circuit (on the left) and 2D model (on the right) implemented on the software

The results obtained are shown below, focusing not only on the value of the resistance but also in his K, ratio between the value and the DC value, that is the one used in the simulation of the motor. Indeed, the approximate function of K has been extrapolated interpolating the points, and this will be multiplied for the equivalent DC resistance of the motor. It is interesting to see that at maximum frequency studied the resistance of one slot will be almost 100 times the DC one.

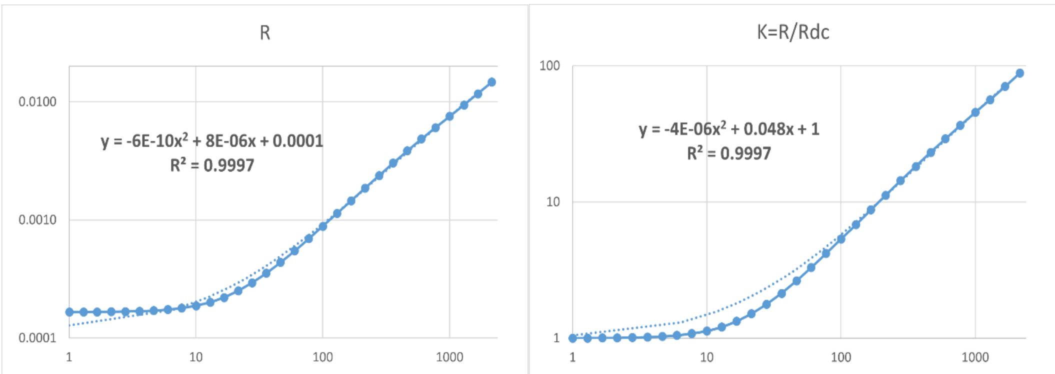


Fig.17 Resistance (left) and K (right) values of a single slot

3.4.1.1.3 Squirrel cage end ring impedance

As is well explained in [12], different parameters influence the squirrel cage end ring impedance, included the frequency. So, inserting the specifics of the motor, and thanks to a Matlab code (Annex 1) it is possible to reach the shape of both the resistance and reactance of the squirrel cage end ring (Fig.18). Focusing on the graphs, is evident that, the inductance is lower than the theoretic one (5nH), even at high frequencies. Instead, the resistance is bigger (1.31 μΩ at 1 Hz instead of 0.27 μΩ). Like for the slot analysis the interpolating functions have been taken and replaced with the old values.

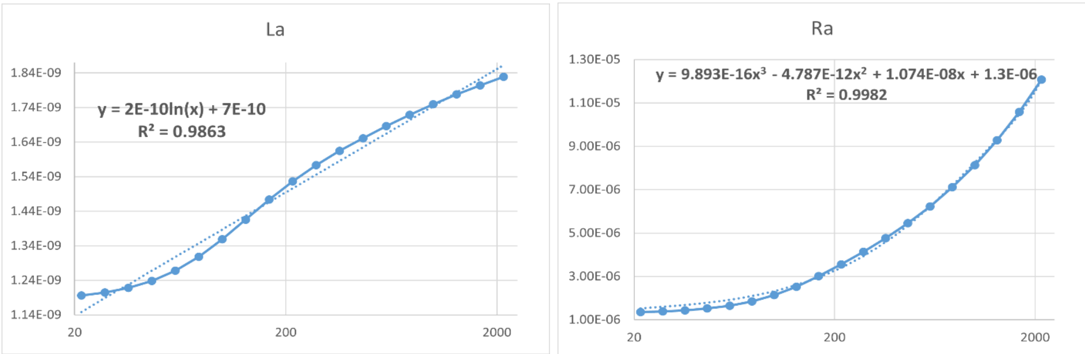


Fig.18 Squirrel cage end rings inductance (left) and resistance (right)

3.4.1.1.4 New results comparison

Implementing the new parameters on the simulation motor model and running it, the following results are obtained. The values of module did not change that much in fact the test values are still 1.5 times the simulation ones. On the contrary, the first values of the phase are bigger, because the variation of the resistance is more important than the inductance, but the shape remain the same, it goes down to -90° with the growth of the frequency.

