FEDERAL UNIVERSITY OF TECHNOLOGY - PARANÁ
ACADEMIC DEPARTMENT OF ELECTROTECHNOLOGY

RAFAEL CARDOSO PIETSCH

EVALUATION OF A METHOD FOR SENSING THE OIL LEVEL AND OIL QUALITY USING A CAPACITIVE LEVEL SENSOR

UNDERGRADUATE THESIS

CURITIBA

2019

RAFAEL CARDOSO PIETSCH

EVALUATION OF A METHOD FOR SENSING THE OIL LEVEL AND OIL QUALITY USING A CAPACITIVE LEVEL SENSOR

Undergraduate thesis presented to the Academic Department of Electrotechnology of Federal University of Technology - Paraná as partial requirement to obtain the degree of “Bachelor” – Field of study: Electrical Engineering.

Mentor: Prof. Dr. Amauri Amorin Assef

Co-mentor: M. Sc. Stefan Traub

CURITIBA

2019

RAFAEL CARDOSO PIETSCH

Avaliação de um método para detecção do nível e qualidade do óleo usando um sensor de nível capacitivo

Este Trabalho de Conclusão de Curso de Graduação foi julgado e aprovado como requisito parcial para a obtenção do Título de Engenheiro Eletricista, do curso de Engenharia Elétrica do Departamento Acadêmico de Eletrotécnica (DAELT) da Universidade Tecnológica Federal do Paraná (UTFPR).

Curitiba, 15 de agosto de 2019.

Prof. Antonio Carlos Pinho, Dr.
Coordenador de Curso
Engenharia Elétrica

Profa. Annemarlen Gehrke Castagna, Ma.
Responsável pelos Trabalhos de Conclusão de Curso
de Engenharia Elétrica do DAELT

ORIENTAÇÃO

Prof. Amauri Amorin Assef, Dr.
Universidade Tecnológica Federal do Paraná
Orientador

BANCA EXAMINADORA

Prof. Amauri Amorin Assef, Dr.
Universidade Tecnológica Federal do Paraná

Prof. Delvanei Gomes Bandeira, Dr.
Universidade Tecnológica Federal do Paraná

Prof. Eduardo Félix Ribeiro Romaneli, Dr.
Universidade Tecnológica Federal do Paraná

A folha de aprovação assinada encontra-se na Coordenação do Curso de Engenharia Elétrica

To my parents, Lucieile and Enio, thanks for all the support and education given along all my journey. I love you.

ACKNOWLEDGEMENTS

This undergraduate thesis is just a small part of all the experience and knowledge acquired during this incredible nine months living in Friedrichshafen and working at ZF. It would take several pages to express gratitude to every one that transmitted and teached me something new during this period, but some key people need to be quoted here.

Starting with my family, which I would like to thank for all the support and confidence, since the beggining of my life and in all the steps that I have taken so far. Thank you, mom and dad, Lucieile do Carmo Cardoso and Enio Carlos Pietsch, to always believe in me and give support in everything, you are my foundation. Thanks for all the time together and the experience shared along our lifes, my brother, Gabriel Cardoso Pietsch. Also, to my grandparents, Alvari and Diva, Zely and Eugenio (*in memoriam*), thank you all for the life experiences, stories and examples passed on to me.

For all my dearest friends, the ones for a longer time, Ana Luiza, Lucca, Torres, Curan, Nina, Passini, Aron, William, Eduardo, Natália, Camilla, Bruno, Zé, and the newer ones, Curti, Guilherme, Augusto, Marc, Becchi, Marcelo, Polatti, Crespim and Eduardo, I am very grateful to have you all by my side. Thanks for all the conversations and time spent together, I will always be beholden for your friendships.

For my supervisor and mentor in work, Stefan Traub, who supported and encouraged me during my entire journey in ZF, thank you for made possible this enormous and important experience for me. Also, I really apreciate your believe in my potential and to help on my growth in personal and professional aspects.

Finally, thanks to all my coworkers and friends in Friedrichshafen, Mauro, Arun, Ajay, Jairo, Jorge, Paulo, Maren, Johannes, Jörg, Matthias, Ingo, Andreas and Jürgen, for all the experience and knowledge shared that helped me in my work at the company.

Com o seu poder da mente, a sua determinação, o seu instinto e experiência, você pode voar alto.

With your mind power, your determination, your instinct, and the experience as well, you can fly very high.

- Ayrton Senna

RESUMO

CARDOSO PIETSCH, Rafael. **AVALIAÇÃO DE UM MÉTODO PARA DETECÇÃO DO NÍVEL E QUALIDADE DO ÓLEO USANDO UM SENSOR DE NÍVEL CAPACITIVO**. 2019. 90 f. Trabalho de Conclusão de Curso (Graduação – Curso de Engenharia Elétrica). Universidade Tecnológica Federal do Paraná. Curitiba, 2019.

Nesta tese de bacharelado, é proposto um sistema para medir o nível e a qualidade do óleo com um sensor capacitivo, aplicando a técnica de Espectroscopia de Impedância. O projeto foi desenvolvido durante o estágio do autor na empresa ZF Friedrichshafen AG, localizada em Friedrichshafen, na Alemanha, que durou três meses e meio. Primeiramente, foi realizado um estudo sobre a aplicação do método de Espectroscopia de Impedância a diversas aplicações, sua eficiência e características, bem como para a medição da impedância do óleo, com base em outros trabalhos. Após, para a avaliação do sistema, foram realizados alguns testes, a fim de analisar a viabilidade e praticabilidade do mesmo. Para esses experimentos, foram consideradas quatro variáveis distintas, que poderiam alterar a impedância do óleo, levando a medidas diferentes. Essas quatro variáveis foram: nível, temperatura, idade e porcentagem de água. Como resultados, a medição do nível demonstrou uma boa relação linear entre o nível aplicado ao sensor e a impedância medida. A temperatura mostrou uma alteração muito pequena nos valores de impedância. Para diferentes idades do óleo, as medidas resultaram em quase nenhuma diferença e apenas duas amostras de idade foram testadas, o que levou a resultados inconclusivos sobre a diferenciação da idade do óleo. Considerando a contaminação com água, com pequenas quantidades de água no óleo, a impedância apresentou um decaimento que pode ser detectado nas medições. E, relacionado à faixa de frequência, verificou-se que o melhor espectro para um melhor desempenho do sistema, examinando as medidas de impedância e fase, estava entre 30 kHz e 70 kHz. No geral, o sistema, mesmo apresentando algumas limitações e erros, mostrou-se viável para a medição do nível e qualidade do óleo e para a aplicação em transmissões *off-highway*.

Palavras-chave: Nível do Óleo. Qualidade do Óleo. Óleo Lubrificante. Espectroscopia de Impedância. Sensor Capacitivo. Automotivo. Transmissão

ABSTRACT

CARDOSO PIETSCH, Rafael. **EVALUATION OF A METHOD FOR SENSING THE OIL LEVEL AND OIL QUALITY USING A CAPACITIVE LEVEL SENSOR**. 2019. 90 p. Undergraduate thesis (Graduation degree – Electrical Engineering Course). Federal University of Technology - Paraná. Curitiba, 2019.

In this undergraduate thesis, a system to measure the oil level and quality with a capacitive sensor, applying the Impedance Spectroscopy technique is proposed. The project was developed during the author's internship in the company ZF Friedrichshafen AG, located in Friedrichshafen, Germany, which lasted three and a half months. First, a study concerning the application of the Impedance Spectroscopy method to various applications, its efficiency and characteristics, as well as for the measurement of oil impedance, based in other works were made. After, for the evaluation of the system, some tests were taken, in order to analyze the feasibility and practicability of it. For these experiments, it was considered four distinct variables, which could change the oil impedance, leading to different measurements. These four variables were: level, temperature, age and water percentage. As results, the level measurement demonstrated a good linear relation between the level applied to the sensor and the impedance measured. The temperature showed a very small alteration in the impedance values. For different oil ages, the measurements showed almost no difference and just two age samples were tested, guiding to inconclusive results about the concerning the oil age differentiation. Considering the water contamination, with small amounts of water in the oil, the impedance presented a decay that could be detect in the measurements. And, related to the frequency range, it was found that the best spectrum for a better system performance, examining the impedance and phase measurements, was between 30 kHz and 70 kHz. Overall, the system, even presenting some limitations and errors, showed to be feasible for measurement of the oil level and quality and for the application in off-highway transmissions.

Keywords: Oil Level. Oil Quality. Lubricating Oil. Impedance Spectroscopy. Capacitive Sensor. Automotive. Transmission

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADC	Analog-to-Digital Converter
CSV	Comma Separated Values
DFT	Discrete Fourier Transform
DSP	Digital Signal Processing
GF	Gain Factor
IS	Impedance Spectroscopy
RC	Resistor-Capacitor
TCU	Transmission Control Unit

LIST OF SYMBOLS

ppm	parts per million
Ω	Ohm
V	Voltage
I	Current
Z_i	Complex impedance
$\|Z\|$	Absolute value of complex impedance
θ	Phase angle of complex impedance
ε	Permittivity
$\vec{E}$	Electric field
$\vec{D}$	Electric flux density
ε_0	Vacuum permittivity
ε_r	Relative permittivity
S	area
d	distance
$\dot{C}_x$	relative capacitance
C_0	vacuum capacitance
R_{FB}	Feedback Resistor
$Z_{UNKNOWN}$	Unknown impedance

SUMMARY

1 INTRODUCTION

1.1 THEME

1.1.1 DELIMITATION OF THE THEME

For the oil level measurement in a vehicular transmission, normally a resistive sensor is used, which has a mechanical arm with a float, that moves by changing the resistance of a resistor element. When interpreting this measurement, the value of the level of the oil inside the transmission is obtained. Figure 1 illustrates a sensor level with a float. The float runs within the rail on the side of the sensor length and can be seen on the middle of the long sensor part.

Figure 1: Resistive sensor with float.

Source: Own author.

Another type of sensor used is the capacitive sensor, that utilizes a more modern measuring system. This system detects the oil level through the change in capacitance around the resistive element of the sensor, due to the difference between the permittivity of the air and the fluid. In Figure 2, there is a capacitive sensor model for the measurement of the oil level.

Figure 2: Capacitive sensor for oil level measurement.

Source: Continental… (2018)

The oil level and quality measurement of this within engines and transmissions are of great importance to the maintenance and efficiency improvement of the machinery. When there is low quantity of lubricating oil, the gears and bearings begin to have more friction and to wear faster, reducing the useful life of the equipment (CASH, 2012).

Furthermore, if the oil has impurities, such as water (moisture) or small debris, its efficiency in relation to its lubrication is decreased. This also leads to the same problem mentioned previously, reducing the useful life time of the mechanisms due to the corrosion and friction caused by these contaminating substances.

In order to improve the detection to the oil level and its quality, one intends to use a capacitive sensor, as a transducer of the medium, together with an electronic chip with the application of the Impedance Spectroscopy technique to measure the capacitive impedance of the medium, where the sensor is immersed. With this, analyzing the data obtained after the tests, it will be assessed if it is possible to apply this technique in off-highway transmissions.

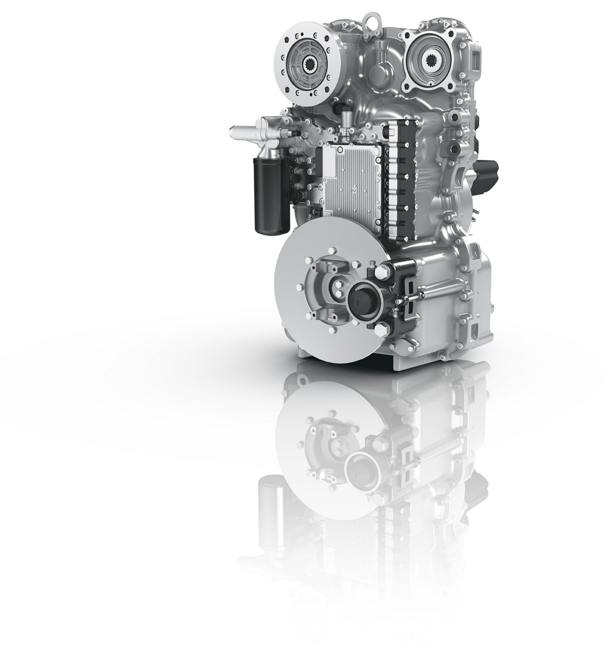
1.2 PROBLEMS AND PREMISES

The Impedance Spectroscopy technique is based on the application of an alternating electric current or voltage (excitation) in the system to be investigated, and in monitoring the response (in amplitude and phase) of the resulting voltage and current. The measurements are carried out over a range of frequencies, so that different physical and chemical processes can be separated by their time constants. The Impedance Spectroscopy is inexpensive, non-invasive, and simple to implement (BARSOUKOV; MACDONALD, 2005).

Some problems to be faced will be the detection of a low amount of water in emulsion with oil, which already begins to affect the life of the gears and bearings of the transmissions. Small percentages of water present in the oil, between 200 to 600 ppm (parts per million), or 0.02% to 0.06%, are the maximum values that the oils can contain of water, until this water begins to affect the lubrication produced by the oil. (Noria Corporation, 2010).

Considering the main goal application of the system proposed to be on the ZF cPower transmission (CP290), Figure 3, which contains about 41 liters of oil, the quantity of water to be detect in this amount of oil is, approximately, between 8 to 25 ml of water. This is a very small portion of water to be detected, compared to the oil volume, making hard to identify this contamination in the transmission.

Figure 3: ZF cPower transmission.



Source: ZF… (2019)

Also, since there is an expressive variation of the temperature in a transmission in operation, this will have to be considered in the tests, because with the change of temperature, the oil permittivity also changes, thus varying the impedance measured by the system. The variation of the measurements shall be taken into account in the tests to analyze how much the temperature variation changes the measured system.

1.3 OBJECTIVES

This section presents the main and specific objectives.

1.3.1 MAIN OBJECTIVE

This work aims at the evaluation of a measurement system based on the technique of impedance spectroscopy. This has as purpose the simple and efficient measurement of the oil level and its quality, using a capacitive sensor, for future applications focused on off-highway transmissions.

1.3.2 SPECIFIC OBJECTIVES

- Review techniques for measuring impedances through spectroscopy;
- Apply an existing sensor, together with evaluation board hardware and software, to measure impedance and evaluate the oil level and quality;
- Testing the electronic system in the laboratory;
- Analyze the test results and feasibility of the electronic system used for application in off-highway systems, which have special requirements to shock and temperature conditions.

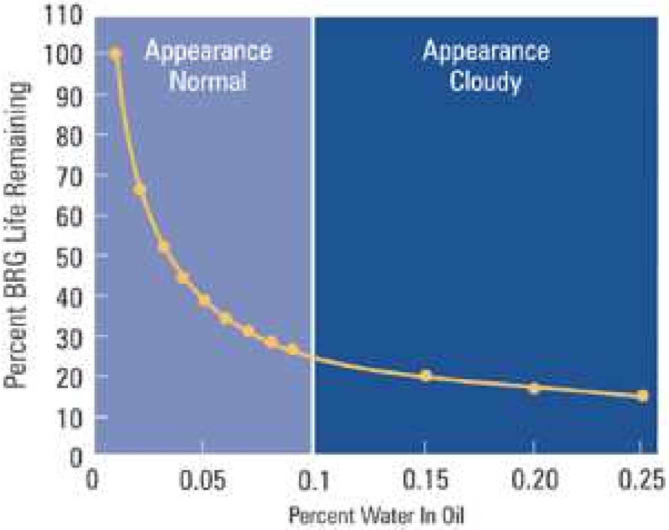
1.4 JUSTIFICATIVE

In oil level measurement, which is usually done with resistive sensor with floats, there are some mechanical problems such as maximum and minimum height not being detected normally, as well as problems when the vehicle's inclination passes from a certain roll and pitch angle. In addition, this type of sensor requires a larger space to act, because of the float that needs to move inside the vessel to indicate the liquid level.

The capacitive sensors have the advantage of requiring little space for their installation, being better at the oil level measurement compared to the float sensor. However, they cannot detect the oil quality by normally using only one frequency in the capacitance measurement. More, they are also affected by conductive objects, by the temperature of the medium and by the viscosity and concentration of salts of the liquid to which it is immersed (LANKA; HANUMANTHAIAH, 2017).

As already mentioned, the presence of debris and water in the lubricating oil decreases the useful life of the equipment, as it reduces the effective lubrication of the oil, thus causing more friction between the moving parts. Figure 4 presents a graph showing the decay of bearing useful life as a function of the percentage of water present in the oil. It is noted that with a negligible amount of water, 0.1% of water in the oil, the bearing life drops to approximately 25% of the total useful life.

Figure 4: Relation of the percentage of the remaining useful life of a bearing to the percentage of water in oil.



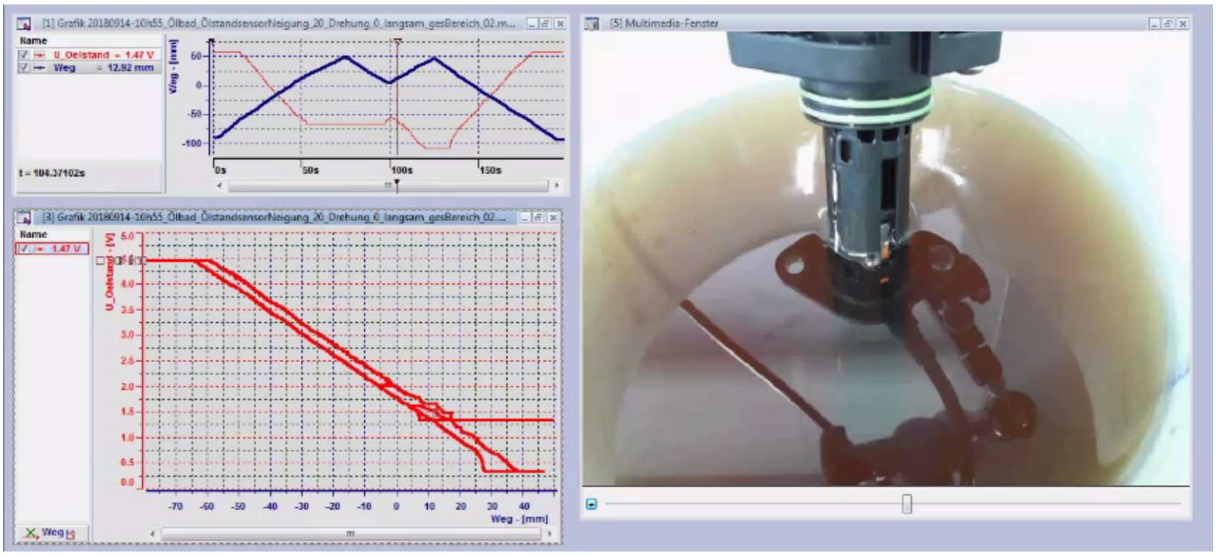
Source: Noria Corporation (2010)

This problem was visualized during an internship carried out by the author of this thesis at the company ZF Friedrichshafen AG, in Germany, on the year 2019. In the department in which the tasks of the internship were carried out, software is developed for transmission of construction machinery. It has been reported by the internship supervisor engineer that within the transmissions produced by the company for these machines, there is the previously reported problem of measuring the oil level with the mechanical sensor with float, presented in Figure 1, in addition to not being able to obtain the amount of water present in the oil.

Figure 5 presents one of the tests developed with the float sensor, presented in Figure 1, to analyze its reliability and accuracy in the measurements. It presented a problem where sometimes the float stucked in the rail and did not perform reliable level measurements, depending of the installation angle. Thus, it was not feasible to be used in the vehicle transmissions, needing a new solution to solve the problem of measuring the oil level in gearboxes.

With the new system, it is desired to improve the identification of the oil level and measure its quality, in relation to the amount of water and debris present in it. Along with

Figure 5: Test with float resistive sensor. On the left side, there are the graphs of sensor depth in oil (blue) and sensor voltage (red) and, on the rigth side, there is an image of the sensor inside the oil with the float stucked.



Source: Own author.

this, it is planned to evaluate if the system will be able to meet the requirements listed in this document, for application in off-highway transmissions.

Thus, if it is possible to measure this quality, the mechanical problems that occur in the transmissions are diminished, being able to predict more accurately the degradation of the lubricating oil, due to the presence of these residues.

With this in mind, it is intended to improve efficiency and better prediction of maintenance time to increase the life of off-highway transmissions, reducing fuel consumption by decreasing the friction between the parts and increasing the reliability of the product delivered to the customers.

Therefore, it is intended to study the method proposed by this work for application in off-highway transmissions, together with the company, aiming at the trend of digitalization and data analysis. In this way, the work also converges with the vision and movement of the company regarding the creation of new applications associated to Data Science and Artificial Intelligence, which are related to the analysis of the parameters of the oil and improvement in the forecast of maintenance of the off-highway transmission systems produced by the ZF Friedrichshafen AG company.

1.5 METHODOLOGICAL PROCEDURES

The following steps were organized to obtain the best technical and intellectual utilization in the development of the objectives proposed in this work.

1st step: Literature review

In this step, the bibliographical material will be collected in books and articles about the topics covered in this work. In order to carry out the literature review, it will be necessary to have a basic knowledge about the subject, which will be obtained through previous collection of materials and previous studies in this area, in addition to the help of the tutor and co-tutor that can indicate appropriate literature on the subject.

2nd step: Specification of the system

This step will consist of a study of the system that will be adopted. Here, the system will be specified to attend the goals of this work. The necessary components of the hardware will be defined for measurement of the impedance, as well as the softwares that will be used for running the measuring system and for the analysis of data obtained through the sensor. Also, the influences coming from the environment where the system is will be investigated, such as temperature, oil age and water contamination, in order to see how they change the measurements of the proposed system.

3rd step: Preliminary tests

During this step, preliminary tests will be carried out with the hardware and software to better understand the operation of the system. Also, within this step, the calibration of the system will be made using known values of impedance, to analyze the response of the system and make sure it is running as expected.

4th step: Development and tests

For this step, the development of the system will be carried out, which will be divided into several phases. These phases of the project include:

- Calibration of the measuring system;
- Evaluation tests;
- Hardware and software evaluation after the main tests;
- Test reviews to evaluate the system overall operation;
- Other minor phases.

5th step: Data and results analysis

In this step, an analysis of the data obtained through the tests of the system will be performed. This analysis aims to verify the validity of the results obtained in the tests performed. As well, this part will evaluate the general results of the tests and assess the system according to the objectives of the work.

1.6 STRUCTURE OF WORK

This work will be composed of five chapters arranged as follows: Chapter 2 aims to describe the basic concepts of the theory envolved in the project development. The current technique of oil level measurement and oil properties will be described for the possible application of the new sensing technique to measure its level and quality. Some fundamentals of impedance measurement techniques will be cited in it, giving a greater focus on capacitive impedance and spectroscopy methods.

Chapter 3 will present the methodological procedures for the development of the work, calibration and testing procedures. It will also be described how each step of the project will be developed to achieve the specified final product, as well as the description of the software development of the system.

In Chapter 4, the results will be presented, which were obtained during the tests realized along the development of the project and also the obtained final result. The last chapter covers the conclusions about the work developed and possible improvements and complements to be made in the final system.

2 BACKGROUND

This chapter introduces the reader to the background theory of the concepts used in the development of this undergraduate thesis. It gives the basic knowledge needed by the reader to comprehend the topics and concepts discussed and used within this study. If necessary, more in-depth information will be provided in further discussions of the topics that are explored in this chapter.

2.1 STATE OF THE ART

The actual section presents the related works to the present thesis, which were used during the development of this work related to the technique proposed to the oil level and quality measurements. There are some works about the use of the technique turned to other fields, as the measumerent of the water content of edible oils (Fendri et al., 2017) and also of mineral oils used in insulation of power transformers (Zbojovský et al., 2018). About engine lubricating oils, there was an article using ultrasonic sensor to detect the water content within the oil (Juliastuti et al., 2017) and other about a monitoring system for oil contamination using a capacitive sensor (Yang et al., 2009). Thereby, these articles have a different goal compared to this work, but they brought some important information as basic knowledge that helped in the development of this thesis.

The main goal of this work is to apply the knowledge acquired from these works and apply it to analize the feasibility of a system to measure the level and quality of automotive lubricating oil, mainly to transmissions. Also, it is important to evaluate if it is possible to produce the system within the Transmission Control Unit (TCU), so this could run the system and make possible to implement the system for use in off-highway vehicles.

The use of the Impedance Spectroscopy technique is not new, it goes back to the 1980s decade. The first main work about the method was the book from Macdonald, published in 1987 (MACDONALD, 1987). The first edition of the book explained the Impedance Spectroscopy technique, turned more to the analysis of solid materials, and intended to serve as a reference and textbook about the topic. The book presents the background about the method and further explains some applications of it. The second edition was published in 2005 and was used by the author here as a great reference within this work (BARSOUKOV; MACDONALD, 2005). More, in 1992, Macdonald also published an article about the method condensing the previous book, with a brief history, definitions, elements and applications of Impedance Spectroscopy in this work (MACDONALD, 1992).

With the development of electronic components over the years, it has become possible to create smaller and better systems to handle the Impedance Spectroscopy method. The improvement in the processing speed and encapsulation sizes of microcontrollers and other electronic components, neccessary to run the method, permitted the expansion of the technique to be applied in other fields and applications. Thus, in the last ten years, the IS method began to be more researched having most of the articles about it been produced on this period, also expanding to different areas, as material property analysis, biomedical sensors, corrosion monitoring, among others.

In 2009, the work from Dingxin proposed a monitoring system of oil contamination, based on the dielectric constant measurement. They used a cylindrical capacitive sensor to measure the oil dielectric constant, with a high precision system and also showed a good correlation with physical and chemical indexes of lubricating oil. More, the system can be used for online monitoring of engine lubricating oil, aiming a better preventive maintenance (Yang et al., 2009).

Guirong et al. (2011) describe a new approach to the development of a multifunctional sensor, used for monitoring oil temperature and oil level. They developed a simple capacitive sensor with two coils enroled together on a plastic pipe, which used the resistive and capacitive responses of this sensor to estimate the oil level and temperature. The oil temperature is measured using the resistance of the coil wires, as the oil level do not induce change in the resistance of these wires. Then, the oil level is measured obtaining the capacitance between the coils. They show that these measurements have linear correlations, making possible to obtain the oil level and temperature using the proposed sensor.

In the article Quality assessment of engine oil: an impedance spectroscopy based approach, Chowdhury et al. (2016) explore the use of the IS method to measure the quality of engine oil. They measure 10 different samples of engine oil with different concentration of contaminants, using a sinusoidal signal with the frequency range going from 0.1 Hz to 10 kHz, also varying the temperature from 70 to 100 °C. With this tests, they could conclude that the application of the technique is viable, and propose the use of intelligent classifiers to predict the engine oil quality.

More recently in 2016, Longo develops an electrical impedance spectroscopy system that was calibrated and validated. It is explained how the system is composed and some tests with it using known substances were done, showing good first results. They could monitor the ice formation process making use of the Impedance Spectroscopy technique (Longo et al., 2016).

Juliastuti et al. (2017) present in the paper a solution using ultrasonic waves to detect the water content in lubricating oil. They base the application in the fact that mechanical waves change their speed accordingly to the medium that they travel. Thus, the ultrasonic waves travel during different times depending on the amount of water present in the lubricating oil, for the same distance. They could show a inverse proportional linear relation among the percentage of water in the oil and the travel time of the ultrasonic waves. However, a more certain conclusion could not be presented, due to the uncertainty of some conditions, as stirring methods and sample conditions, which leaded to measurement drifts.

Also in 2017, Fendri and Ghariani published a paper investigating the efficiency of the impedance spectroscopy, called dielectric spectroscopy by them, for the detection of water content in different vegetable oils. They used a capacitive sensor to measure the dielectric properties of the oils and found that the sensor used had a very good sensitivity and linearity to the change in the water content. It could detect a change of 0.1% in the water content and also permitted the characterization of the different types of oil used by its different dielectric properties (Fendri et al., 2017).

The measurement of the oil level inside a transmission is very important to maintain the good lubrication between the moving parts, as bearings, gears and shafts. Other characteristic that has to be taken into account is the oil quality, because it also changes the oil behavior in the transmission and affects the action of lubricating oil. With these two characteristics, the oil level and quality, the system has its useful life increased and it decreases the maintenance time of the transmissions. Since it is a problem that is a high concern to the automotive industry, some studies have been done about the measurement of the oil level and oil quality over the last years.

The moisture in lubricating oil can cause some problems in a transmission, starting within accelerating the oxidation of the parts inside the transmission. Among other things, it also disturbs the efficiency of lubrication as the water acts differently from oil when under high pressure and high temperature. This occurs in small points of the moving parts, which results in more friction between these components.

These works described and cited in this section gave a basic expertise about the theme.

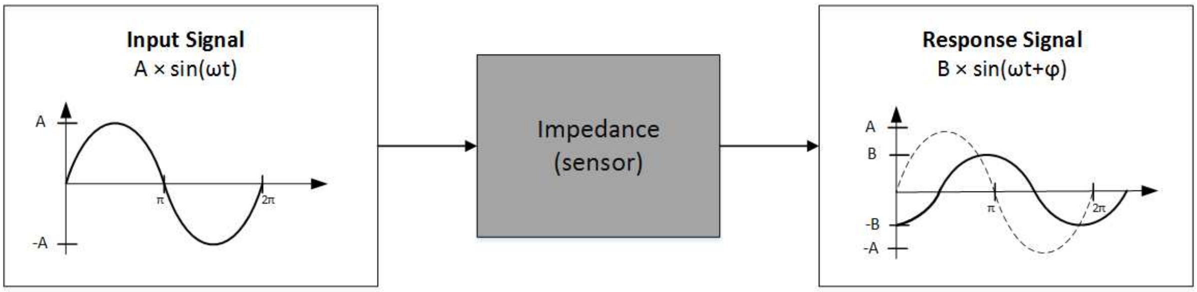
Together with the knowledge acquired during the graduation time, this whole know-how directed the hypothesis created, helped to conceive the tests and established what to be expected in the results.

2.2 IMPEDANCE SPECTROSCOPY

This section explains how the Impedance Spectroscopy (IS) technique works, giving the basic knowledge to the reader to understand the principles of the method. The impedance and permittivity concepts are also explained later to improve the understanding about the topic.

The IS technique is a method to measure the dielectric properties of a medium, object or material applying an alternated wave as a signal in a range of frequencies to the sample being measured. The response of this signal is then analized to measure these properties of the element that is being submitted to the signal, comparing the output signal with the input signal using, per example, an Analog-to-Digital converter.

Figure 6: Diagram of input and output signals in Impedance Spectroscopy technique.



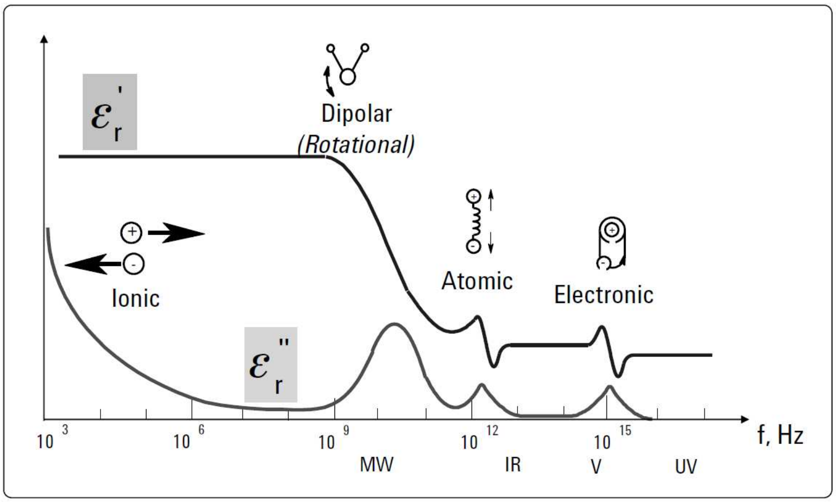
Source: Own author.

Figure 6 presents the basic concept in a diagram of the IS technique, where there is an input signal, normally a sinusoidal wave. Then, it runs through the impedance (medium, material) under analysis, alterating the signal and answering with the output signal. Later, this one is compared with the input signal to return the impedance and dielectric characteristics of the material that was analyzed.

When the signal is applied to a material, the molecules that compose it tends to orientated themselves following the input signal. For some types of materials, these molecules get orientated quicker than others types in determined frequencies, which increases the magnitude of the response signal in these frequencies. This orientation speed depends on the frequency applied and the dielectric characteristics of the material being analyzed.

Thus, the response signal, in comparison with the input signal, will rely upon the dielectric characteristics of the material under analysis. Figure 7 demonstrates the several dielectric mechanisms or polarization effects that compose the overall permittivity of the material. In the image, one can see that, accordingly to the their relaxation frequency, each different dielectric mechanism acts in distinct frequency ranges.

Figure 7: Frequency response of dielectric mechanisms.



Source: Agilent (2006)

These divergent characteristics of the materials make the differentiation of water and oil possible, just measuring the dielectric characteristics. It also permits differentiation of pure oil and oil with debris, as the debris change the dielectric characteristics of the oil. In this work, because of the properties and limitations of the evaluation board, explained on Section 2.3, the IS method was made from 5 kHz to 95 kHz.

Looking for the graph in Figure 7, the dielectric mechanic used is basically just the ionic polarization, which is a good factor for the measurements, since water has good ionic properties because of the ions present in it and the oils are, on the other hand, non-ionic mediums.

2.2.1 IMPEDANCE

Impedance is the characteristic of materials or mediums to impede a electrical current to go through it. It is measured in Ohms (Ω), which is the ratio between the voltage applied to the sample being measure and the current that flows through it. The Equation 1 shows the relation explained here.

$$Z = \frac{V}{I} \tag{1}$$

where Z is the impedance measured in Ω, V is the voltage applied to the body in Volts (V) and I is the current in Ampéres (A) that flows through the test body.

In this work, the complex impedance will be used to analyze the characteristics of the oil. Thus, the complex impedance permits to visualize the changes in the absolute value (magnitude) of the impedance and in its complex angle (phase), when the impedance of the oil is altered by contaminants, such as water or debris. The Equation 2 shows the formula of a complex impedance, with Z_i being the complex impedance, $|Z|$ the impedance absolute value and θ the phase angle of the impedance.

$$Z_i = |Z| \cdot e^{i\theta} = |Z| \cdot \cos\theta + i \cdot |Z| \cdot \sin\theta \tag{2}$$

2.2.2 PERMITTIVITY

Permittivity, noted by the Greek letter ε (epsilon), is a macroscopic material property of a medium, which relates the electric field, $\vec{E}$, to the electric flux density, $\vec{D}$, within it. The permittivity unit in the SI is farad per meter (F/m or F·m^{-1}). The vacuum permittivity, also called electric constant, is the lowest possible one, it is represented by ε_0 and has a scalar constant value of approximately $8.854 \cdot 10^{-12}$ F/m.

The relative permittivity (ε_r) of a material, also known as dielectric constant, is its absolute permittivity (ε) as a ratio relative to the vacuum permittivity (ε_0). It is represent by the Equation 3 and its minimum value is, by definition, the permittivity of the vacuum, of exactly 1.

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{3}$$

Further, the complex permittivity is a tensor that is frequency dependent. It is used for normal materials, which the response to an external field normally depends on the frequency of the field. The Equation 4 shows the relation of the tensor in a complex scalar, for an isotropic medium (IEEE. . . , 2019).

$$\dot{\varepsilon}_r = \varepsilon_r' + j\varepsilon_r'' \tag{4}$$

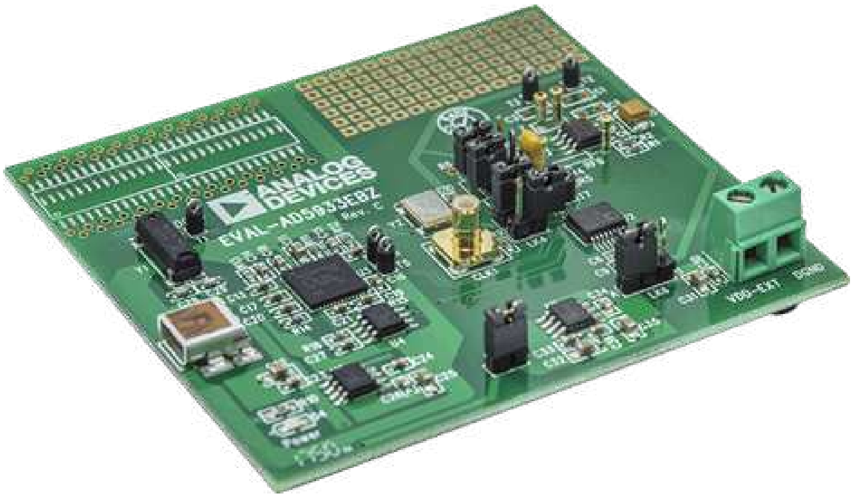
2.3 EVALUATION BOARD

2.3.1 EVAL-AD5933EBZ

The Evaluation Board EVAL-AD5933EBZ, made by Analog Devices, is designed to measure the impedance of a sample connected to it. It has a high precision impedance converter system which has an on-board frequency generator and a 12-bit, 1 MSPS, Analog-to-Digital Converter (ADC). The signal generator excites the external complex impedance with known frequencies. Then, the response signal from the impedance is read by the on-board ADC and, after that, it is transformed with a Discrete Fourier Transform (DFT) using an on-board DSP engine. This returns the real and imaginary data for each output frequency.

The device has as main component the AD5933 chip, which is responsible for the impedance conversion. The chip has a programmable output excitation voltage to a maximum frequency of 100 kHz, programmable frequency sweep capability, frequency resolution of 27 bits (<0.1 Hz), impedance measurement range from 1 kΩ to 10 MΩ, accuracy of 0.5%, temperature range from -40 °C to +125 °C, an internal temperature sensor with accuracy of ±2 °C and it is qualified for automotive applications.

Figure 8: Evaluation Board Kit AD5933EBZ.



Source: Analog Devices (2019)

The kit can be used for several applications, as electrochemical analysis, corrosion monitoring, biomedical and automotive sensors, proximity sensing, material property analysis and other more applications. In this work, it was used to apply the impedance spectroscopy technique to a capacitive sensor.

As the time to make this thesis was very short, the implementation of a complete hardware and software was inconceivable. With this, the kit was chosen because of its easy configuration, faster learning time, simple interface and its readyness for use. It also already has an evaluation software that attended the necessity of the project, as it easily configures the hardware, reads and shows the graphs of the measurements done, and also permits to save the data of the measurement in a CSV (Comma Separated Values) file, which allows a faster handling of the data using other specific softwares.

Further analysis and discussion to apply a similar system in a Transmission Control Unit (TCU) have been done in Appendix A as it was not possible to conceive an entire new system within this thesis development, due to the very short time for implementation and programming using this equipment.

2.4 CAPACITIVE SENSOR

A capacitive sensor is one that uses the capacitive coupling characteristics of the sensor probe to measure position, fluid level, proximity, humidity or force. This type of sensor can have some different formats, but it has essentialy two conductive elements that are separated by a dieletric material between these two elements.

The sensor uses the property of the capacitive coupling between the two elements, normally two metalic plates or cylinders, to measure the permittivity between these two parts, obtaining indirectly the capacitance using the Formula 5 at the vacuum and then the Formula 6 to acquire the new capacitance from the relative permittivity measured.

$$C_0 = \varepsilon_0 \cdot \frac{S}{d} \tag{5}$$

where $\varepsilon_0 = 8.854 \cdot 10^{-12[F/m]}$, S is the area of the electrodes and d is the distance between the two electrodes.

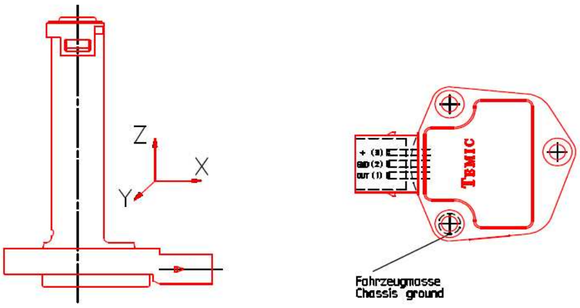
$$\dot{C}_x = \varepsilon_r \cdot C_0 \tag{6}$$

where $\dot{C}_x$ is the relative capacitance, ε_r is the relative permittivity and C_0 is the capacitance with the vacuum as dielectric material.

The sensor used in this thesis is the model QLT75M-C, produced by the company Continental, in the division of Powertrain - Sensors and Actuators. It is specified to measure the oil level, oil quality and the ambient temperature by its embedded system and this sends the information via an inverted Pulse Width Modulation (PWM) signal of 5 V to a connected device. Figure 9 has a technical draw with the side and low part of the sensor, with the electrical terminals and in Figure 10 one can see a photo of the real sensor. The sensor is approximately 130 mm high and its sensing part is 75 mm long.

Moreover, the sensing part of the sensor consists of two capacitive measuring elements, formed by one external long cylindrical part, and two other internal cylindrical parts, one shorter and other longer. The shorter cylinder with the external one composes the capacitive element used as reference measurement, and the longer one also with the external cylinder measures the level.

Figure 9: Technical draw of the capacitive sensor QLT75M-C model.



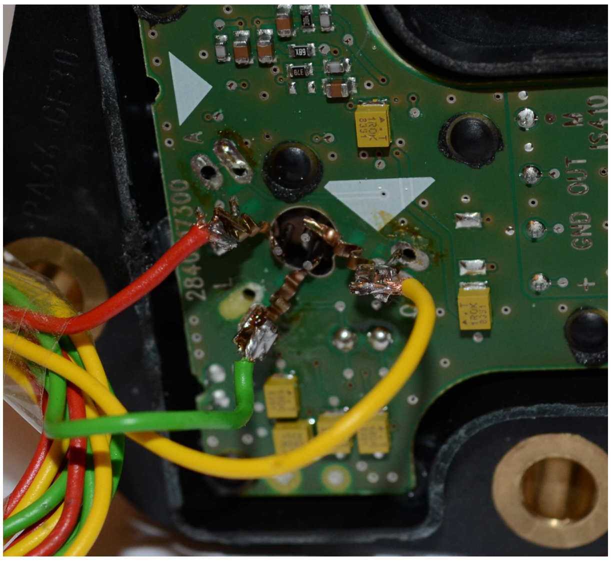
Source: Continental (2011)

Figure 10: Capacitive sensor QLT75M-C model.

Source: Own author.

For this work, the sensor was opened and its embbeded system was disconnected from its sensing part. This embedded system was not used, as it does not suit for the goal of this work. After, wires were soldered to its sensing parts (metalic cylinders), so it could be connected to the evaluation board used. Figure 11 presents the sensor with the different wires of each part of the sensor in details.

Figure 11: Connections of the capacitive sensor QLT75M-C model.



Source: Own author.

2.5 LUBRICATING OIL

The main goal in this work, as specified before, is to analyze the level and quality of the lubricating oil contained inside off-highway transmissions. The lubricant is formed of various components, that change the performance of the oil, so it can work properly for its intended application. It can be separated in natural, semi-synthetic or synthetic, which differs the way the oil works and how it modifies the properties during utilization.