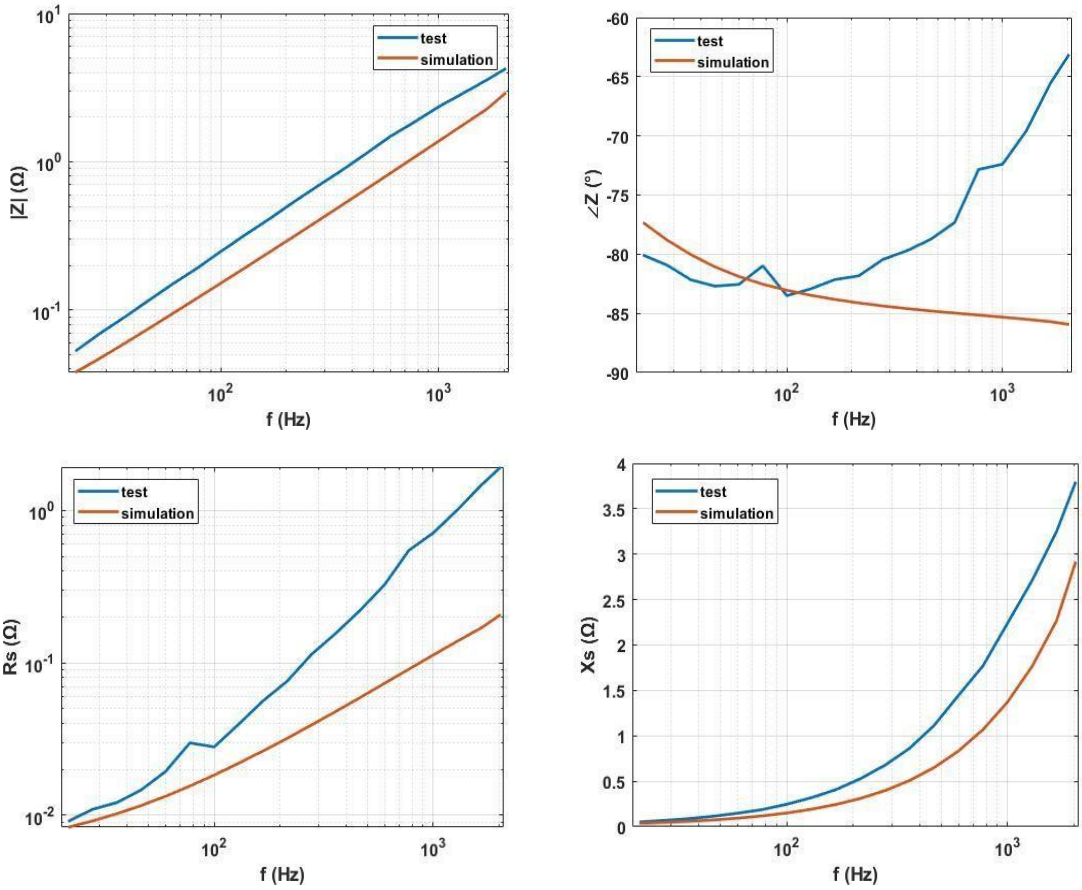


Fig.19 Comparation between the new simulation results and the test results

3.4.2 SSFR test and simulation results comparation

Unfortunately, we did not have time to analyse those data and deepen on them but is quite clear that also in this case there are parameters that need to be fixed in the motor because we are definitely far from the test results.