A lubricant is composed most of base oil and additives. Normally, the base oil composes approximately 90% of the mixture. The other part of the lubricating oil consists of additives, which have three basic roles: enhance existing base oil properties, suppress undesirable base oil properties and impart new properties to base oils (Noria Corporation, 2018).

Basically, the two factors that most affect the oil quality are debris and water contamination, respectively. The first one occurs because of contamination by dirt coming from the air, the oxidation of the parts that create particles, among other solid particle contaminants that can enter in contact with the oil.

The problem caused by the debris is basically an increase on the friction between the parts. This rubbing growth to a level bigger than the lubricant applied can handle causes abrasion and erosion on the components. Because of that, the useful life of these elements are reduced, leading to more maintenance time and, possibly, early breaks. For a transmission system product, this effect is not good, as it gets known by poor quality, reliability problems, short time of useful life and inferior productivity for the user.

Three stages composes the water contamination in oil. The first one is the dissolved water, when it is evenly dispersed in the oil and the oil still appears clean, without any cloudy spots. This one does not bring problems to the oil functions. The second one is the emulsion of oil and water, when the amount of water passes the saturation point. It takes the oil to no more dissolve the water and it starts to become cloudy and turbid. Free water is the third stage of water contamination, when the water and oil get separated in two stages on areas without much turbulance (Noria Corporation, 2014).

The worst case of water contamination turns to be the emulsion of water and oil. This alters the oil properties and its performance, changing its lubricating ability. Thus, this condition of water contamination is the one that needed to be identified. For that, the moisture content should be in the range of 500 to 1000 ppm or 0.05% to 0.10%, depending on the application's criticality, as well as the oil type and temperature (Noria Corporation, 2017).

The water in oil causes some problems, similar to the debris complications that also takes down the useful life of the components and increase its maintenance time. First of these problems is the quicker corrosion and oxidation of the metalic parts. It produces small oxide particles that helps to increase the debris, leading to an increase in friction between the components.

Further, the other problem of water pollution is one of the reduction of the oil effectiveness, as the water behaves differently from the lubricant when under conditions of high stress, pressure and temperature. In these conditions, the thin protective layer that oil creates between the parts fades away because the presence of water, which does not form the same protective and slippery layer. Without this, the elements have more abrasion, friction and erosion, leading to the problems metioned before.

Complementing the explanation of the intent of this work, this is to identify this small amount of water that contaminates the oil and also the debris quantity present on oil, helping to reduce maintenance time and increasing reliability of off-highway vehicle gearboxes. With this identification, it will be possible to predict better the conditions and the maintenance time of the transmission systems, heading to an improvement in reliability, efficiency and productivity. This will contribute to a superior and better product supplied by ZF to the customers in the Off-Highway Transmissions area.

3 METHODOLOGY OR IMPLEMENTATION/TESTS

This part presents the methodology of the tests made to analyze the feasibility of the system proposed. The tests are divided in calibration tests, preliminary tests with known impedance values of electronic components and circuits, reference values, tests changing just one variable and then tests changing two variables simultaneously. The tests were composed accordingly to the variables chosen that possibly interfere in the impedance value.

Tests changing more than two variables at the same time were not made due to the complexity they have to control all the variables together. Also, the number of measurements needed to conclude these tests would be very high, being very hard to complete them inside the deadline of the thesis.

In total, four different variables were considered to be analyzed, so one could see how they interfere in the changing of the measured impedance. The variables were the oil temperature, age, level and percentage of water in the oil. Each of these variables may affect in someway the impedance value, changing the permittivity by physical and chemical effects or by the quantity of oil.

The oil temperature changes the oil viscosity, consequently changing the permittivity of the oil, as it gets thinner while it gets hotter. The oil age was used to simulate the degradation and contamination of the oil during the use on the gearboxes. Further, the oil level needed to be varied, so it could be measured and also to see how the other variables affect its measurement. Finally, the water percentage was altered to analyze if the system can detect the amount of water that mix with the oil during the transmission operation.

About the number of measurement repetitions on each step of the tests, 5 (five) different measurements were made on every step of the tests, so they could be averaged and give the measurements more reliability and trustworthiness. For each variable, the steps to be done on the tests were defined to get the best range possible, taking into account all the restrictions and limitations encountered in the system used and in the laboratory equipments and during the tests.

Appendix B shows the table created by the author with the variables considered and the number of measurements to be done in each test. It was used to calculate and have a better notion of the time to make the tests and also their size and complexity. For the calculation of these numbers, the Equation 7 was used to calculate the number of measurements in each test.

$$N_m = N_r \cdot N_i \cdot \ldots \cdot N_{i+n} \tag{7}$$

where N_m is the number of measurements per test, N_r, the number of repetitions in each measurement and N_i, the number of steps of each variable considering the corresponding test.

For the control of each variable, specific measuring instruments were used. In the case of the temperature, it was controlled by a Fluke 62 Mini Infrared Thermometer (Figure 12a) with resolution of 0.2 °C, range from -30 to 500 °C and emissivity preset of E = 0.95. About the control of the level, a digital depth calliper from Atorn was used (Figure 12b), with 300 mm of measuring range and resolution of 0.01 mm. It was fixed in the press that was used to control the height of the sensor, related to the oil, giving different levels of contact between the oil and the sensor.

Figure 12: Measuring instruments - Infrared Thermometer and Digital Depth Calliper.

(a) Fluke 62 Mini Infrared Thermometer.

(b) Atorn Digital Depth Calliper 300 mm.

Source: Own author.

The water percentage was controlled when adding small amounts of water to the oil. The new oil used on the tests was considered without water, serving as the basis for water application to simulate water contamination. Then, based on the quantity of the oil in the vessel being used, the quantity of water to be add were calculated for each percentage step. To add this water and control the amount, two small syringues were used, shown in Figure 13.

Figure 13: Syringues of 2.0 ml and 5.0 ml.

Source: Own author.

The oil used in the experiments was the John Deere Plus-50 II 10W-30 Premium Oil. It is used in the ZF cPower transmissions for lubrication of the moving parts and the company had it available in great quantity, both new and used from test benchs, to be used in these experiments.

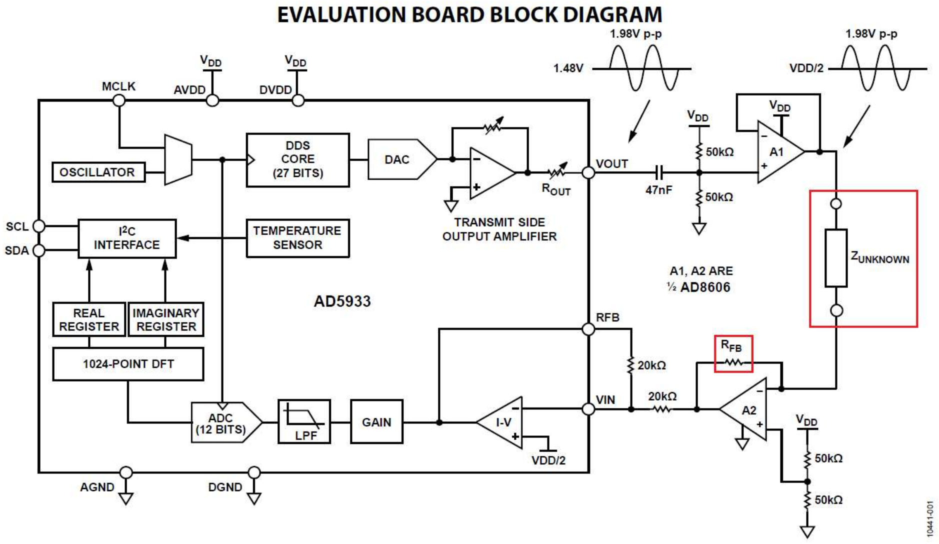
After the tests, the data acquired from them was analyzed using the software Matlab®. It was used to compare the data from the different measures and allowed to make a faster and better data analysis. The graphs presented in the Results (Chapter 4) and in Appendixes C, D and E were also created utilizing this software.

3.1 CALIBRATION TESTS

For the calibration of the system, a test with a known impedance value needed to be conducted. The evaluation board needed to be calibrated before every time it was used, so it could measure properly the unknown impedances, in other words, measure the sensor impedance in the tests. It needed two impedances of same value to calibrate the system using a variable called Gain Factor (GF).

One of these impedances is connected to the Feedback Resistor (R_{FB}) pins and the other one to the pins of the unknown impedance ($Z_{UNKNOWN}$). This factor was calculated automatically by the software of the evaluation board, making easier to use the system. Figure 14 presents the functional block diagram of the board, where one can see the feedback resistor and the unknown impedance on the right, emphasized by red rectangles.

Figure 14: Block diagram of the evaluation board EVAL-AD5933.



Source: Analog Devices (2017)

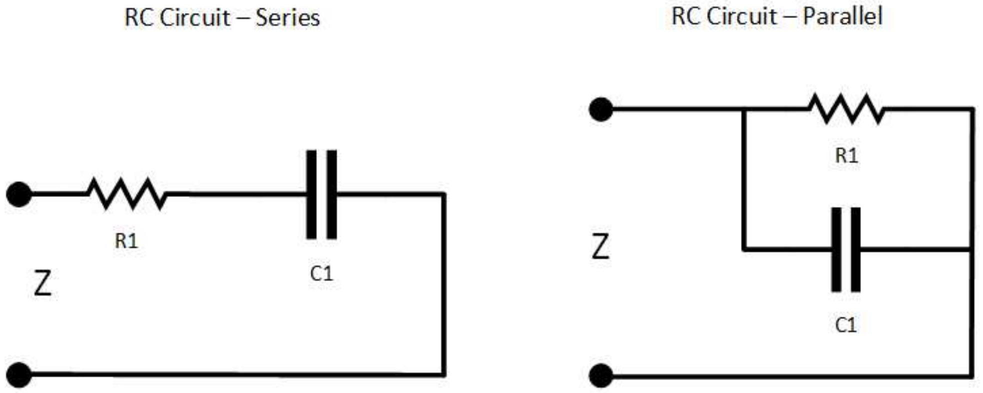
The value of the impedances chosen to the calibration was 100 kΩ, taking into account the frequency range that the tests would be made. Also, it was simpler to detect errors in the calibration measurement, because a resistor has a constant impedance and phase values for any frequency.

3.2 PRELIMINARY TESTS

Before the bench tests in the laboratory using lubricating oil, some tests with known value impedances were held. The first ones were using only simple impedances, a resistor and a capacitor. After that, the resistor and the capacitor were combined to form two different circuits, which are called Resistor-Capacitor (RC) circuits. They were mounted to measure their total impedance and help analyze the measuring capability of the evaluation board.

Figure 15 exhibits the two RC circuits mounted, series and parallel. The values of the resistor and the capacitor applied were 100 kΩ and 30 pF, respectively, and both were also employed in the simple circuits before, to measure the impedance of each one separately.

Figure 15: RC circuits – series and parallel.



(a) RC series circuit.

(b) RC parallel circuit.

Source: Own author.

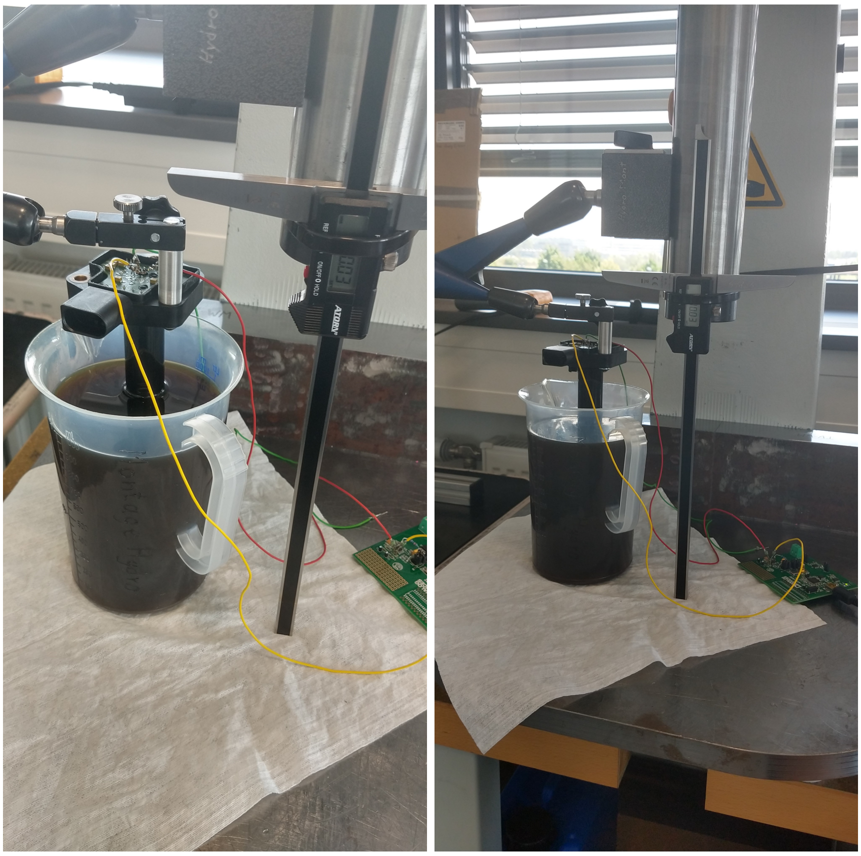
After the tests with the electronic components, measurements of references were conducted. The references were the sensor in the air and full of water. These measurements were used to compare with the others and as control measurements, as they represented situations were the sensor were fully imersed in the air or water.

3.3 TESTS CHANGING ONE VARIABLE

The first tests conducted in the laboratory, using lubricating oil, where the ones changing just one of the variables. The other variables remained as constantly as possible. As four different variables were chosen, four tests were conducted changing each one separately.

First, the more simple were the level test. One liter of new oil was handled inside a plastic vessel, in ambient temperature of 24 °C. The sensor was fixed to the ram of the mechanical press, which moved the sensor up and down to simulate the oil level to be measured by the sensor. The linear paquimeter was also attached to the ram and measured the level of the sensor, having as reference the basis of the press. Figure 16 shows the mounting of the sensor in the laboratory in two different angles.

Figure 16: Mounting of the sensor in the laboratory for tests.



Source: Own author.

Before the measurements start, the linear paquimeter were calibrated to zero when the sensor's bottom cap touched the oil surface. Also, the temperature of the oil was measured using the thermometer, to assess that it was at ambient temperature and the evaluation board system was calibrated too, following the calibration test steps (Section 3.1).

In the level test, the following steps were measured to analyze the capability of the sensor in evaluate the oil level detected by it. Table 1 presents these steps and the basic information about the test.

The comparison test of different age oils was between new oil and used oil for about 350 hours, during bench tests of the ZF cPower CP290 transmission. The used oil presented

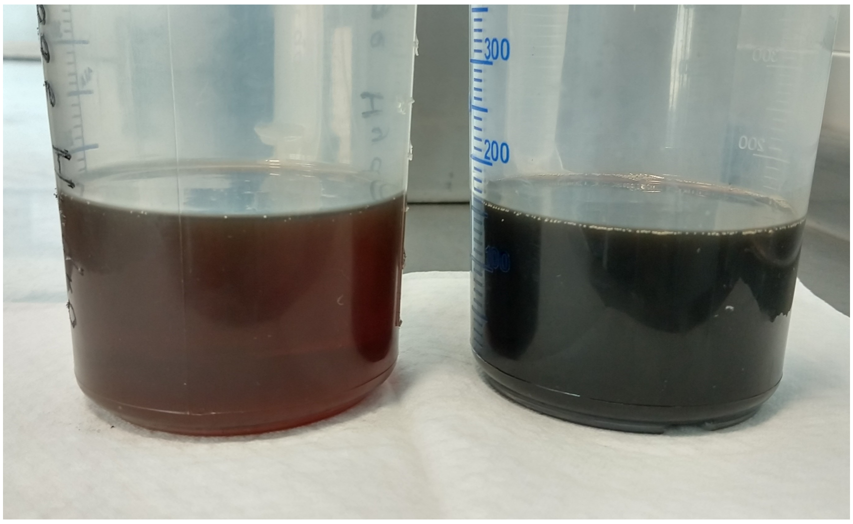
Table 1: Steps in Level test.

Steps	1	2	3	4	5	6
Level (mm)	00.0	10.0	20.0	30.0	40.0	50.0
Steps	7	8	9	10	11	
Level (mm)	60.0	70.0	80.0	90.0	100.0	
Oil	New	1000 ml				
Temperature	24 °C	Ambient				

Source: Own author.

some debris and dark coloration due to clutch discs burns occured along the tests of the gearbox. Figure 17 demonstrates the visual difference betweeen the new and the used oil, side by side. The sensor was maintained fixed in 80 mm of level, that covered entirely the longer capacitive element of the sensor, which was used in all the tests.

Figure 17: Visual comparison of small samples of new and used oil.



Source: Own author.

For the temperature tests, the temperature variation adopt was from -20 °C to 50 °C, with steps of 10 °C. The minimum temperature was limited by the freezer available in the company, that cold down the oil until the minimum temperature of -35 °C, and also because the oil at -30 °C was too much viscous, making it difficult to settle the oil at the exact level inside the sensor.

With that, it warmed up faster than it would be possible to take the test, if one waited for the oil to settle at the exact level. The maximum temperature was restricted because of the bench mounting adopted, that constrained the maximum temperature to 50 °C because of the increase in the oil steam released into the laboratory in higher temperatures, leading to an unsafe and toxic test environment.

In this test, the sensor was also fixed in 80 mm of level to be able to analyze the measurement alterations, accordingly to changes in the temperature. Again, new oil was used because of the preserved and comparable properties of it.

Going to the test with insertion of water, it was done using new oil and it was contaminated by normal water (tap water). The water quantity was calculated based on the oil quantity presented in the vessel and was added using pharmaceutical syringues of 2 and 5 ml. Figure 13 presents the two syringues used and Table 2 shows the water percentages adopted to the test.

Table 2: Steps in Water Percentage test

Steps	1	2	3	4	5
Water Percentage (%)	0.00	0.01	0.02	0.05	0.10
Steps	6	7	8	9	10
Water Percentage (%)	0.20	0.50	1.00	2.00	3.00
Oil	New	1000 ml			
Temperature	24 °C	Ambient			

Source: Own author.

3.4 TESTS CHANGING TWO VARIABLES SIMULTANEOUSLY

Further, tests changing two variables at the same time were conducted, in order to find out if there was changes in the measurements when they were modified concomitantly. The methodology applied to these tests are described below, with the description of the procedures taken and the steps used for each variable on each test.

The first test with two variables changing was the one to compare the oil age and level measurements. The new and used oil were taken and used to measure the sensor level inside them. The steps in Table 3 were the ones used for both oils, new and used, to compare the differences after in the measurements between them.

Table 3: Steps in Level and Age test

Steps	1	2	3	4	5
Level (mm)	00.0	20.0	40.0	60.0	80.0
Oils	New	1000 ml	Used (350 h)	1000 ml	
Temperature	24 °C	Ambient			

Source: Own author.

The test considering the oil age and temperature was the second to be made. The oils were cooled to about -30 °C in the freezer of the laboratory. Then, when the test started, the oil temperature was expected to reach about -20 °C, controlling it using the thermometer, to start measuring the oil impedance using the system with the sensor fixed at 80 mm. First, the new oil was employed and then, the used one. Table 4 shows these steps and basic information of this test.

Table 4: Steps in Temperature and Age test

Steps	1	2	3	4	5	6	7	8
Temperature (°C)	-20.0	-10.0	0.0	10.0	20.0	30.0	40.0	50.0
Oils	New	1000 ml	Used (350 h)	1000 ml				
Level (mm)	80							

Source: Own author.

Further, the test changing the water percentage and oil age was conducted. The water was added to the oils, taking into account the steps chosen and the difference in the amount of water to be added between those steps. Again, first the new oil was used and after the used one. Also, the sensor was fixed at 80 mm level to make the measurements with the system. In the Table 5, one can see the information of this test.

Table 5: Steps in Water Percentage and Age test

Steps	1	2	3	4	5
Water Percentage (%)	0.00	0.01	0.02	0.05	0.10
Steps	6	7	8	9	10
Water Percentage (%)	0.20	0.50	1.00	2.00	3.00
Oils	New	1000 ml	Used (350 h)	1000 ml	
Temperature	24 °C	Ambient	**Level (mm)**	80	

Source: Own author.

Later, the test considering the oil temperature and level variables was made. The temperature varied from -20 to 50 °C and, on each temperature step, the sensor level was ranged from 0 to 80 mm, in steps of 20 mm. This was done because the lower temperatures (below 0 °C) changed faster than the time to measure in 10 mm steps and also to reduce the number of measurements to be taken. One liter of new oil was employed. Table 6 displays the information of the test.

Table 6: Steps in Temperature and Level test

Steps	1	2	3	4	5	6	7	8
Temperature (°C)	-20.0	-10.0	0.0	10.0	20.0	30.0	40.0	50.0
Level (mm)	00.0	20.0	40.0	60.0	80.0			
Oil	New	1000 ml						

Source: Own author.

Subsequently, the test changing the variables Level and Water Percentage has been taken. The new oil used, in ambient temperature, was contaminated with the water, in each step, as defined in Table 7, from 0% to 2.0%. On every water percentage step, the sensor was put in the levels from 0 to 80 mm, in steps of 20 mm, and the impedance was measured.

Table 7: Steps in Level and Water Percentage test

Steps	1	2	3	4	5	6	7
Water Percentage (%)	0.00	0.01	0.05	0.10	0.50	1.00	2.00
Steps	1	2	3	4	5		
Level (mm)	00.0	20.0	40.0	60.0	80.0		
Oil	New	1000 ml					
Temperature	24 °C	Ambient					

Source: Own author.

The last performed test taken was the one to analyze the impedance changing the temperature and water percentage. It has been simplified in number of steps due to the large time required to cool each sample and the small time remaining to perform the test, which limited the amount of steps. The Table 8 presents the steps of water percentage, from 0.0 to 1.00%, and temperature, from -20.0 to 20.0 °C. Repeated, the sensor was fixed at 80 mm level and a liter of new oil was used.

Table 8: Steps in Temperature and Water Percentage test

Steps	1	2	3	4
Water Percentage (%)	0.00	0.01	0.10	1.00
Steps	1	2	3	4
Temperature (°C)	-20.0	0.0	10.0	20.0
Oil	New	1000 ml		
Level (mm)	80			

Source: Own author.

4 RESULTS

In this chapter, the results gained from tests conducted during the production of this work are presented. It is divided into sections following the goals of the tests done and, on each section, the corresponding results achieved are explained, discussed and justified.

First, it will be evaluated the accuracy and precision in the measurements made by the evaluation board system, using the results of the preliminary tests. Then, it will be done the evaluation of measurement alterations for each of the four variables: level, temperature, age and water percentage. Also, it will be observed if they alter the measurements between them. Finally, it will be analyzed the frequency influence and predominance in the measurements of the impedance and phase, with the data obtained during the tests.

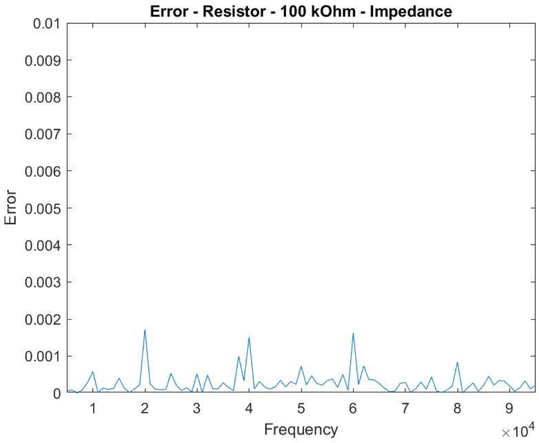
In Appendixes C, D and E, all the graphs generated to the Preliminary tests, Tests with one variable changing and Tests with two variables changing, respectively, are presented, so the reader can take a deeper analysis of the work performed during the development of this thesis.

4.1 COMPARISON BETWEEN MEASURING DATA AND THEORICAL DATA OF KNOWN VALUE CIRCUITS

To evaluate the accuracy and precision of the system used, the preliminary tests were taken. These tests, explained on Section 3.2, demonstrate that the evaluation board has a good response in the frequency range chosen. For a better comparison of the measured impedance values, these measurement data were plotted together with the theorical data correspondent to the total impedance of the circuits used, in function of the frequency applied by the evaluation system.

For the resistor impedance measurement, it showed almost no error. The error in the impedance measurement, shown in Figure 18 stayed below 0.1% all along the frequency range. This happened because the same resistor, of 100 kΩ were used to the calibration of the evaluation board.

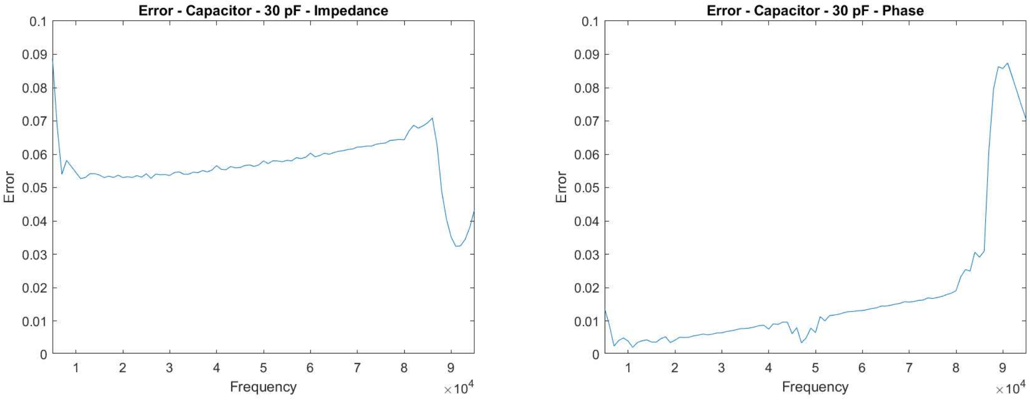
Figure 18: Error in Impedance measurement - 100 kΩ resistor.



Source: Own author.

In the 30 pF capacitor impedance measurement, the error kept around 6.0% almost all the frequency spectrum. As can be seen in Figure 19, it was higher, 9% of error, from 5 to 7 kHz, before it decreased to around 6.0%. Also, after 80 kHz, the error decreased to less than 5.0%. The phase measurement of the capacitor impedance showed a greater error in higher frequencies, growing faster after 80 kHz, but it had a very low error in smaller frequencies, staying under 2.0% of error before this frequency.

Figure 19: Error of impedance and phase measurements - 30 pF capacitor.



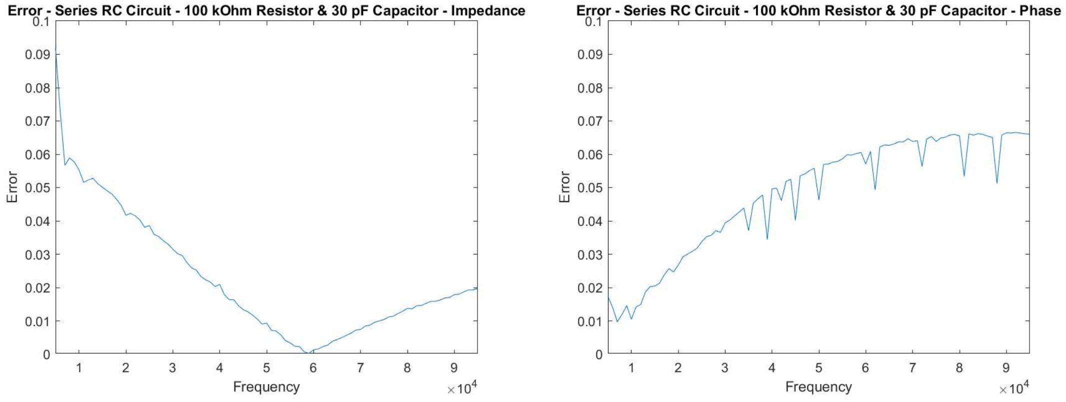
(a) Error of impedance measurement. (b) Error of phase measurement.

Source: Own author.

In the RC series circuit impedance, the system demonstrated again a very good response and measurement of the impedance. It started with a high error of 9.0%, however the error decreased to around 6.0% at 8 kHz, as presented in Figure 20, and continued decreasing until 58 kHz, where the measured and theorical data had a coincident point, close to 0% of error.

After, it started increasing again reaching 2.0% of difference at 95 kHz. In phase measurement, the error started at 1.5% and increased until stabilize around 6.5%, after 60 kHz.

Figure 20: Error of impedance and phase measurements - Series RC circuit - 100 kΩ resistor and 30 pF capacitor.

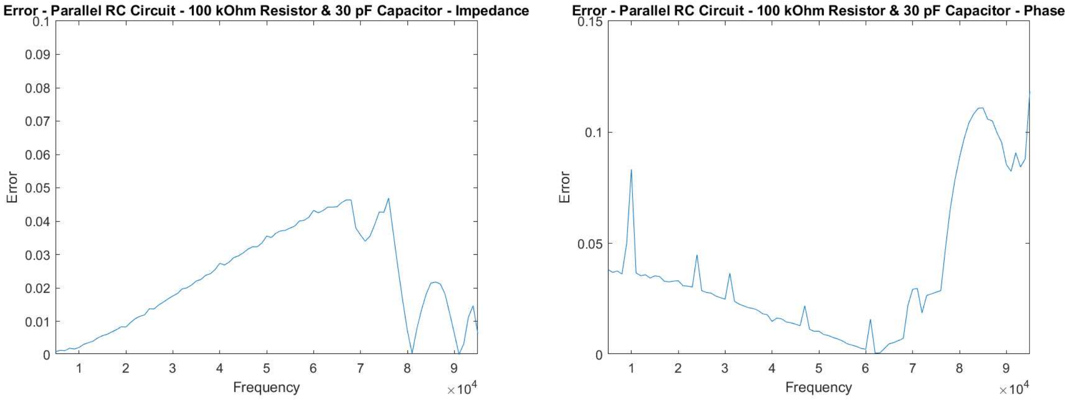


(a) Error of impedance measurement.	(b) Error of phase measurement.

Source: Own author.

For the parallel version of the RC circuit, in the impedance graph, Figure 21a, it showed an error around 0.1% at the beginning and reached 4.5% close to 70 kHz. After this frequency, the error decreased, but the data showed a strange behavior. This unexpected behavior also happened in the phase measurement, in Figure 21b, but with a high increase of the error, reaching more than 10.0% after 80 kHz. Before the 70 kHz, the error of the phase measurement stayed low, under 4.0%.

Figure 21: Error of impedance and phase measurements - Parallel RC circuit - 100 kΩ resistor and 30 pF capacitor.



(a) Error of impedance measurement.	(b) Error of phase measurement.

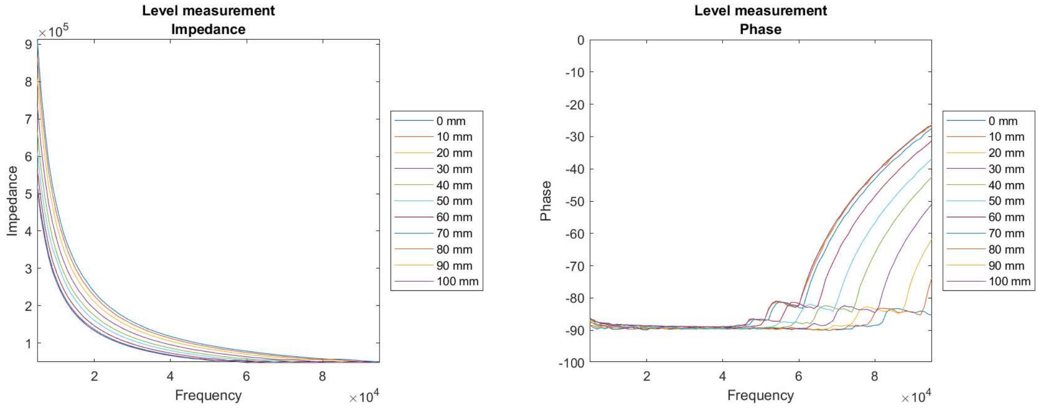
Source: Own author.

The Appendix C contains all the graphs of impedance and phase, as well the error between the theoretical and measured data for the four different circuits tested in the preliminary tests.

4.2 LEVEL MEASUREMENT

The data shown in Figures 22 demonstrates that the level measurement was possible to be made and it presented a difference in the impedance between 8.0 and 10.0%, among the levels tested. The phases measured also presented a difference in higher frequencies, starting from 50 kHz.

Figure 22: Level - Impedance and phase measurements.



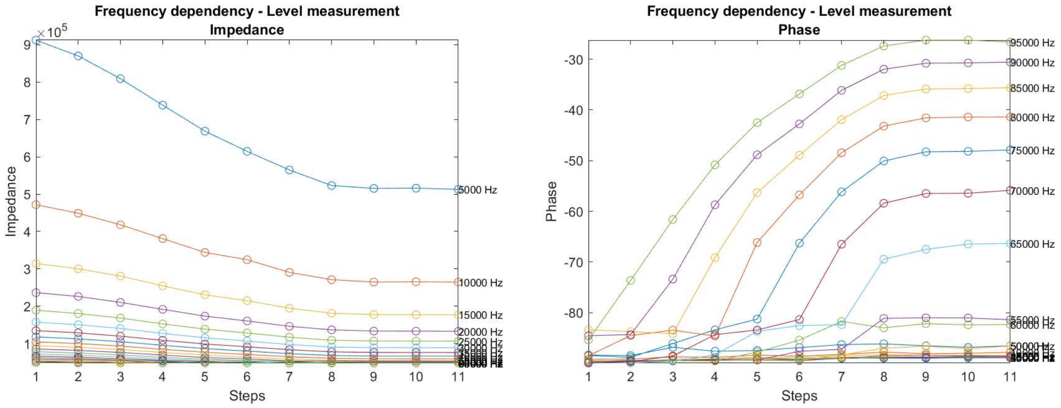
(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

From 0 to 10 mm, as the bottom cap to the sensing part had a small gap, it had not the same impedance difference between the level, as seen on the other levels from 10 mm until 70 mm. More, the longer element of the sensor has a sensing part of around 75 mm, accordingly to its datasheet. So, the measurements above 80 mm had almost the same impedance indicated as the sensing part was completely drowned after this length. One can see that they are essentialy the same, comparing the measurements of 80, 90 and 100 mm.

More, the level also could be detected including the other variables, as age, temperature and water percentage with a good response in frequencies between 10 kHz and 60 kHz for the impedance values and between 50 kHz and 70 kHz for the phase. Looking for the Frequency graph, on Figure 23, one can see that the impedance decreases as the level increases, because the lines have a negative slope, between the steps of the experiment.

Figure 23: Level - Frequency dependency of impedance and phase measurements.



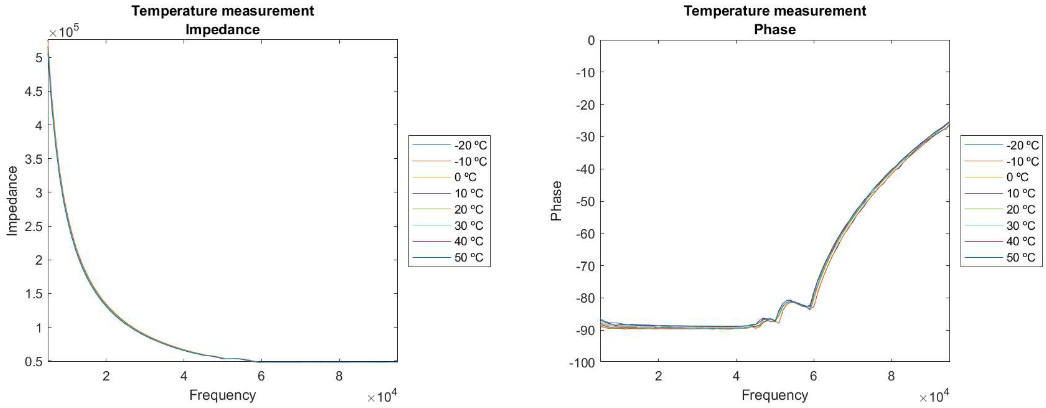
(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

4.3 INFLUENCE OF OIL TEMPERATURE ON MEASUREMENTS

About the influence of the oil temperature on the measurements, the graphs shown in Figure 24, one can see that the changing in temperature almost had no effect on the oil impedance. Different as expected before, the temperature changed the impedance just around 1.0% for each 10 °C step increased. The root cause for the difference is the expasion of the oil because of the temperature alteration, which could modify the level gathered by the sensor and show this difference in the measurement.

Figure 24: Temperature - Impedance and phase measurements.

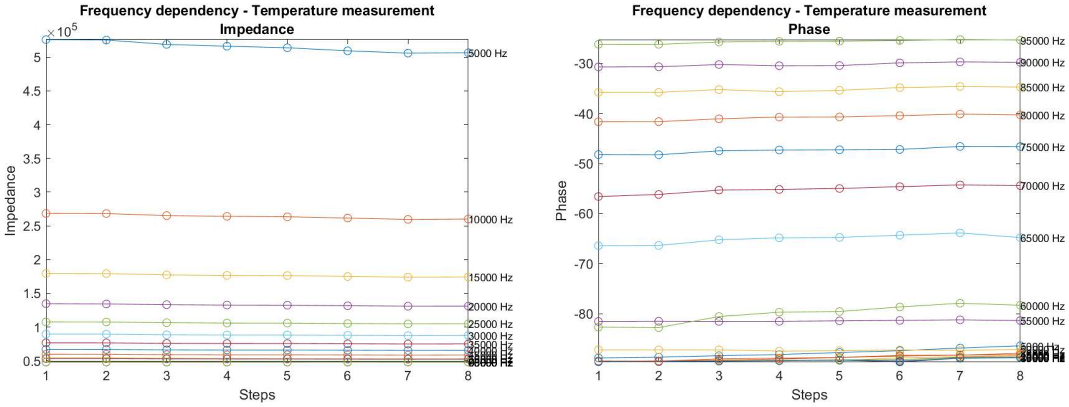


(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

Figure 25, related to the frequency in the test with different temperatures, one can observe that the curves are practically constant, which leads to the consideration that there is not a relevant change in the measurement values. This can also be seen in the Figure 26, where the difference in impedance measurement, considering both variables, temperature and age, differs less than 8.0%. In the phase measurement the maximum different is about 10.0%.

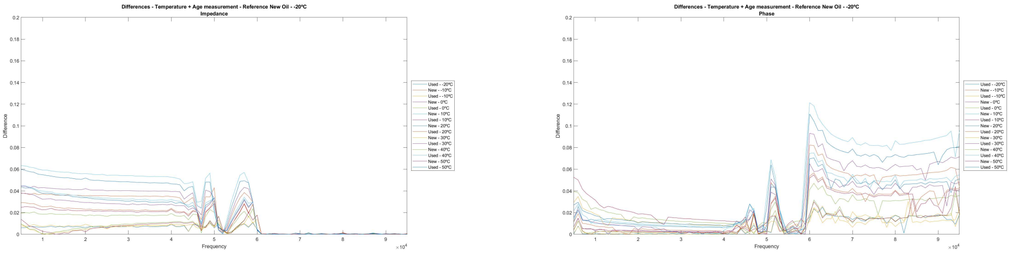
Figure 25: Temperature - Frequency dependency of impedance and phase measurements.



(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

Figure 26: Temperature + Age - Differences in impedance and phase measurements - Reference 0 mm.



(a) Theorical and measured impedance. (b) Theorical and measured phase.

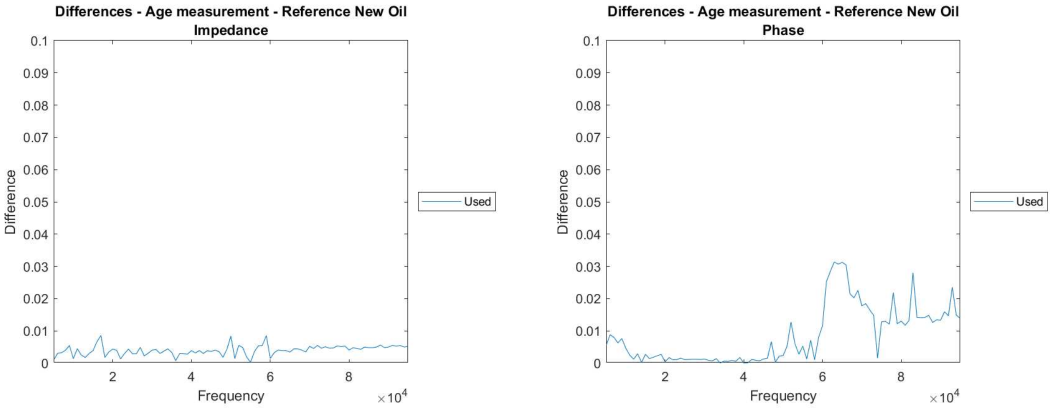
Source: Own author.

4.4 OIL AGE COMPARISON

Examining the graph shown in Figure 27a, one can see that the change in oil age had practically no effect in the oil impedance value too. Also, looking in the phase graph, Figure 27b, there is almost no difference between the phase of the new and used oil. There is only a small difference between 60 and 70 kHz, but still too small to consider it feasible to determine the oil age.

The difference in the impedance measurement between the oils was less than 1.0%, and the phase had an average difference of 2.0% in frequencies over 60 kHz. With that, it was not possible to differentiate the oil samples used just by age, because the measurement differences was inside the measurement error, characteristic from the system.

Figure 27: Age - Differences in impedance and phase measurements - Reference New oil.

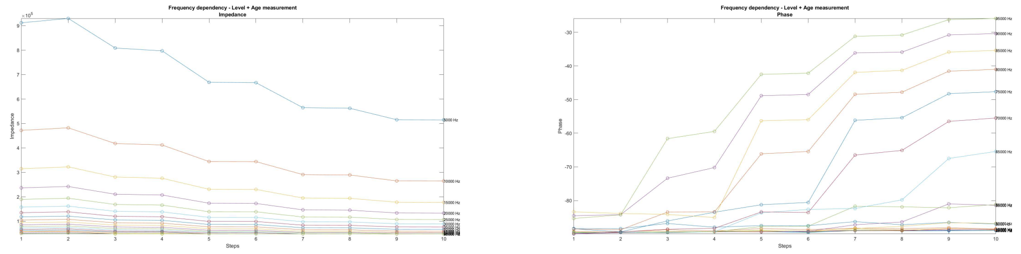


(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

Also, analyzing the graph of frequency in the Level + Age test, presented in Figure 28, it is possible to observe that between the two different aged oils, the curve is essentialy constant, conducting to no difference in impedance and phase values between these two oils, for each level step applied.

Figure 28: Level + Age - Frequency dependency of impedance and phase measurements.