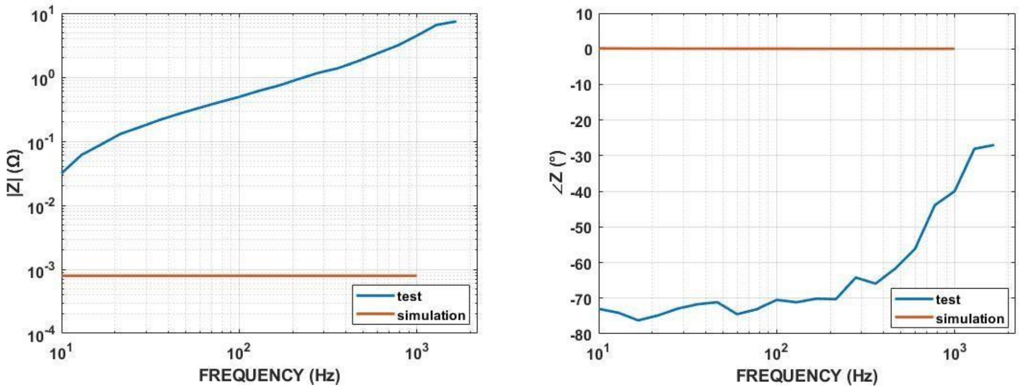


Fig.20 SSFR test results

3.5 Equivalent circuit

The last step would have been to identify the parameters of the equivalent electrical diagram of the machine by using an optimization algorithm in order to make the experimental and computed curves of the equivalent impedance of the machine match [5]. Different types of equivalent models can be identified with this method, from the classical equivalent electrical diagram of the machine to more complex harmonic models.

In fact, following [7], 4 different equivalent circuits have been detected and showed in the Fig.21:

- Classical equivalent electrical diagram (on the top right)
- Square root model (on the top left)
- Ladder model (at the bottom right)
- Harmonic model (at the bottom left)

Using an optimization software, developed by G2Elab, called CADES, would have been possible to compute the parameters of each equivalent circuit in order to reach the same behaviour as the machine, see which one of them fits better and has the closer values to the real ones, and at the end validate both the 2D model and the equivalent electrical diagram. As we did not reach yet the final results of the motor parameters, was impossible for us start with this step. However, the code has been implemented but since we did not try it, maybe it needs some changes before launch it.

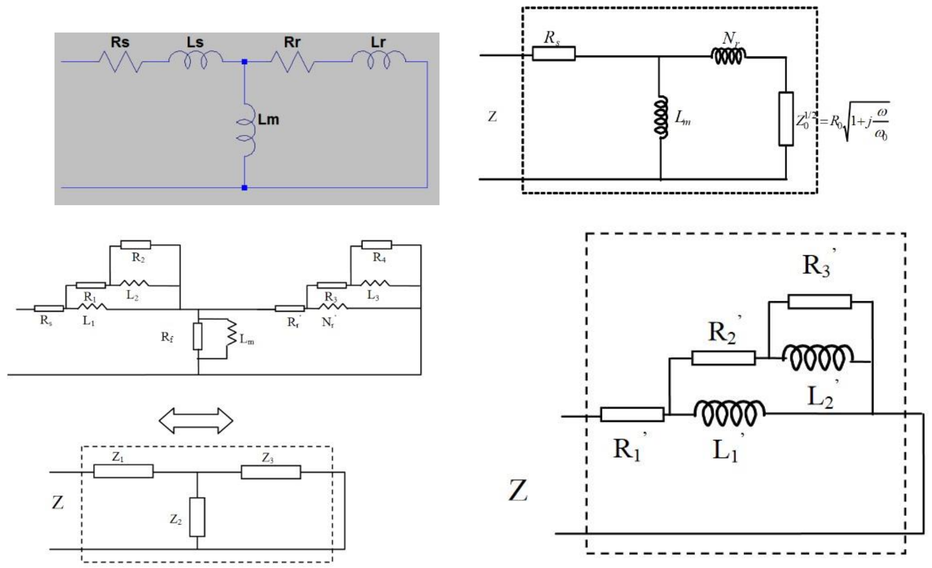
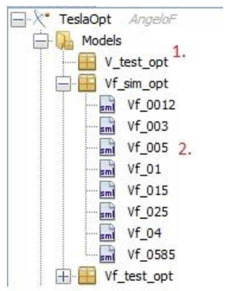


Fig.21 Harmonics models of the equivalent circuit

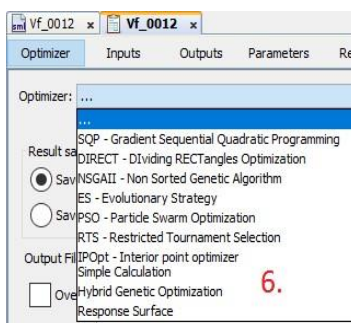
3.5.1.1 Cades' code implementation

The code is divided basically in 6 main parts:



1. Different folder for different kind of test/simulation (V constant, V/f constant).
2. Inside the folder, different .sml file for different test/simulation values.
3. With an « if cycle » define which equivalent circuit parameters we want to find out.
4. Compute the equivalent module and phase of the impedance.
5. Compute the error.
6. Optimize.

```
for i in 0:65

    w[i]=2.0*PI*f[i];
3.
if k==1 //simple model like Flux motor

        Real[i]= ;              4.
        Imm[i]= ;

    else if k==2 //Ladder model (en échelle)

    else if k==3 // 1/2 order model

    else if k==4 // Harmonic model


end;

    Eq_M[i]= sqrt(pow(Real[i],2)+pow(Imm[i],2));
    Eq_P[i]= atan(Imm[i]/Real[i])*180/PI;
                                                5.
    M_err[i]= abs(Eq_M[i]-M[i])/M[i] ;
    P_err[i]= abs(Eq_P[i]-P[i])/abs(P[i]) ;

end;
```



Anyway, the full code could be found in the Annex 2.

4.Conclusion

Overall, my experience at G2Elab has been very positive. Immediately, I was able to show a lot of initiative and autonomy, thanks to the trust placed by my staff. After the first months, I was fully autonomous in my work, I was offered the opportunity to make my own decisions, but obviously still being accountable to my superiors.

It introduced me to the world of research, in which I was fascinated, and at the end I can say that I have just positive feedback about that. Studying and analyse current engineering problems, find a way to figure out and discover, day by day, something new. Every day I did not just face with the main goal of the project, but also with all the troubles that appeared day-by-day during the tests or the simulations that were not taken in account at the beginning, for example the electromagnetic influence of the 50 Hz electric network of the grid that did not let me go under a certain frequency. I learnt a pragmatic and scientific way to write, drawing up, for the first time, an abstract, directed and helped by who was following me in this project.

Speaking about the project, it was a really hard challenge, and honestly, I did not expect like that. The two different frequency response tests have been applied on a Tesla Model S induction motor, and in simulation as well, using the 2D FE model of the motor, everything done with precision and attention, trying to avoid any kind of error which could change the values measured.

Unfortunately, we did not reach the goal planned, but it is part of this work, sometimes you get stuck and need more time to find the solution. I hope the best to my colleagues and to my work team and that they finish this project in the best way.

5.References

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6. Annex 1

```
p=4;
rho=
2.6e-
8;
Nr=
74;
H=1
9.6e-
3;
s=1;
Dext=153.56e-3;
Di=50e-
3;
Dr=132.
86e-3;
e=13.42
e-3;
mu0=4e
-7*pi;
h=H;
f=logspace(0,4,37);

Daext=Di+h;
csi=e*sqrt((pi*mu0*f*s)/rho);
eps=csi.*((sinh(2*csi)+sin(2*csi))./(cosh(2*csi)-
cos(2*csi))); h_p=H./eps; Dreq=Dext-h_p;
hb=h_p-(Dext-Daext)/2;
Ra=((rho*pi*p)/(e*h))*(Dr-Di)*((Dr^(2*p)+Di^(2*p))/(Dr^(2*p)-Di^(2*p)));
heq=(rho*pi*Daext)/(Ra*e+rho*pi);
X=heq./hb;

if X<2.36
   K=0.01*X.^2-0.08*X+1.07;
else
   K=-
0.017*X+0.977
; end

e_eq=e*(K./eps);
lambda=0.365*log10((3*(Daext-heq)*pi)./(4*(heq+e_eq))); ra=(((rho*pi*p)./(Nr*e_eq*h)).*(Dreq-
Di)).*((Dreq.^(2*p)+Di^(2*p))./(Dreq.^(2*p)-Di^(2*p))); La=(pi*mu0/Nr)*(Daext-heq)*lambda;
```

7.Annex 2

Vf=
0.01
2; PI
=
3.14
159
26;
unit PI ="-";

array f[66]; f=[*the values depend on the type of
test chosen*]; // Y values unit f="Hz"; label
f="frequency";

array M[66];
M=[*the values depend on the type of test chosen*];

array P[66];
P=[*the values depend on the type of test chosen*];

array
w[66];
array
Real[6
6];
array
Imm[6
6];
array
Eq_M
[66];
array
Eq_P[
66];
array
M_err
[66];
array
P_err[
66];
array sum_err[66];

array
ReZ_A[
66];
intern
ReZ_A;
array
ImZ_A[

66];
intern
ImZ_A;
array
MoZ_A
[66];
intern
MoZ_A
; array
PhZ_A[
66];
intern
PhZ_A;
array
ReZ_B[
66];
intern
ReZ_B;
array
ImZ_B[
66];
intern
ImZ_B;
array
MoZ_B
[66];
intern
MoZ_B;
array
PhZ_B[
66];
intern
PhZ_B;
array
ReZ_C[
66];
intern
ReZ_C;
array
ImZ_C[
66];
intern
ImZ_C;
array
MoZ_C
[66];
intern
MoZ_C;
array
PhZ_C[
66];
intern
PhZ_C;
array

ReZ_D[
66];
intern
ReZ_D;
array
ImZ_D[
66];
intern
ImZ_D;
array
MoZ_D
[66];
intern
MoZ_D
; array
PhZ_D[
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PhZ_D;
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ReZ_E[
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ReZ_E;
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ImZ_E[
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ImZ_E;
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MoZ_E[
66];
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MoZ_E;
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PhZ_E[
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intern
PhZ_E;
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ReZ_F[
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ReZ_F;
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ImZ_F[
66];
intern
ImZ_F;
array
MoZ_F[
66];
intern
MoZ_F;

array
PhZ_F[
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PhZ_F;
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ReZ_G[
66];
intern
ReZ_G;
array
ImZ_G[
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intern
ImZ_G;
array
MoZ_G
[66];
intern
MoZ_G
; array
PhZ_G[
66];
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PhZ_G;
array
ReZ_H[
66];
intern
ReZ_H;
array
ImZ_H[
66];
intern
ImZ_H;
array
MoZ_H
[66];
intern
MoZ_H
; array
PhZ_H[
66];
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PhZ_H;
array
ReZ_I[6
6];
intern
ReZ_I;
array
ImZ_I[6
6];
intern

ImZ_I;
array
MoZ_I[
66];
intern
MoZ_I;
array
PhZ_I[6
6];
intern
PhZ_I;
array
ReZ_J[6
6];
intern
ReZ_J;
array
ImZ_J[6
6];
intern
ImZ_J;
array
MoZ_J[
66];
intern
MoZ_J;
array
PhZ_J[6
6];
intern
PhZ_J;
array
ReZ_K[
66];
intern
ReZ_K;
array
ImZ_K[
66];
intern
ImZ_K;
array
MoZ_K
[66];
intern
MoZ_K
; array
PhZ_K[
66];
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PhZ_K;
array
ReZ_1[
66];