(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

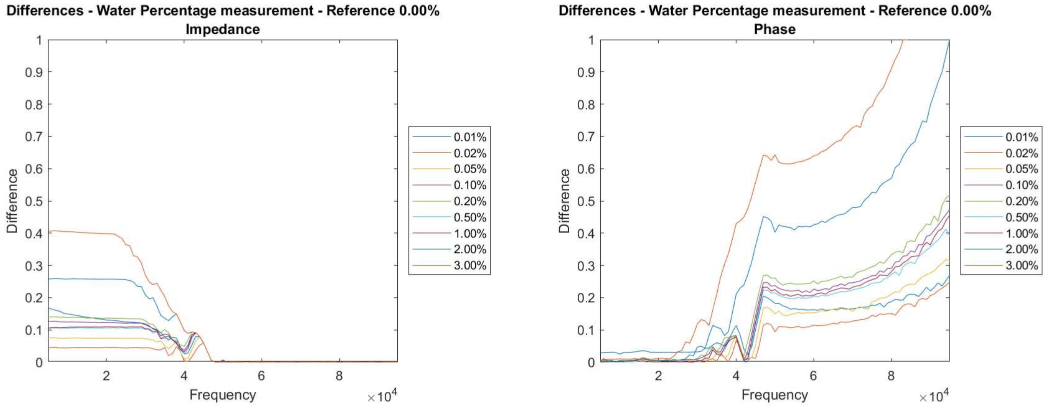
Considering that the oil was taken from a bench test and was used in a new transmission, it had not a great amount of debris that can polute the oil, as dust, rust and other contaminants, which would increase the difference in the impedance measurement of the used oil, compared with new oil. Even though it was contaminated by the burned clutch disc, this was not enough to characterize it as used, just looking in the measurement data.

4.5 DETECTION OF WATER CONTAMINATION

Examining the Figure 29, the water contamination showed some difference in the oil impedance, altering it proportionaly to the increase in the water percentage present in the oil. However, a great difference was presented in the phase measurement, changing more than 10.0% already from the first step of the test, from 50 kHz of wave frequency.

Some errors in the measurement appeared in few percentage steps, but they did not influence in the overall results obtained to analyze the water contamination in the tests. These errors may have occurred because of the mixture of oil and water, after the addition of the new amount of water, even though care has been taken to mix the emulsion well.

Figure 29: Water Percentage - Differences in impedance and phase measurements - Reference 0.00%.

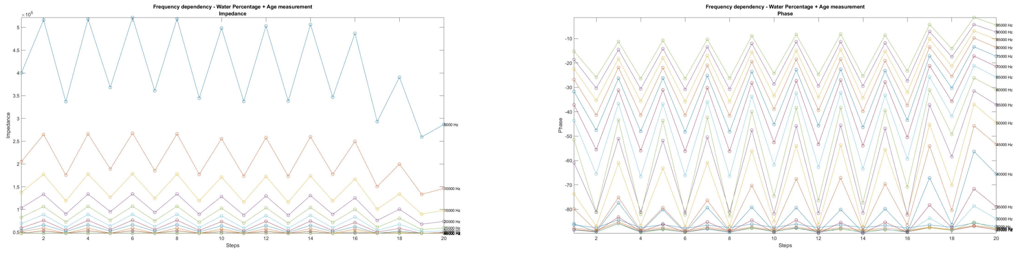


(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

Another good observation that can be made was that the water contamination in the oil affected more the used oil. It can be seen in Figure 30 that the variation increases in the steps at the end of the test, with a greater amount of water added. A greater inclination between the points for the used oil as compared to the points of the new oil can be observed.

Figure 30: Water Percentage + Age - Frequency dependency of impedance and phase measurements.



(a) Theorical and measured impedance. (b) Theorical and measured phase.

Source: Own author.

4.6 FREQUENCY SPECTRUM ANALYSIS

For the frequency spectrum utilized in the tests, some observations can be made about it. Looking the graphs of each step *versus* impedance or phase, they show that in lower frequencies, the impedance changed more because of the high value of it, taking into account that the probe had capacitive properties. Similarly, the phase values also presented higher variations, however, it happened at higher frequencies.

Taking into consideration the errors found in the Preliminary Tests, Section 3.2, to the capacitive circuit, the impedance measurement had a higher error in lower frequencies, until 10 kHz. And the phase measurement presented a greater error in higher frequencies, from 80 kHz to the end. With that, these frequencies, from 5 to 10 kHz and from 80 kHz to 95 kHz, may be excluded so only the part of the frequency range with more linearity could be analyzed, giving more reliability to the measurements.

For even better measurement results, the frequency range considered can be narrower, going from 30 kHz to 70 kHz. In this range, the first half of it, from 30 to 50 kHz, can be used to the impedance measurement, because the changes in the oil variables affected more the impedance value before the 50 kHz frequency. For the phase measurement, it can be used the frequencies from 50 kHz to 70 kHz, as the phase values altered more after the 50 kHz line. Using these frequencies, the ones which presented higher errors are excludedand it gathers good ranges for measurements the impedance and the phase values.

In addition, a single frequency can be applied to the system and the measurement can be realized in this condition. However, using just one point of frequency, one needs to know that the system reliability and accuracy may decrease, as the number of points in comparison between the measurements is smaller. If a system with only one frequency is built, it is advisable to use a frequency within the range cited above, and consider how the values of impedance and phase changes in the chosen frequency.

5 CONCLUSION

5.1 GENERAL CONCLUSIONS

Here, the main conclusions taken from this entire work are exposed and explained. Following the main objective of this thesis, and taking into account all the tests and points observed in the results, the measurement system of oil level and quality using a capacitive sensor, which was developed and used here, showed to be applicable to the desired application, besides some limitations presented by the system used.

The tests done to study the applicability of the system demonstrated good results in general. Some errors were found in the measurements of a few test steps, but considering the test results as a whole, the analysis of the electronic system applied could be done and the following conclusions about the variables chosen could be achieved.

Considering the oil level, the measurement of the level presented a very linear growth between the points taken into measurement. It was very clear that the system could be used to measure the oil level by analyzing the impedance or phase values, as they alter linearly in most of the frequencies used. With that, one of the goals here was achieved, as the oil level is one of the most important characteristics to be considered to have a healthy usage of an off-highway transmission.

A small percentage of water in the oil could be detected, when compared with the oil without any water. The difference reached 10.0% in the impedance measurement, with the addition of the smallest amount of water (0.01% of water in oil) practiced in the tests. This demonstrates that is possible to analyze the oil, then determine if it contains small amounts of water, especially when in emulsion with the oil, that is even more harmful to the parts of the transmissions.

About the oil temperature, it did not changed the measurements in a considerable level. The differences between the temperatures steps considered, of 10 °C, were undermost to be taken as an effect in measurement. This is very good, thereby the temperature can be excluded from the measurement equations, and permits the transmissions to operate in a extensive temperature range.

Further, the differences between the new and used oils did not show a great difference to be able to differenciate both oils. The impedance and phase between the two samples showed almost no difference in the values measured in the tests which the oil age was considered. Maybe taking a more used and contaminated oil, this difference could be more pronunciated, making possible to recognize the age of the used oil.

Finally, the technique showed to be feasible to be applied to the off-highway transmissions, as the objective to evaluate the oil level and detect water contamination in the oil was possible to be gathered. More, the response time of the system was very low, under 10 ms per measurement, which is ideal for the application in a TCU or automotive sensor. The temperature showed insignificant change to the measurements and just the oil age that could not be evaluated with certainty, leaving for further works to make a deeper analysis about it.

5.2 FUTURE WORK

Considering all the effort spent in this work, it opened some opportunities for future works to be made. Most of them are related to deeper studies following this one, which could give more realiability to the technique used to the applications mentioned and also to other works related to this field. The first topic is to analyze the system used or another similar one applying measurements with higher frequencies to observe if it makes different effects in the oil impedance.

Another work that can be done is the analysis of the response of the system when calibrated with another types of circuits. In this work, it was used a simple resistive circuit for the calibration. The utilization of capacitive circuits or RC circuits is possible and the analysis of a better circuit applied in the calibration of the system may lead to a better reaction and response using these other kinds of circuits. Thus, it could give a better solution and reach improved measurements of the oil level and quality.

Further, aiming the simplification of the system proposed, so it can be applied in more applications, a study of the system using single frequencies can be done. The goal is to discover a single frequency or a very small frequency range where the proposed measurements, oil level and quality, could be made. This can reduce the complexity of the system and make it easier to be applied in a great amount of systems, taking into account that a single frequency wave is much easier to generate than a great number of frequencies in a row.

Furthermore, another topic of study would be the development of a embedded system to integrate it with a capacitive sensor, putting the electronic measuring system directly together with the sensing part, all fitted together in a single package. This would create a single product that could deliver the measurement of oil level and quality to the vehicle using serial communications, as CAN, UART or other types of communication, permitting it to be applied to a larger number of products in automotive field, as engines, various transmissions and other applications with oil.

More, a machine learning analysis system could be created and explored in another project, using the data generated by the tests measurements made on this one. It could examine the data and evaluate it better to discover patterns in the measurements of the level and quality of the oil. With the use of machine learning, it would be possible for the system to learn the characteristics of each system and to adapt to each situation, also considering a larger number of variables and improving the measurements with the insertion of more data for analysis.

Even more, the technique used here could be applied to another applications, as it is very simple and has a great response to almost all the applications possible to be employed. The Impedance Spectroscopy technique is starting to increase its participation in some areas, so new ideas could come to analyze the properties of another mediums or materials.

REFERENCES

AGILENT. **Basics of Measuring the Dielectric Properties of Materials - Application Note**. [S.l.]: Agilent Technologies, Jun 2006.

Analog Devices. **Evaluation Board EVAL-AD5933 User Guide - UG-364**. Analog Devices, 2017. Disponível em: <https://www.analog.com/media/en/technical-documentation/user-guides/UG-364.pdf>.

Analog Devices. **EVAL-AD5933 Overview**. 2019. Disponível em: <https://www.analog.com/en/design-center/evaluation-hardware-and-software/evaluation-boards-kits/EVAL-AD5933.html#eb-overview>.

BARSOUKOV, E.; MACDONALD, J. R. **Impedance spectroscopy theory, experiment, and applications**. 2. ed. [S.l.]: Wiley-Interscience, 2005.

CASH, W. **What Is Lubrication?** Noria Corporation, Feb 2012. Disponível em: <https://www.machinerylubrication.com/Read/28766/what-is-lubrication>.

Chowdhury, S. R. et al. Quality assessment of engine oil: An impedance spectroscopy based approach. In: **2016 IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics Engineering (UPCON)**. [S.l.: s.n.], 2016. p. 608–612.

CONTINENTAL. **QLT75M-C Oil Sensor Datasheet**. [S.l.]: Continental, Apr 2011.

CONTINENTAL Automotive. 2018. Disponível em: <https://www.continental-automotive.com/en-gl/Passenger-Cars/Powertrain/Gasoline-Technologies/Lubrication/Fluid-Sensors/Fluid-Sensor-—-Oil-Level-Passive-Electrothermic>.

Fendri, A.; Ghariani, H.; Kanoun, O. Dielectric spectroscopy for assessment of water content in edible oils. In: **2017 14th International Multi-Conference on Systems, Signals Devices (SSD)**. [S.l.: s.n.], 2017. p. 728–732. ISSN 2474-0446.

Guirong, L.; Xianshan, Z.; Shuyue, C. A new proposal for monitoring oil-temperature and oil-level. In: **IEEE 2011 10th International Conference on Electronic Measurement Instruments**. [S.l.: s.n.], 2011. v. 4, p. 350–353.

IEEE Standard Definitions of Terms for Radio Waves Propagation. **IEEE Std 211-2018 (Revision of IEEE Std 211-1997)**, p. 1–57, Feb 2019.

Juliastuti, E.; Tanogono, E. W.; Kurniadi, D. Detection of water content in lubricating oil using ultrasonics. In: **2017 5th International Conference on Instrumentation, Control, and Automation (ICA)**. [S.l.: s.n.], 2017. p. 188–192.

LANKA, S.; HANUMANTHAIAH, S. **Capacitive sensor challenges and solutions for liquid-level sensing**. Cypress Semiconductor, Jun 2017. Disponível em: <https://www.electronicproducts.com/sensors_and_transducers/sensors/capacitive_sensor_challenges_and_ solutions_for_liquid_level_sensing.aspx>.

Longo, J. P. N. et al. Simple measuring system for impedance spectroscopy analysis of fluids. In: **2016 1st International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT)**. [S.l.: s.n.], 2016. p. 77–80.

MACDONALD, J. R. **Impedance spectroscopy: emphasizing solid materials and systems**. [S.l.]: Wiley, 1987.

MACDONALD, J. R. Impedance spectroscopy. **Annals of Biomedical Engineering**, v. 20, n. 3, p. 289–305, May 1992. ISSN 1573-9686. Disponível em: <https://doi.org/10.1007/BF02368532>.

Noria Corporation. **Water In Oil Contamination**. Noria Corporation, Feb 2010. Disponível em: <https://www.machinerylubrication.com/Read/192/water-contaminant-oil>.

Noria Corporation. Noria Corporation, Nov 2014. Disponível em: <https://www.machinerylubrication.com/View/29944/water-oil-contamination>.

Noria Corporation. **Effects of Water Contamination on Oil**. Noria Corporation, Mar 2017. Disponível em: <https://www.machinerylubrication.com/Read/30762/water-contamination-effects>.

Noria Corporation. **Lubricant Additives - A Practical Guide**. Noria Corporation, Mar 2018. Disponível em: <https://www.machinerylubrication.com/Read/31107/oil-lubricant-additives>.

Yang, D. et al. Oil contamination monitoring based on dielectric constant measurement. In: **2009 International Conference on Measuring Technology and Mechatronics Automation**. [S.l.: s.n.], 2009. v. 1, p. 249–252. ISSN 2157-1473.

Zbojovský, J.; Kruželák, L.; Pavlík, M. Impedance spectroscopy of liquid insulating materials. In: **2018 International IEEE Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE)**. [S.l.: s.n.], 2018. p. 000249–000254.

ZF cPower. ZF Friedrichshafen AG, Mar 2019. Disponível em: <https://press.zf.com/press/en/media/media_1875.html>.

APPENDIX A – SPECIFICATIONS OF IMPEDANCE SPECTROSCOPY (IS) TECHNIQUE APPLIED TO A TCU

Specifications of Impedance Spectroscopy (IS) technique applied for a TCU

A basic system necessary for the application of the Impedance Spectroscopy technique is basically composed by the following parts: signal generator, sensor, response interpreter and data analysis. These parts are presented below and are explained how each can be made for application of the Impedance Spectroscopy technique in a TCU.

1. Signal Generator

The signal input should be a sinusoidal wave. For this purpose, the best way to generate this type of signal is using a DDS. This could be added to a TCU by including a DDS electronic chip, like the AD9838, normally controlled by serial communications, like SPI, UART or I^2C. This electronic device commonly outputs waves with frequencies of up to a few megahertz, which is enough for this application.

A PWM could also be applied to generated a sine wave, but this solution presents some important bottlenecks to the application of the IS technique. First, the maximum frequency generated is very low, normally stopping at a few thousand hertz. Second, it consumes a lot of processing power from the CPU or microcontroller used, because it needs to keep updating the duty cycle of the PWM. Last, normally a filter needs to be add in the output of the signal to help generating the sine wave.

2. Sensor

The sensor part of a system is responsible to convert the physical changes or events in its environment and send electronic signals to other electronics, which can be measured and monitored. It should be composed by a capacitive sensor here, due to this type of sensor be less affected by environmental effects, compared to other types. In addition, it will presenta very simple construction, requiring just two electrodes to work, commonly in cylindrical shape.

3. Response Interpreter

A simple response interpreter could be just an Analog-to-Digital (ADC) port of a microcontroller. It reads the analog value, normally of voltage applied to the port, and transform this value in a digital number. A complex phasor can be achieved in conjunction with a Digital Signal Processing (DSP), which calculates a Fourier Transform, taking the comparison of the output and input signals for the time and voltage difference.

A better resolution is achieved with the response signal as a complex phasor, containing absolute value and phase. This way, it permits to determine the complex impedance phasor, giving more data to the analysis system.

4. Data Analysis

About the data analysis, this is the part where the data acquired from the sensor by the response interpreter is evaluated. It can be simple, like just ADC readings of the signal and comparison of these values to evaluate the impedance. As well, the data analysis can be very complex, considering much points of measurement, and taking into account other variables, as temperature, humidity, among others.

The simpler solution here is to compare the generated signal and the sensor response signal. The difference between these two signals should give the impedance presented in the sensor. Going to a more complete analysis, it would consider the phase of both signals, which would give the phase measurement and more data to analyze the system.

APPENDIX B – CALCULATION OF NUMBER OF TEST MEASUREMENTS

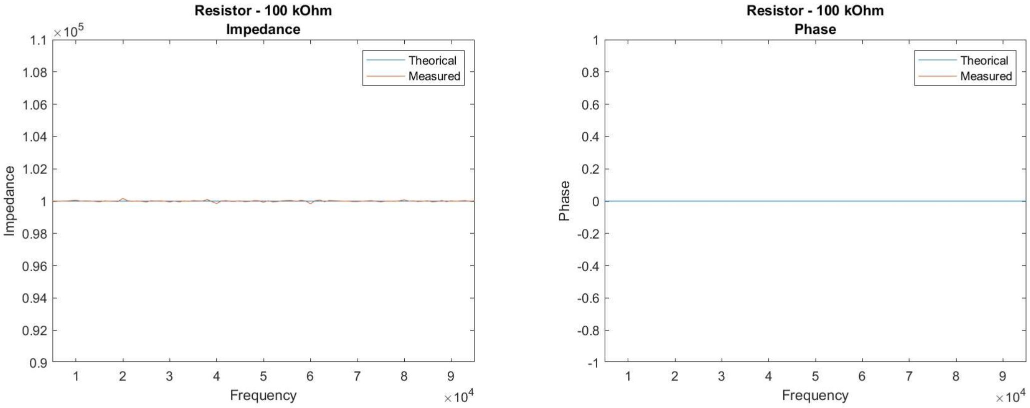
Variables (4)	Oil age	Oil level	Temperature	Water %
Number of points	2	11	8	10
Number of combinations = number of different tests	15	17		
Number of measurement repetitions	5			
Test Nº	Nº variables changing		Number of measurements per test	
1		Known values	20	
2		References	20	
3	1	Changing temperature	40	
4	1	Changing water percentage	50	
5	1	Changing oil level	55	
6	1	Changing oil age	10	
7	2	Changing oil age + oil level	110	
8	2	Changing oil age + temperature	80	
9	2	Changing oil age + water percentage	100	
10	2	Changing oil level + temperature	440	
11	2	Changing oil level + water percentage	550	
12	2	Changing temperature + water percentage	400	1875
13	3	Changing oil age + oil level + temperature	880	
14	3	Changing oil age + oil level + water percentage	1100	
15	3	Changing oil age + temperature + water percentage	800	
16	3	Changing oil level + temperature + water percentage	4400	
17	4	Changing oil age + oil level + temperature + water percentage	8800	
			17855	

Oil age	Oil level (ml)	Temperature (ºC)	Water %
New	0	-20	0,00%
Used (350h)	10	-10	0,01%
	20	0	0,02%
	30	10	0,05%
	40	20	0,10%
	50	30	0,20%
	60	40	0,50%
	70	50	1,00%
	80		2,00%
	90		3,00%
	100		

APPENDIX C – PRELIMINARY TESTS - GRAPHS

C.1 RESISTOR - 100 KΩ

Figure 31: Impedance and Phase measurements - 100 kΩ resistor.



Source: Own author.

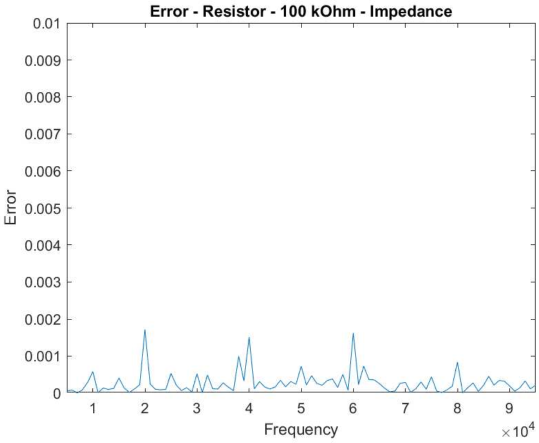
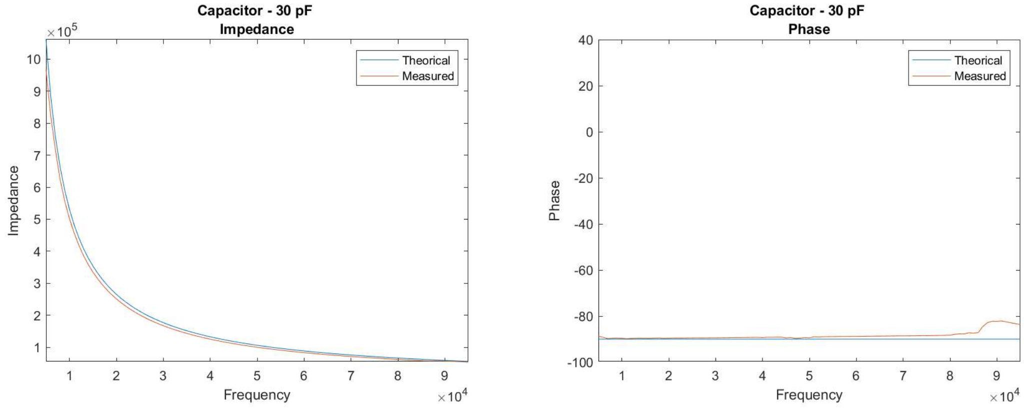


Figure 32: Error in Impedance measurement - 100 kΩ resistor.

Source: Own author.