intern
ReZ_1;
array
ImZ_1[
66];
intern
ImZ_1;
array
MoZ_1[
66];
intern
MoZ_1;
array
PhZ_1[
66];
intern
PhZ_1;
array
ReZ_2[
66];
intern
ReZ_2;
array
ImZ_2[
66];
intern
ImZ_2;
array
MoZ_2[
66];
intern
MoZ_2;
array
PhZ_2[
66];
intern
PhZ_2;
array
ReZ_3[
66];
intern
ReZ_3;
array
ImZ_3[
66];
intern
ImZ_3;
array
MoZ_3[
66];
intern
MoZ_3;
array
PhZ_3[

```
66];
intern
PhZ_3;
array
MoZeq[
66];
intern
MoZeq;
array
PhZeq[6
6];
intern
PhZeq;

array Obj[66];

array
Lm[66
]; array
Rr[66];
array
Rs[66]
; array
Lr[66];
array
Ls[66];
avg_M
_err=0;
avg_P_err=0;

k=; // It depends on which kind of equivalent circuit we want to analyse

for i in 0:65

   w[i]=2.0*PI*f[i];

 if k==1 //simple model like Flux motor

       ReZ_A[i]=-(pow(w[i],2)*Lm*Lr+pow(w[i],2)*Lm*Ls+pow(w[i],2)*Lr*Ls-Rr*Rs);
       ImZ_A[i]=w[i]*(Lm*Rr+Lm*Rs+Lr*Rs+Ls*Rr);
       MoZ_A[i]=sqrt(pow(ReZ_A[i],2)+pow(ImZ_A[i],2));
       PhZ_A[i]=atan(ImZ_A[i]/ReZ_A[i]);
       ReZ_B[i]=Rr;
       ImZ_B[i]=w[i]*(Lm+Lr);
       MoZ_B[i]=sqrt(pow(ReZ_B[i],2)+pow(ImZ_B[i],2));
       PhZ_B[i]=atan(ImZ_B[i]/ReZ_B[i]);

       MoZeq[i]=MoZ_A[i]/MoZ_B[i];
       PhZeq[i]=PhZ_A[i]-PhZ_B[i];
```

```
        Real[i]=MoZeq[i]*cos(PhZeq[i]);
        Imm[i]=MoZeq[i]*sin(PhZeq[i]);

    else if k==2 //Ladder model (en échelle)

        Rs=;
        Lm=2.892*pow(10,-4);
        Rf=70.033;
        Rr=2.081*pow(10,-3);
        Nr=3.038*pow(10,-5);

        ReZ_A[i]=pow(w[i],2)*L1*L2*R1+pow(w[i],2)*L1*L2*R2+pow(w[i],2)*L1*L2*Rs-
R1*R2*Rs;
        ImZ_A[i]=-w[i]*(L1*R1*R2+L1*R1*Rs+L2*R1*Rs+L2*R2*Rs);
        MoZ_A[i]=sqrt(pow(ReZ_A[i],2)+pow(ImZ_A[i],2));
        PhZ_A[i]=atan(ReZ_A[i]/ImZ_A[i]);
        ReZ_B[i]=pow(w[i],2)*L1*L2-R1*R2;
        ImZ_B[i]=w[i]*(L1*R2+L2*R1+L2*R2);
        MoZ_B[i]=sqrt(pow(ReZ_B[i],2)+pow(ImZ_B[i],2));
        PhZ_B[i]=atan(ReZ_B[i]/ImZ_B[i]);

        ReZ_C[i]=Rf;
        ImZ_C[i]=0;
        MoZ_C[i]=sqrt(pow(ReZ_C[i],2)+pow(ImZ_C[i],2));
        PhZ_C[i]=atan(ReZ_C[i]/ImZ_C[i]);
        ReZ_D[i]=1;
        ImZ_D[i]=-Rf/(w[i]*Lm);
        MoZ_D[i]=sqrt(pow(ReZ_D[i],2)+pow(ImZ_D[i],2));
        PhZ_D[i]=atan(ReZ_D[i]/ImZ_D[i]);

        ReZ_E=pow(w[i],2)*Nr*L3*Rr+pow(w[i],2)*Nr*L3*R3+pow(w[i],2)*Nr*L3*R4-Rr*R3*R4;
        ImZ_E=w[i]*(Nr*Rr*R4+Nr*R3*R4+L3*Rr*R3+L3*Rr*R4);
        MoZ_E[i]=sqrt(pow(ReZ_E[i],2)+pow(ImZ_E[i],2));
        PhZ_E[i]=atan(ReZ_E[i]/ImZ_E[i]);
        ReZ_F=pow(w[i],2)*Nr*L3+R3*R4;
        ImZ_F=Nr*R4+L3*R3+L3*R4;
        MoZ_F[i]=sqrt(pow(ReZ_F[i],2)+pow(ImZ_F[i],2));
        PhZ_F[i]=atan(ReZ_F[i]/ImZ_F[i]);

        MoZ1[i]=MoZ_A[i]/MoZ_B[i];
        PhZ1[i]=PhZ_A[i]-PhZ_B[i];
        MoZ2[i]=MoZ_C[i]/MoZ_D[i];
        PhZ2[i]=PhZ_C[i]-PhZ_D[i];
        MoZ3[i]=MoZ_E[i]/MoZ_F[i];
        PhZ3[i]=PhZ_E[i]-PhZ_F[i];
```

```
        MoZ_G[i]=MoZ1[i]*MoZ2[i];
        PhZ_G[i]=PhZ1[i]+PhZ2[i];
        ReZ_G[i]=MoZ_G[i]*cos(PhZ_G[i]);
        ImZ_G[i]=MoZ_G[i]*sin(PhZ_G[i]);
        MoZ_H[i]=MoZ2[i]*MoZ3[i];
        PhZ_H[i]=PhZ2[i]+PhZ3[i];
        ReZ_H[i]=MoZ_H[i]*cos(PhZ_H[i]);
        ImZ_H[i]=MoZ_H[i]*sin(PhZ_H[i]);
        MoZ_I[i]=MoZ1[i]*MoZ3[i];
        PhZ_I[i]=PhZ1[i]+PhZ3[i];
        ReZ_I[i]=MoZ_I[i]*cos(PhZ_I[i]);
        ImZ_I[i]=MoZ_I[i]*sin(PhZ_I[i]);

        ReZ_J[i]=ReZ_G[i]+ReZ_H[i]+ReZ_I[i];
        ImZ_J[i]=ImZ_G[i]+ImZ_H[i]+ImZ_I[i];
        MoZ_J[i]=sqrt(pow(ReZ_J[i],2)+pow(ImZ_J[i],2));
        PhZ_J[i]=atan(ReZ_J[i]/ImZ_J[i]);
        ReZ_K[i]=ReZ_2[i]+ReZ_3[i];
        ImZ_K[i]=ImZ_2[i]+ImZ_3[i];
        MoZ_K[i]=sqrt(pow(ReZ_K[i],2)+pow(ImZ_K[i],2));
        PhZ_K[i]=atan(ReZ_K[i]/ImZ_K[i]);

        MoZeq[i]=MoZ_J[i]/MoZ_K[i];
        PhZeq[i]=PhZ_J[i]-PhZ_K[i];
        Real[i]=MoZeq[i]*cos(PhZeq[i]);
        Imm[i]=MoZeq[i]*sin(PhZeq[i]);

    else if k==3 // 1/2 order model

    else if k==4 // Harmonic model

        ReZ_A[i]=R1*R2*R3-pow(w[i],2)*L1*L2*(R1+R2+R3);
        ImZ_A[i]=w[i]*(R1*L2*(R2+R3)+L1*R2*(R1+R3));
        MoZ_A[i]=sqrt(pow(ReZ_A[i],2)+pow(ImZ_A[i],2));
        PhZ_A[i]=atan(ReZ_A[i]/ImZ_A[i]);
        ReZ_B[i]=R2*R3-pow(w[i],2)*L1*L2;
        ImZ_B[i]=w[i]*(L2*(R2+R3)+L1*R2);
        MoZ_B[i]=sqrt(pow(ReZ_B[i],2)+pow(ImZ_B[i],2));
        PhZ_B[i]=atan(ReZ_B[i]/ImZ_B[i]);

        MoZeq[i]=MoZ_A[i]/MoZ_B[i];
        PhZeq[i]=PhZ_A[i]-PhZ_B[i];

        Real[i]=MoZeq[i]*cos(PhZeq[i]);
        Imm[i]=MoZeq[i]*sin(PhZeq[i]);

end;
```

```
    Eq_M[i]= sqrt(pow(Real[i],2)+pow(Imm[i],2));
    Eq_P[i]= atan(Imm[i]/Real[i])*180/PI;

    M_err[i]= abs(Eq_M[i]-M[i])/abs(M[i]) ;
    P_err[i]= abs(Eq_P[i]-P[i])/abs(P[i]) ;


sum_M_err=(sum_M_err+
M_err[i]);
sum_P_err=(sum_P_err+P_
err[i]);
Obj[i]=M_err[i]+P_err[i];
end;

avg_M_err=sum_M_err/66;
avg_P_err=sum_P_err/66;

test=avg_M_err+avg_P_err;
```