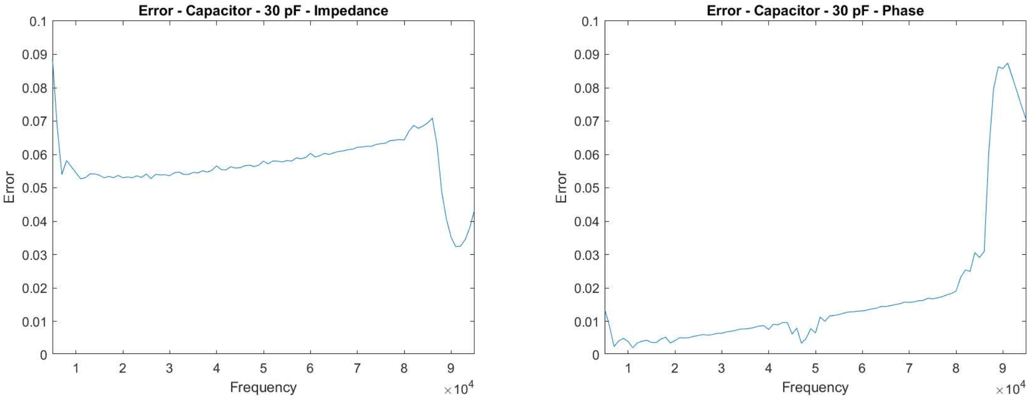
C.2 CAPACITOR - 30 PF

Figure 33: Impedance and phase measurements - 30 pF capacitor.



Source: Own author.

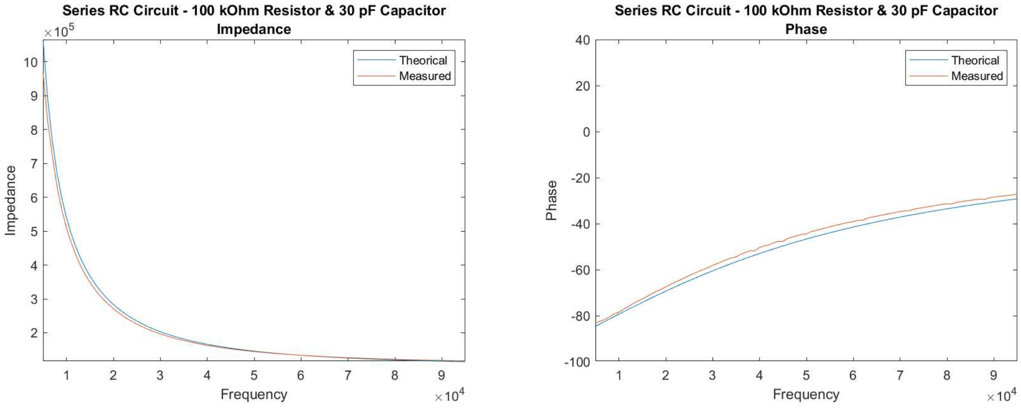
Figure 34: Error of impedance and phase measurements - 30 pF capacitor.



Source: Own author.

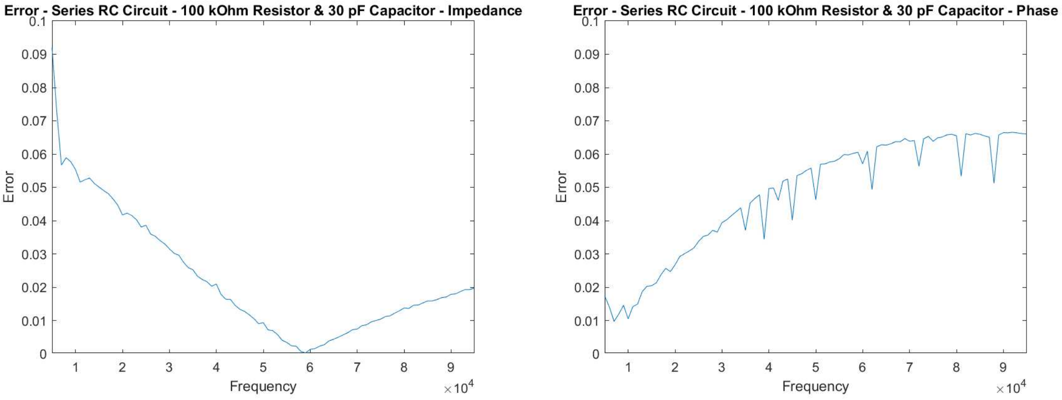
C.3 SERIES RC CIRCUIT

Figure 35: Impedance and phase measurements - Series RC circuit - 100 kΩ resistor and 30 pF capacitor.



Source: Own author.

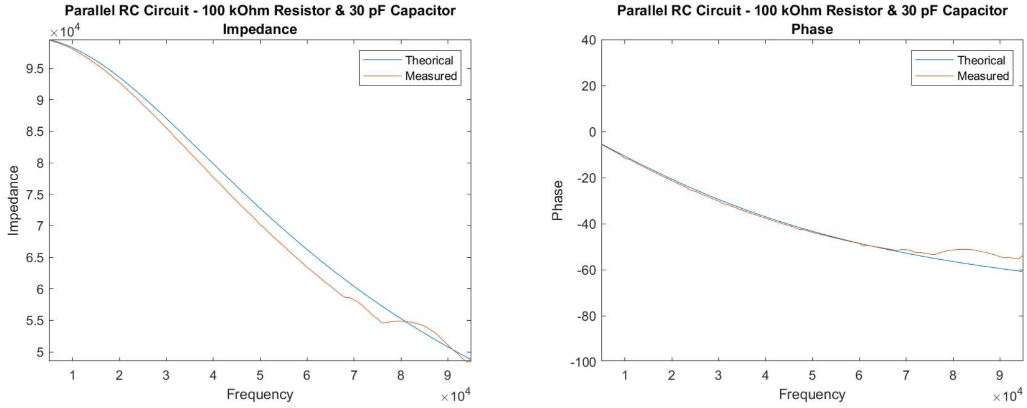
Figure 36: Error of impedance and phase measurements - Series RC circuit - 100 kΩ resistor and 30 pF capacitor.



Source: Own author.

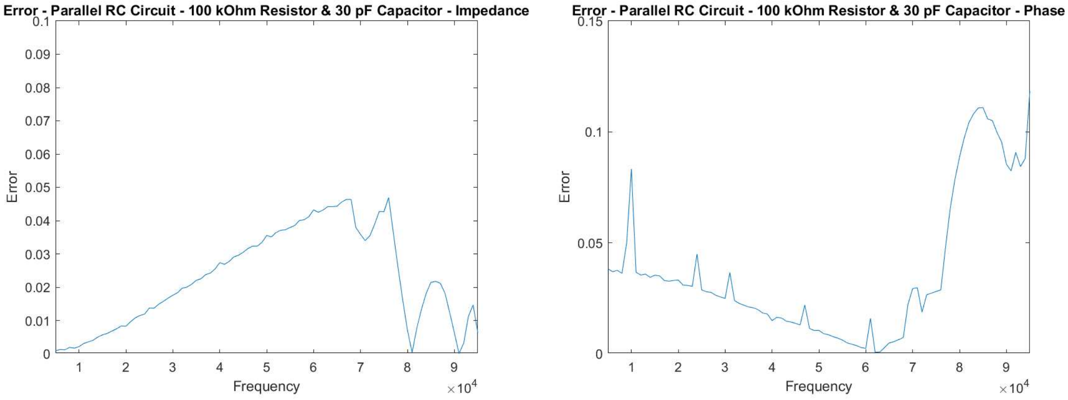
C.4 PARALLEL RC CIRCUIT

Figure 37: Impedance and phase measurements - Parallel RC circuit - 100 kΩ resistor and 30 pF capacitor.



Source: Own author.

Figure 38: Error of impedance and phase measurements - Parallel RC circuit - 100 kΩ resistor and 30 pF capacitor.

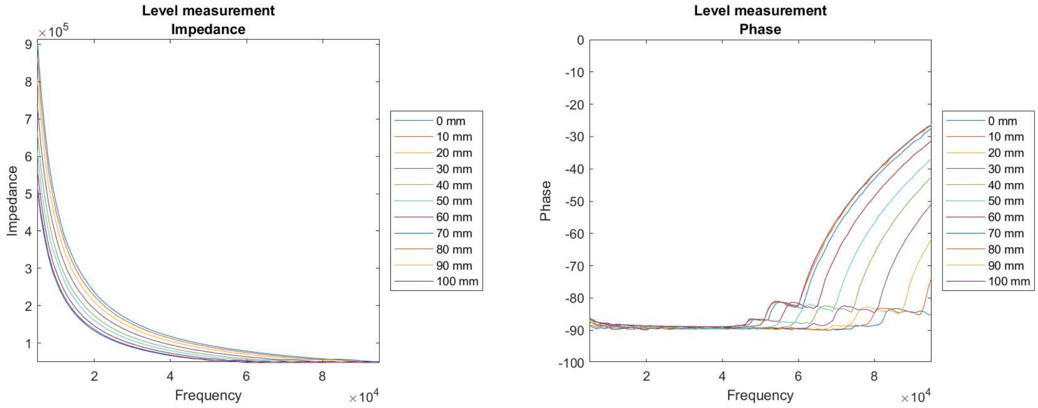


Source: Own author.

APPENDIX D – GRAPHS OF TESTS CHANGING ONE VARIABLE

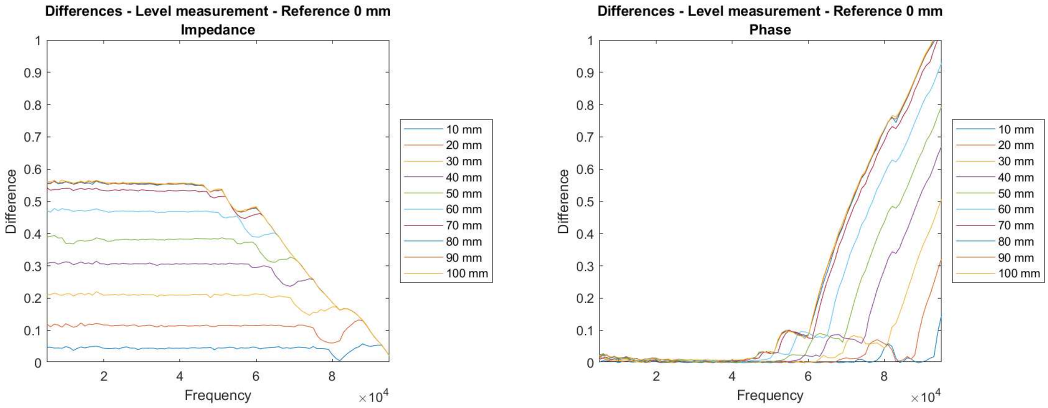
D.1 LEVEL

Figure 39: Level - Impedance and phase measurements.



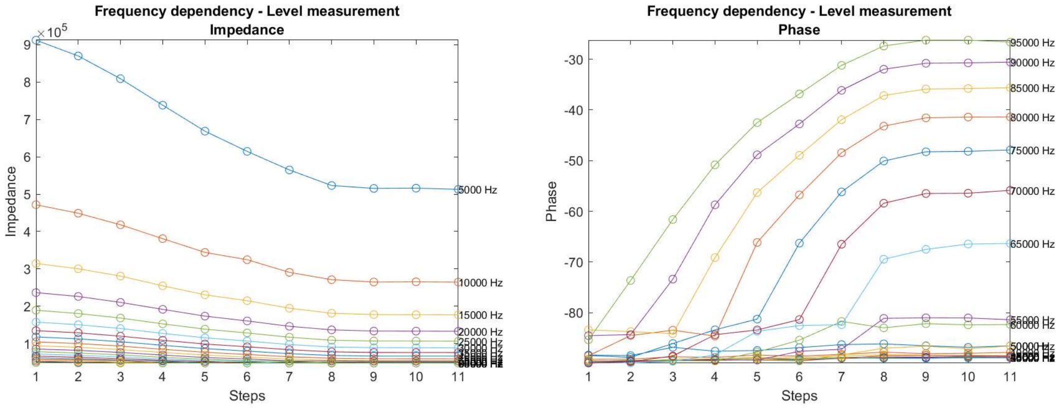
Source: Own author.

Figure 40: Level - Differences in impedance and phase measurements - Reference 0 mm.



Source: Own author.

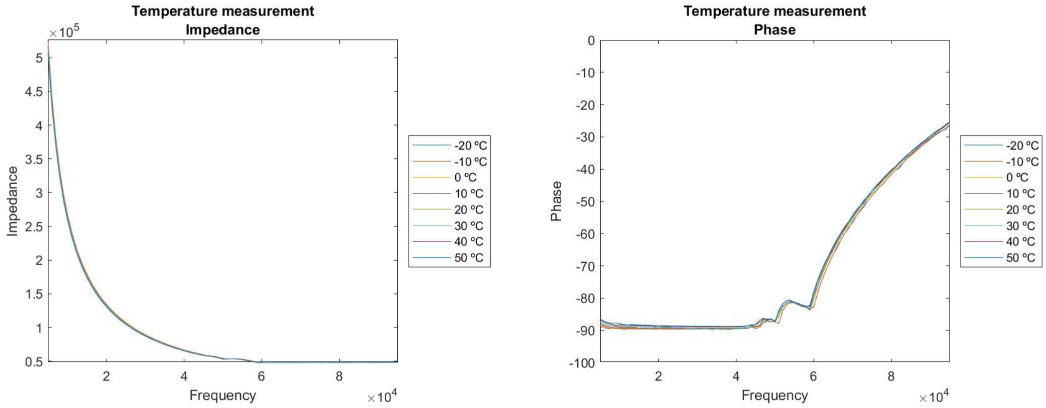
Figure 41: Level - Frequency dependency of impedance and phase measurements.



Source: Own author.

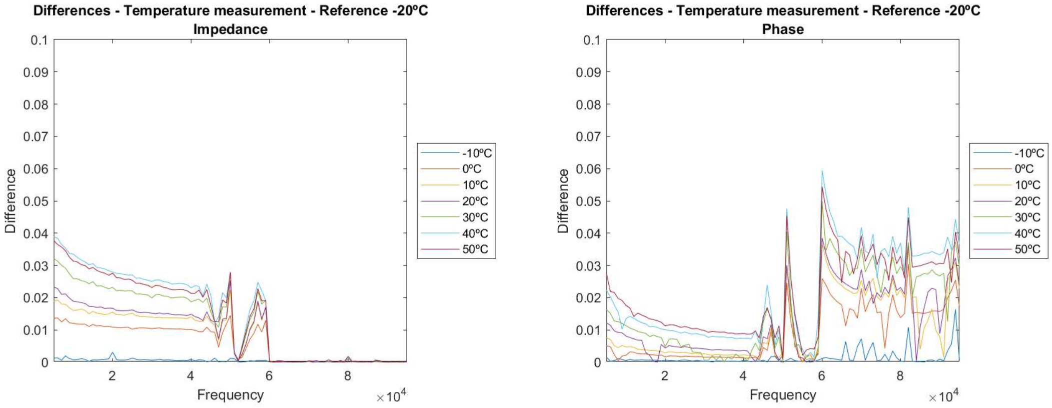
D.2 TEMPERATURE

Figure 42: Temperature - Impedance and phase measurements.



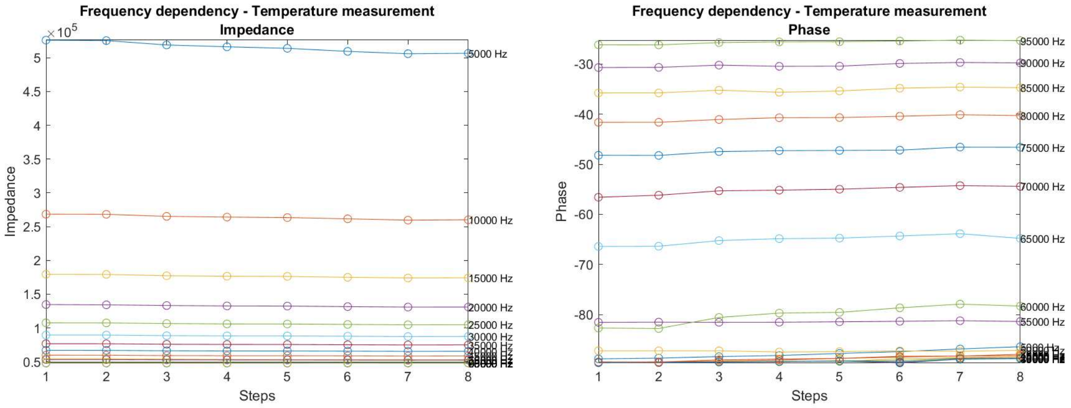
Source: Own author.

Figure 43: Temperature - Differences in impedance and phase measurements - Reference -20 °C.



Source: Own author.

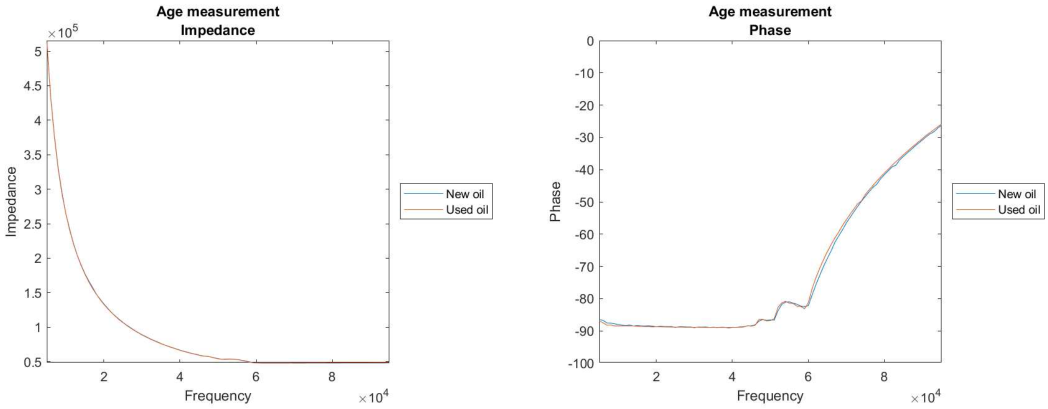
Figure 44: Temperature - Frequency dependency of impedance and phase measurements.



Source: Own author.

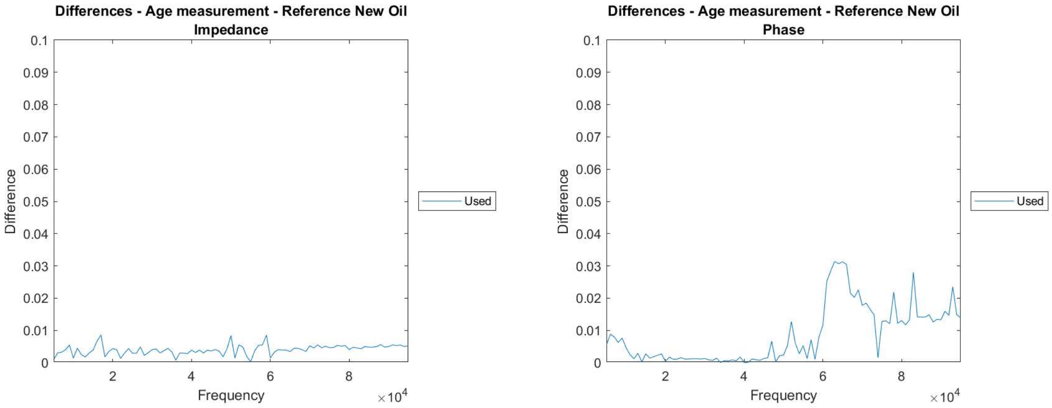
D.3 AGE

Figure 45: Age - Impedance and phase measurements.



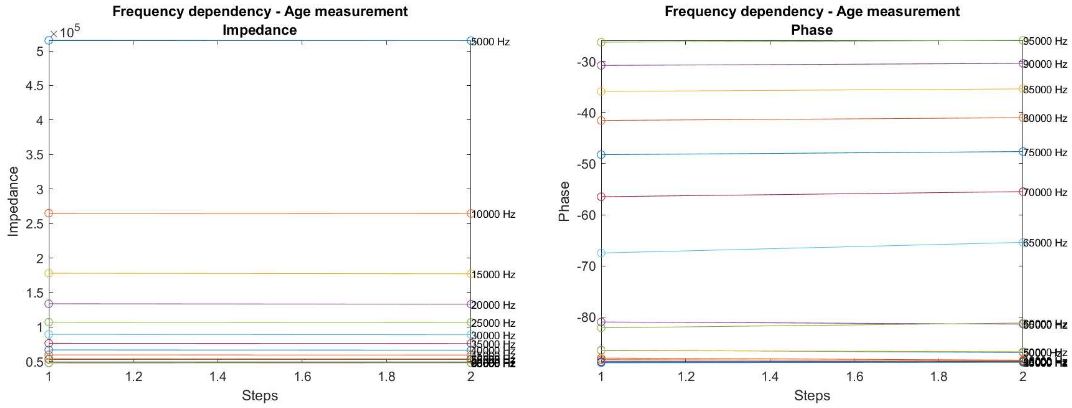
Source: Own author.

Figure 46: Age - Differences in impedance and phase measurements - Reference New oil.



Source: Own author.

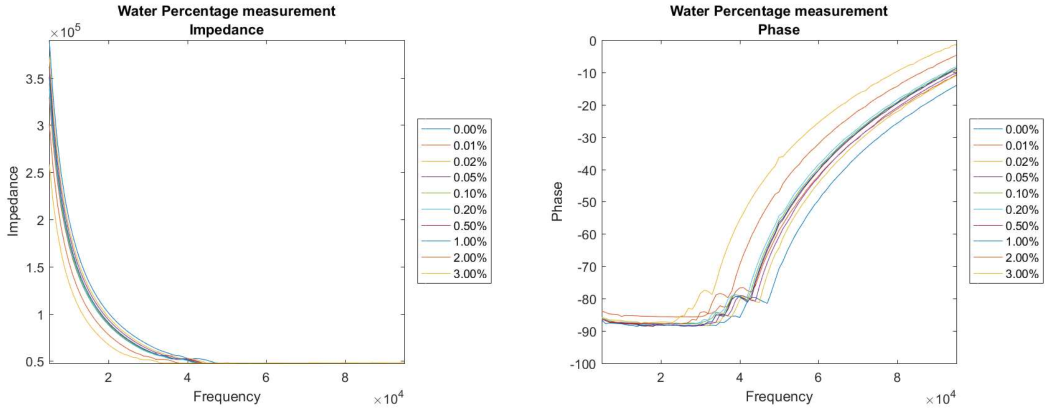
Figure 47: Age - Frequency dependency of impedance and phase measurements.



Source: Own author.

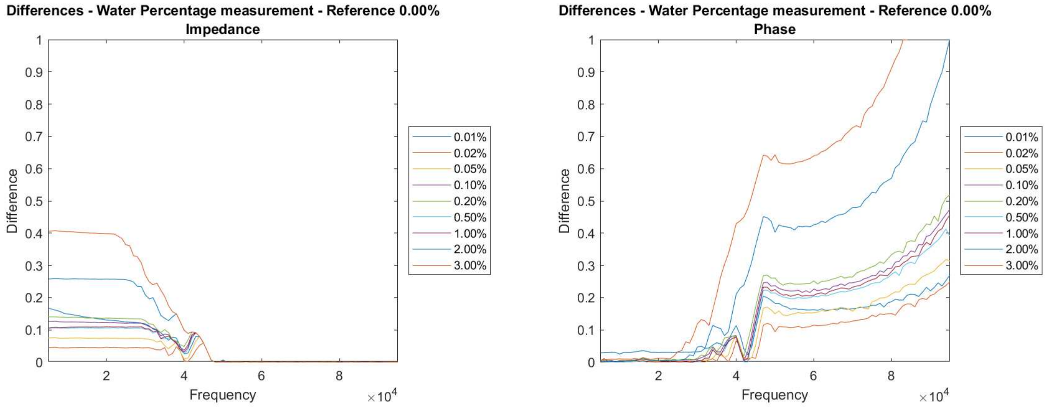
D.4 WATER PERCENTAGE

Figure 48: Water Percentage - Impedance and phase measurements.



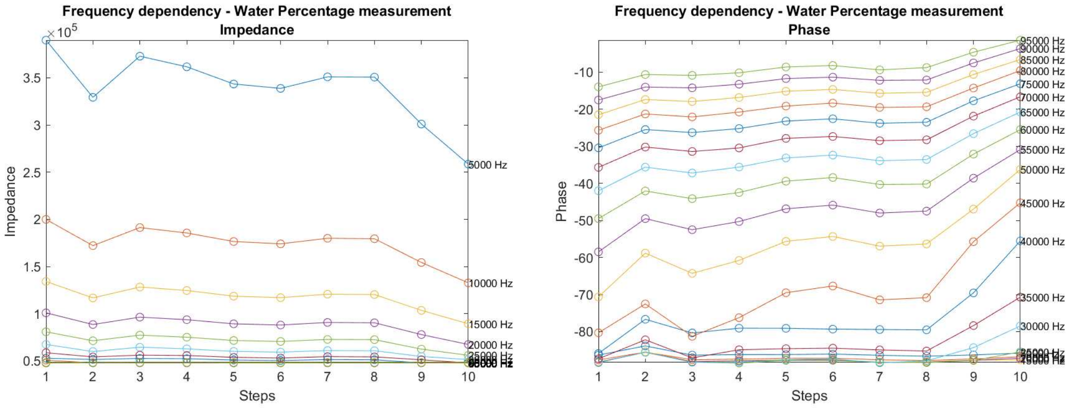
Source: Own author.

Figure 49: Water Percentage - Differences in impedance and phase measurements - Reference 0.00%.



Source: Own author.

Figure 50: Water Percentage - Frequency dependency of impedance and phase measurements.

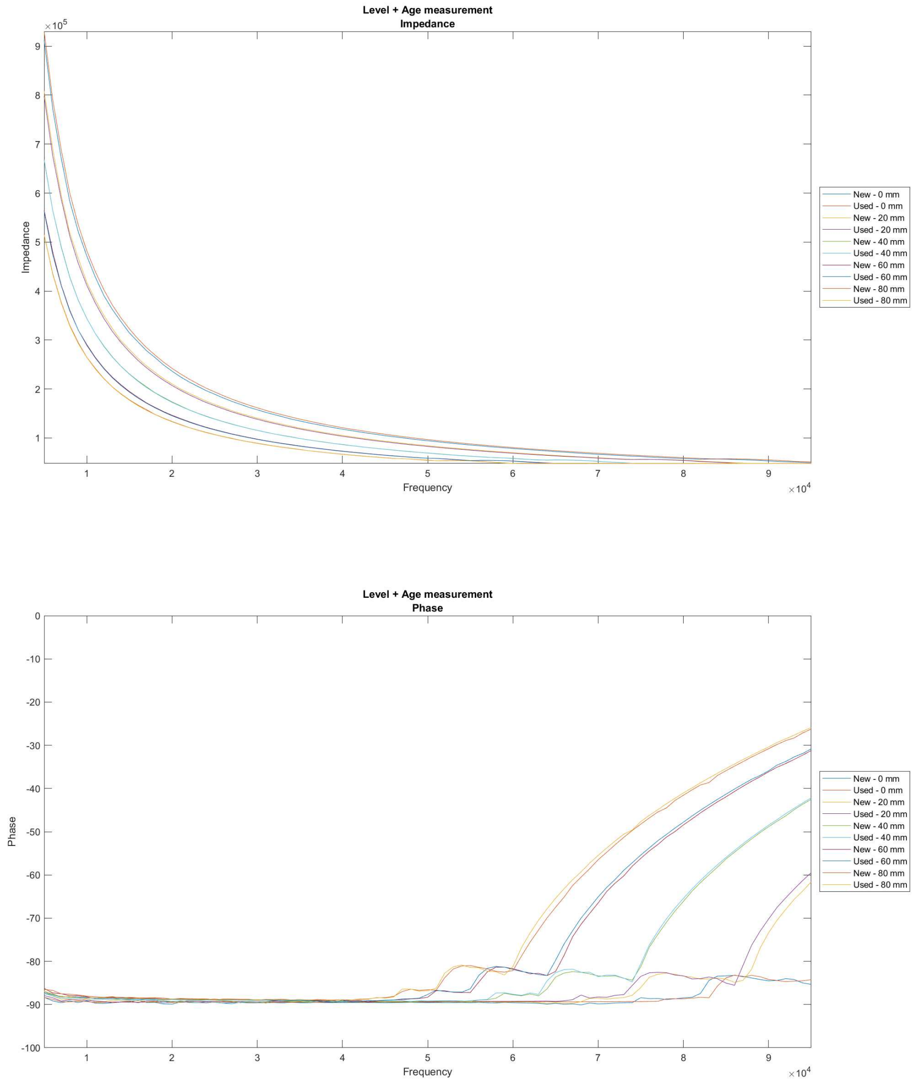


Source: Own author.

APPENDIX E – GRAPHS OF TESTS CHANGING TWO VARIABLES

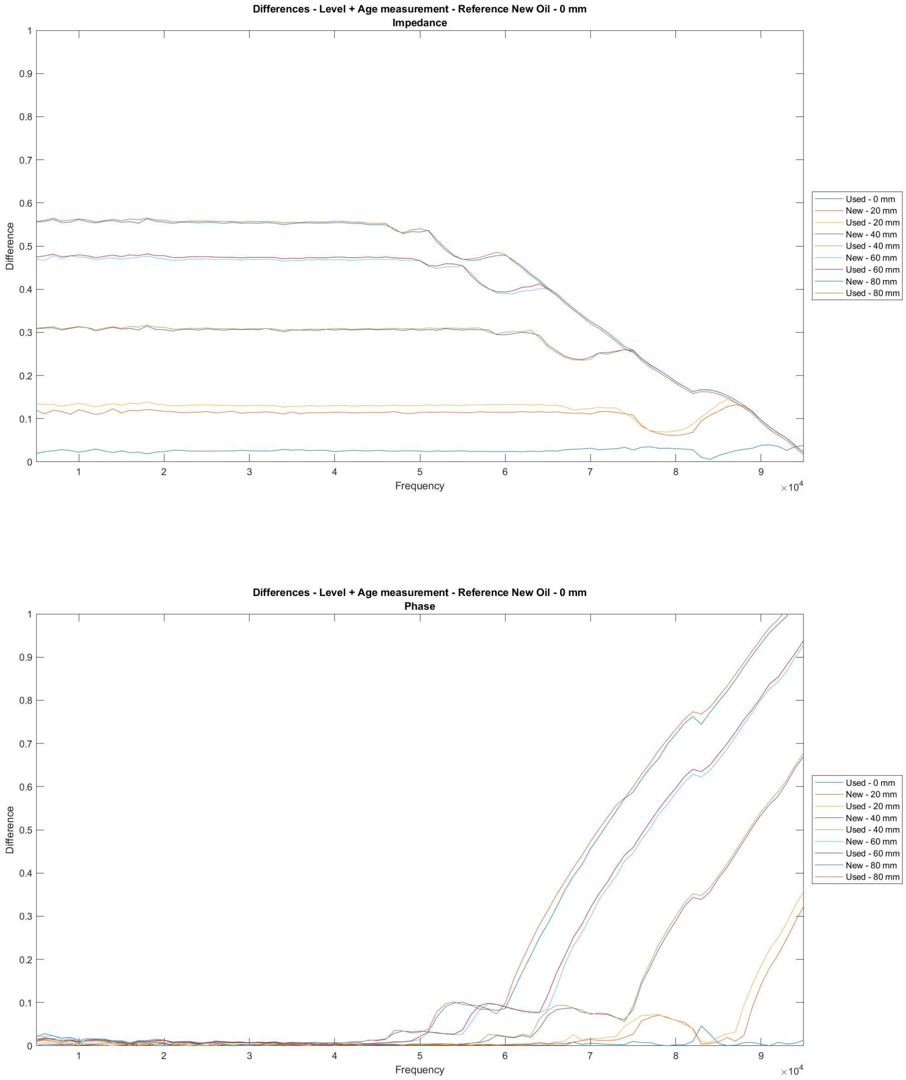
E.1 LEVEL + AGE

Figure 51: Level + Age - Impedance and phase measurements.



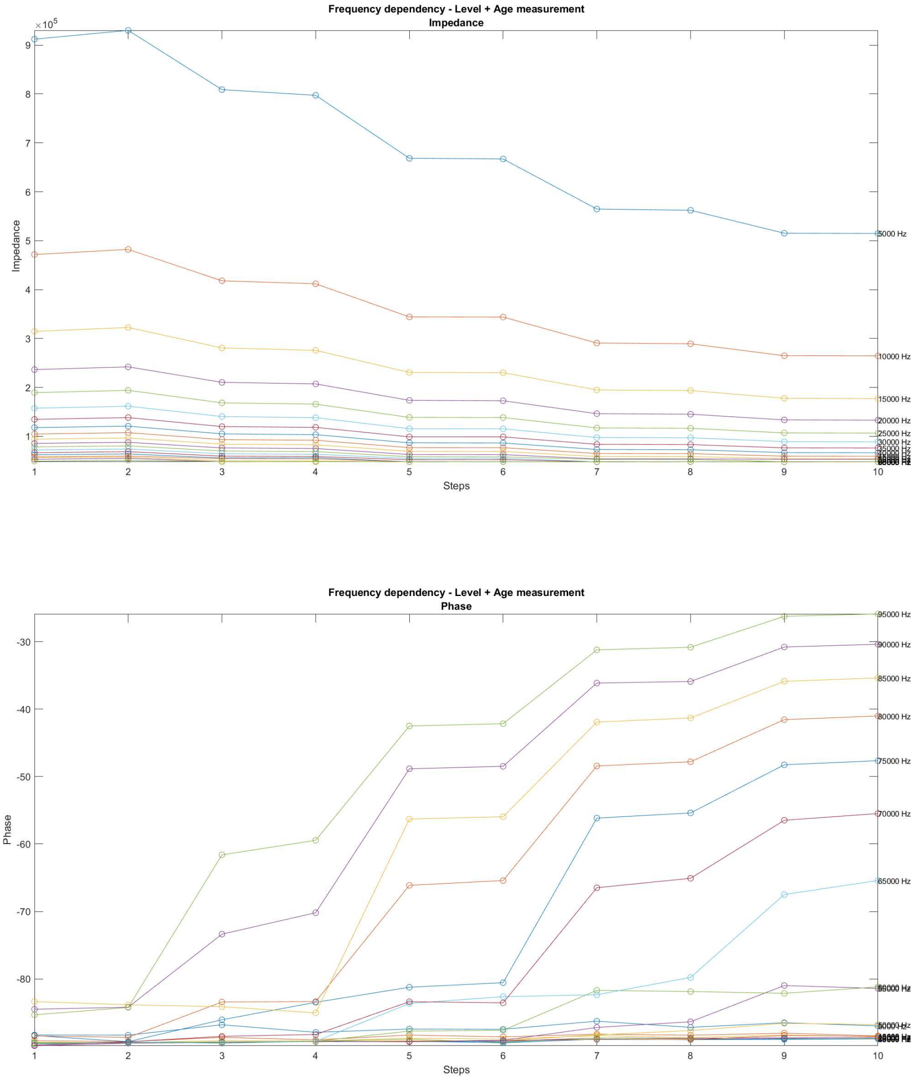
Source: Own author.

Figure 52: Level + Age - Differences in impedance and phase measurements - Reference 0 mm and new oil.



Source: Own author.

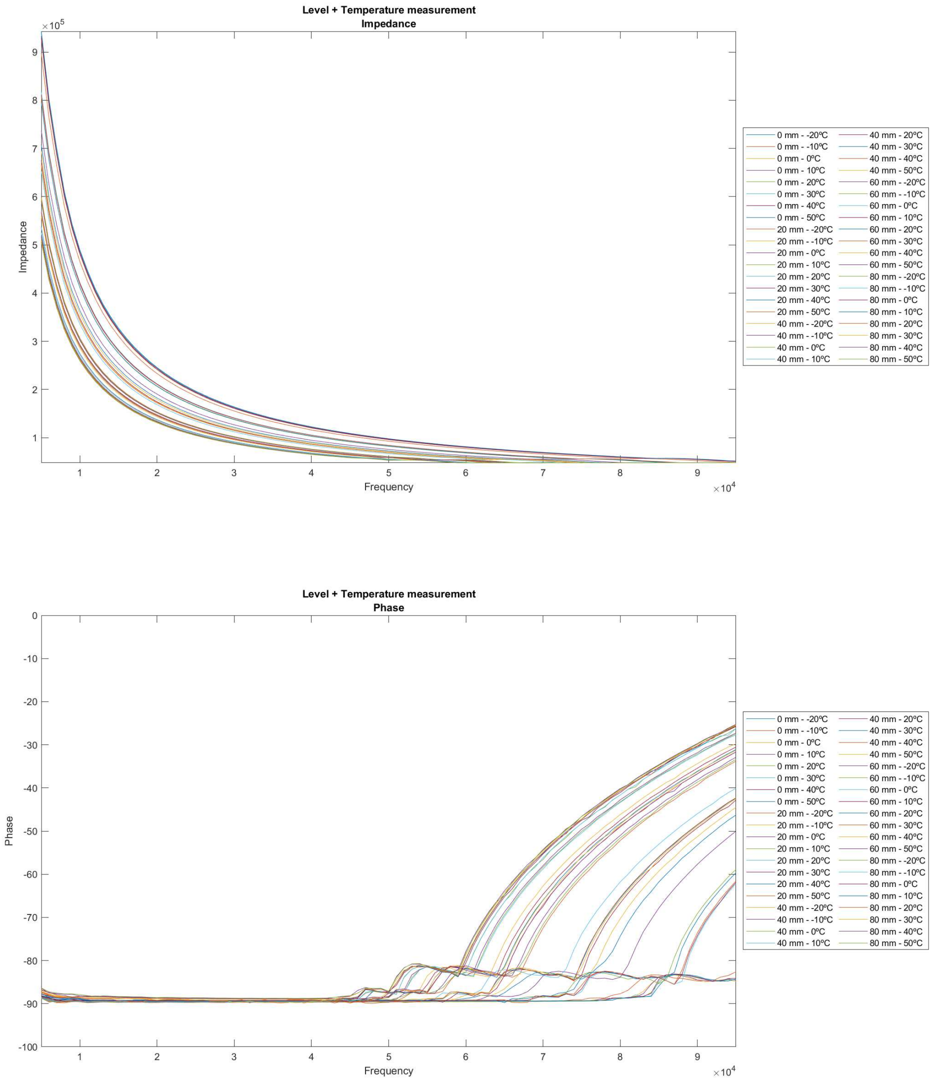
Figure 53: Level + Age - Frequency dependency of impedance and phase measurements.



Source: Own author.

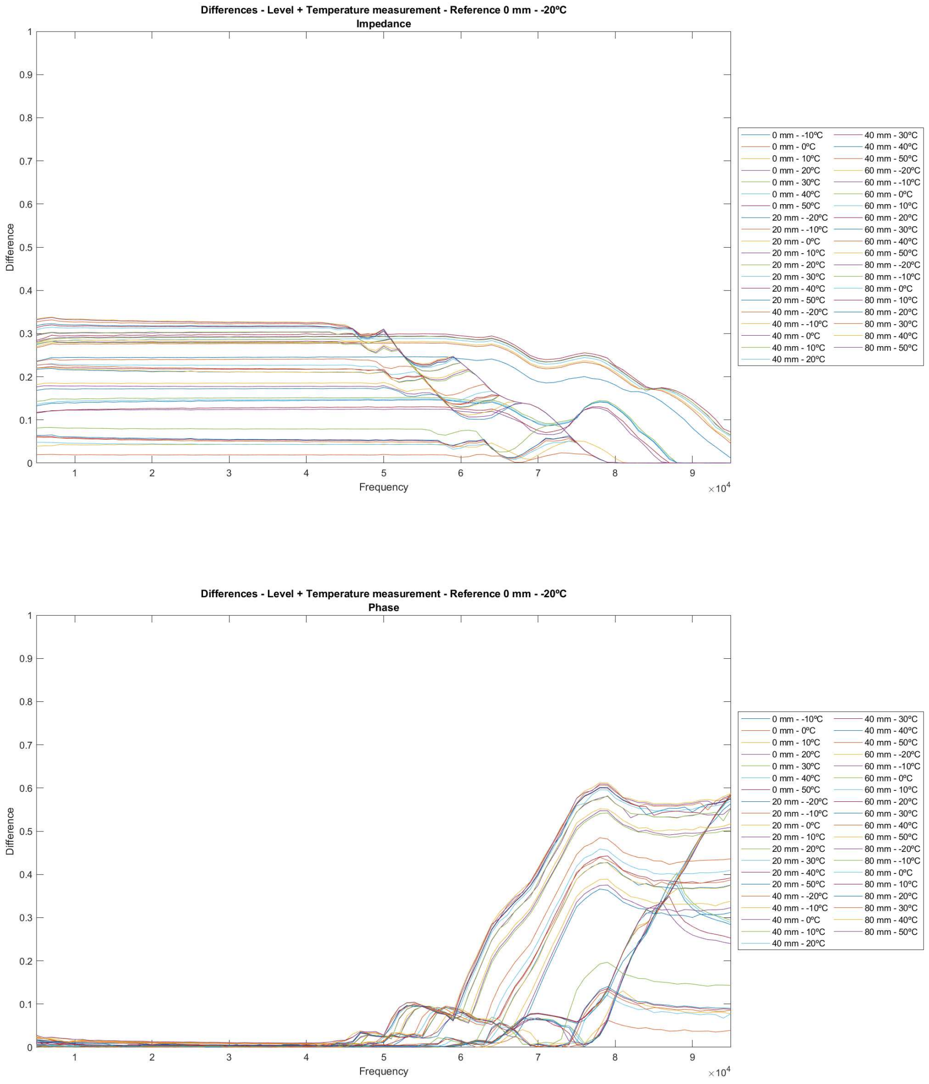
E.2 LEVEL + TEMPERATURE

Figure 54: Level + Temperature - Impedance and phase measurements.



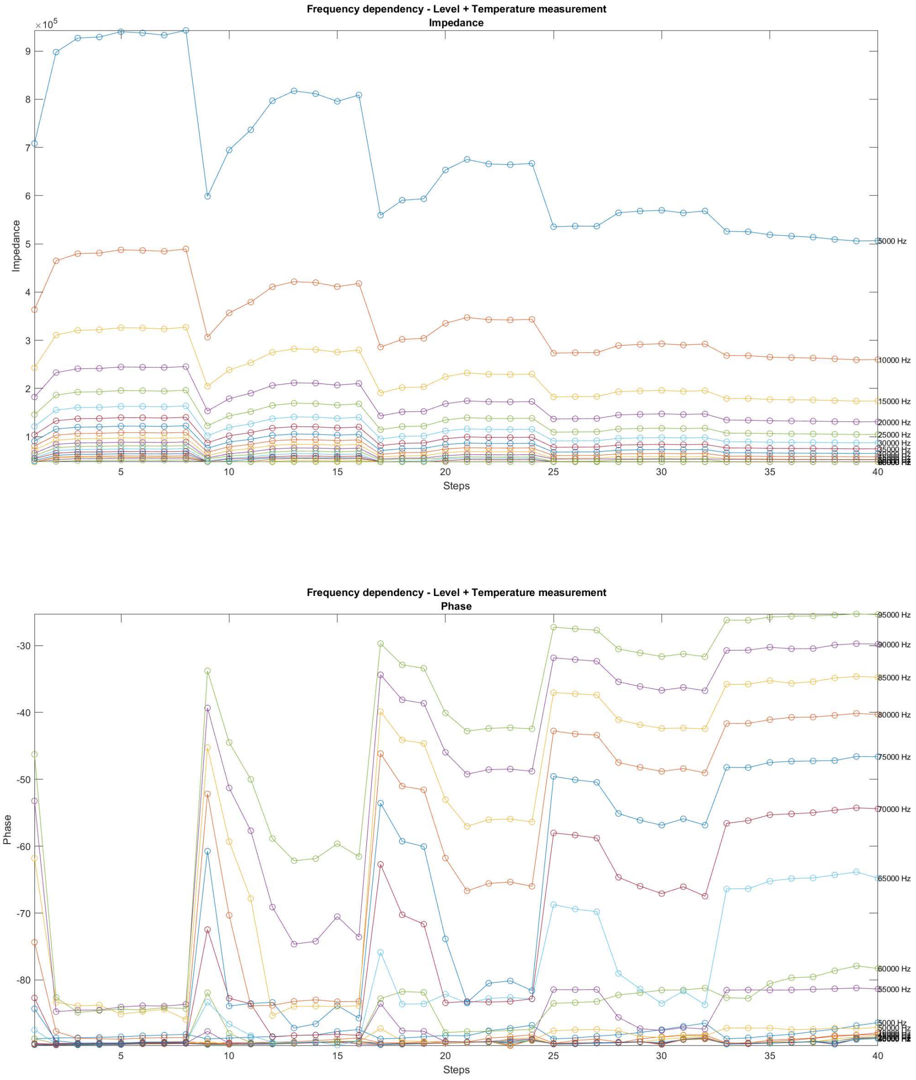
Source: Own author.

Figure 55: Level + Temperature - Differences in impedance and phase measurements - Reference 0 mm and -20 °C.



Source: Own author.

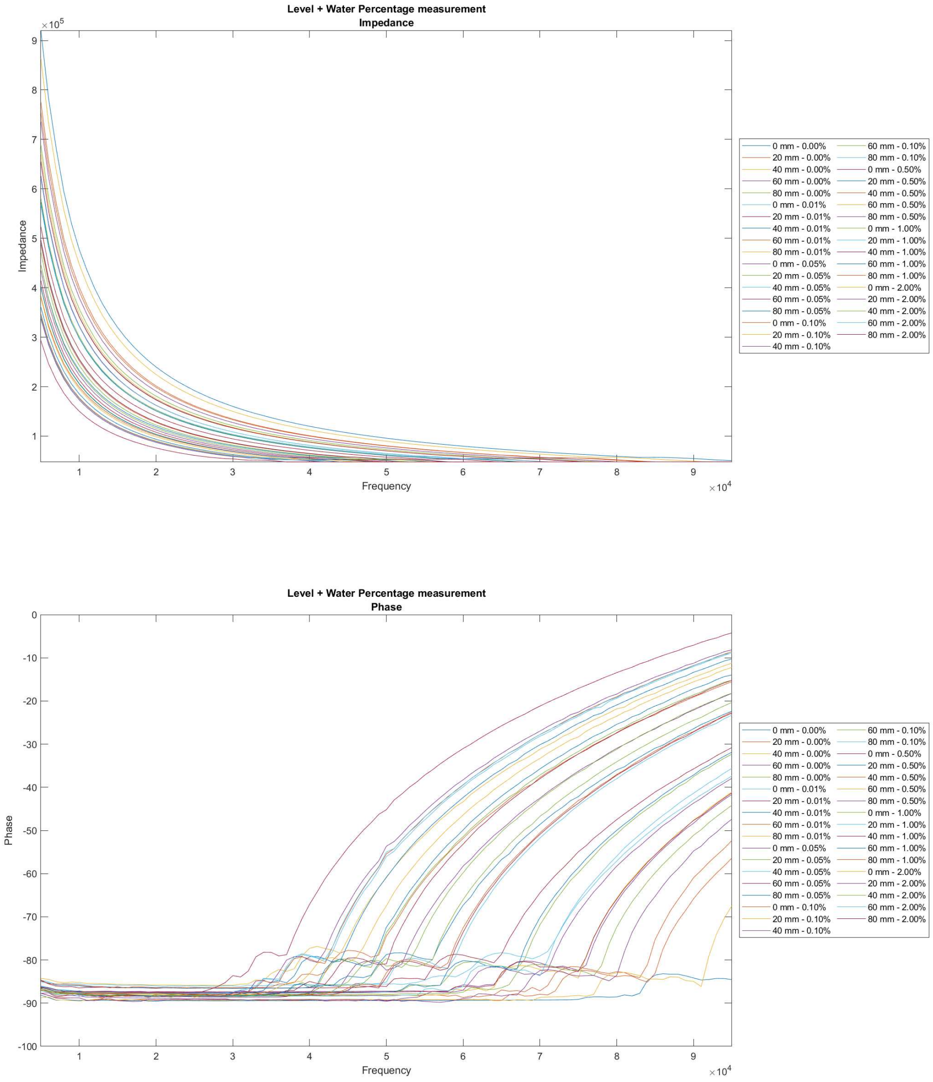
Figure 56: Level + Temperature - Frequency dependency of impedance and phase measurements.



Source: Own author.

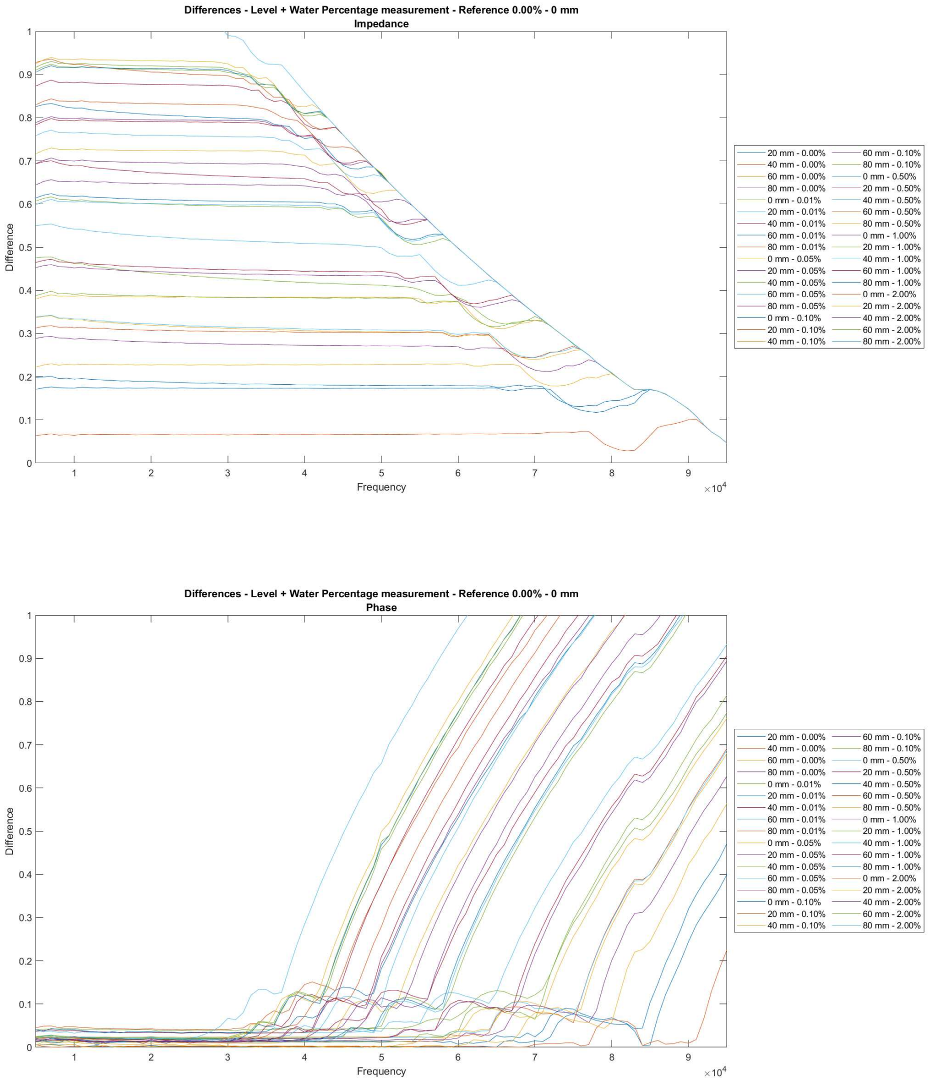
E.3 LEVEL + WATER PERCENTAGE

Figure 57: Level + Water Percentage - Impedance and phase measurements.



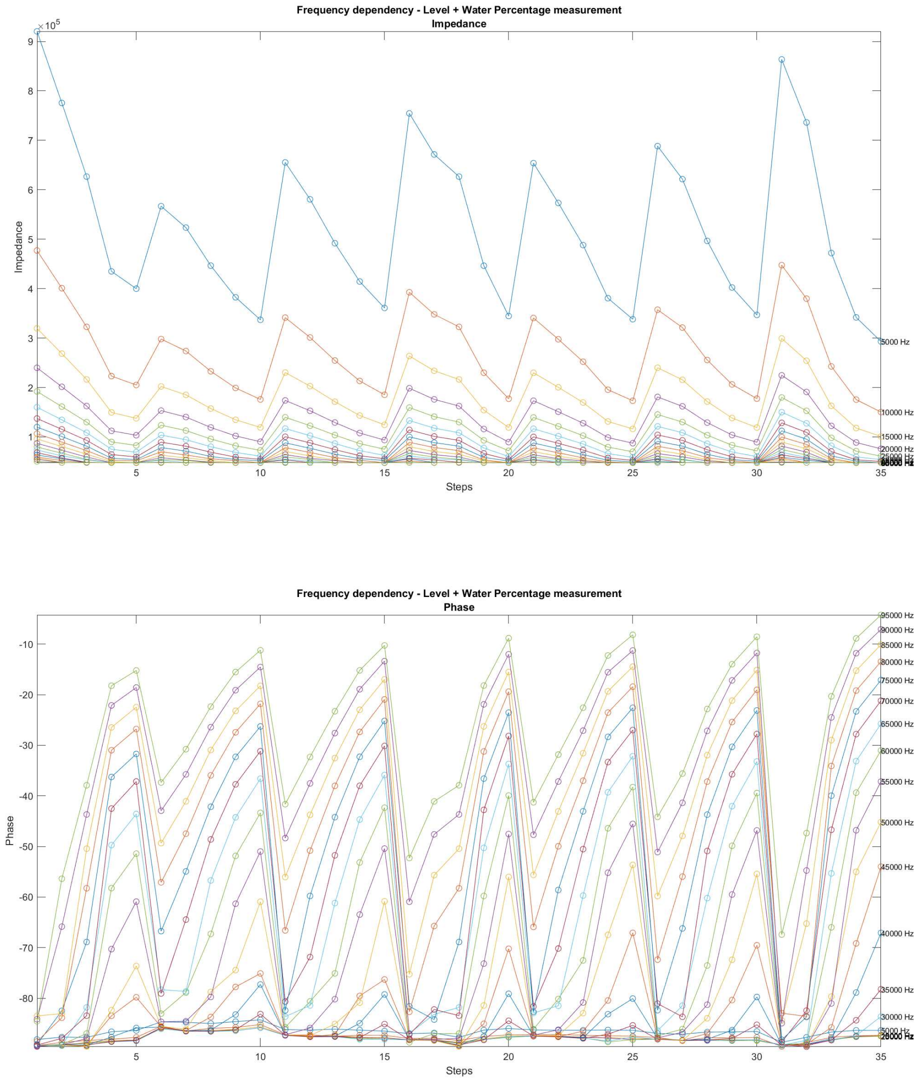
Source: Own author.

Figure 58: Level + Water Percentage - Differences in impedance and phase measurements - Reference 0 mm and 0.00%.



Source: Own author.

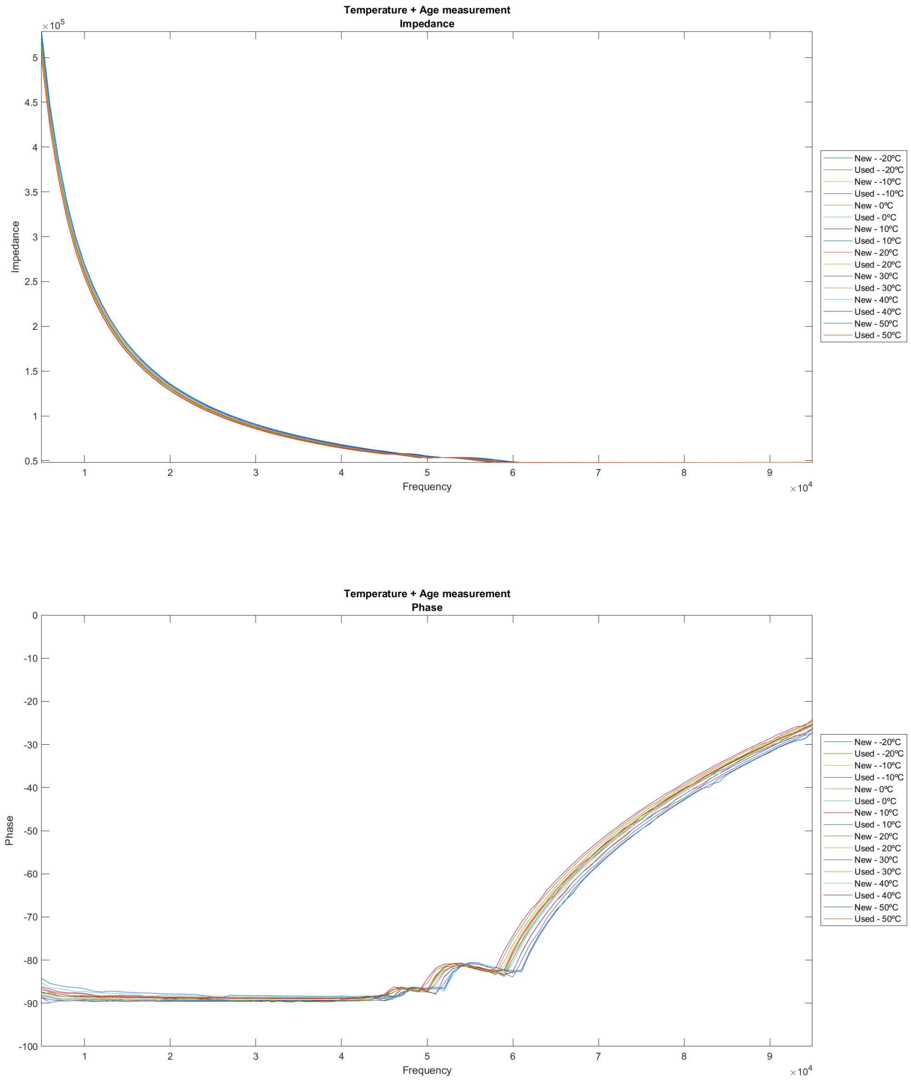
Figure 59: Level + Water Percentage - Frequency dependency of impedance and phase measurements.



Source: Own author.

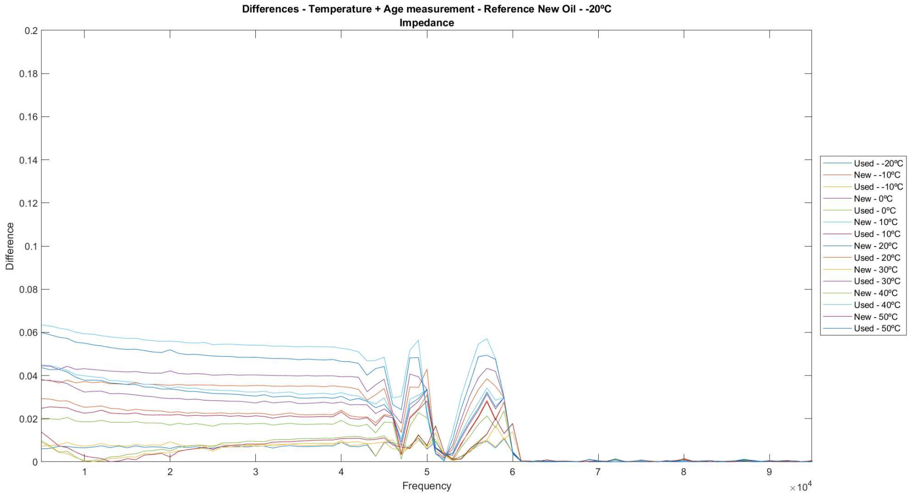
E.4 TEMPERATURE + AGE

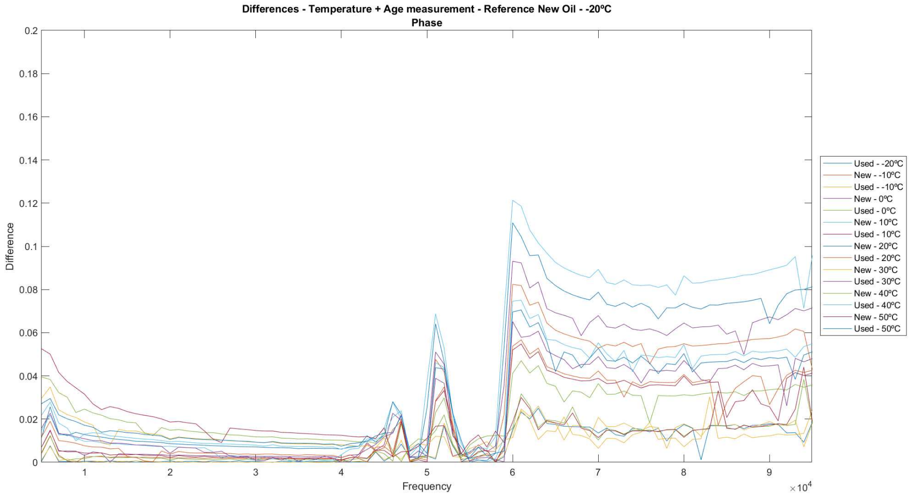
Figure 60: Temperature + Age - Impedance and phase measurements.



Source: Own author.

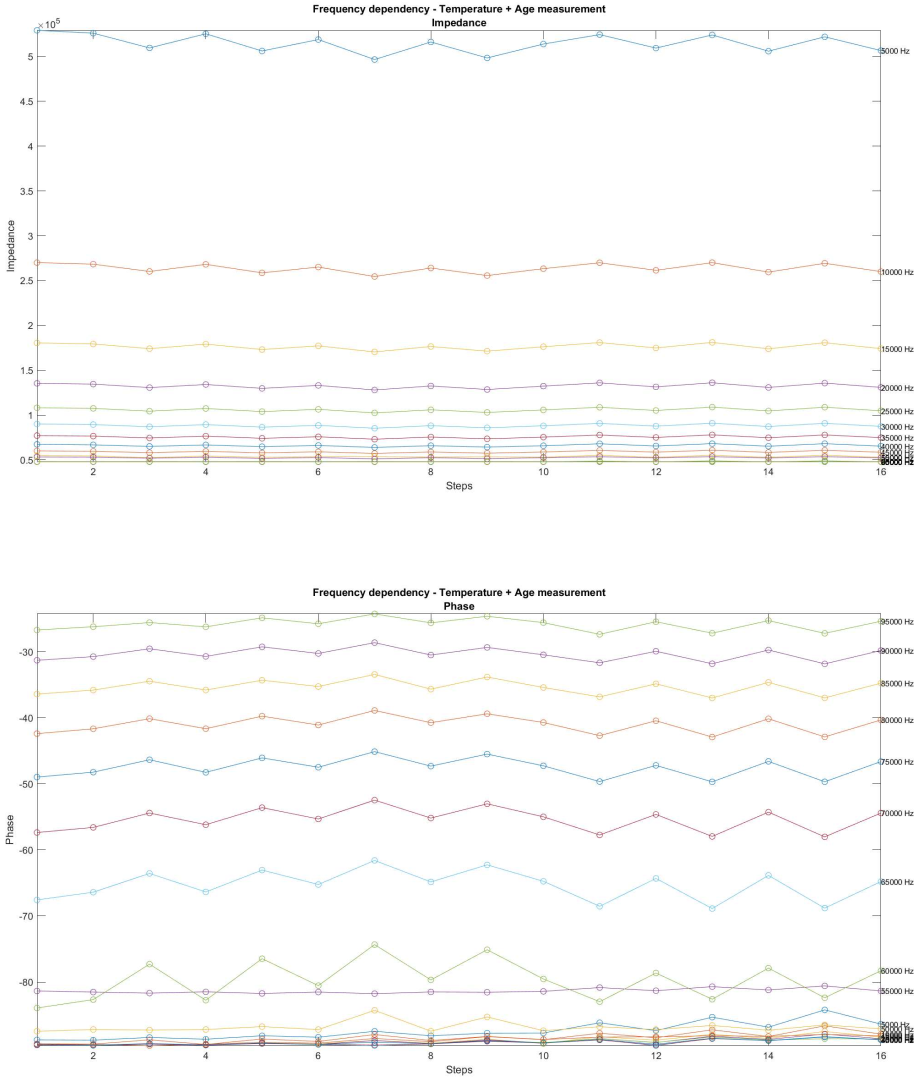
Figure 61: Temperature + Age - Differences in impedance and phase measurements - Reference -20 °C and new oil.





Source: Own author.

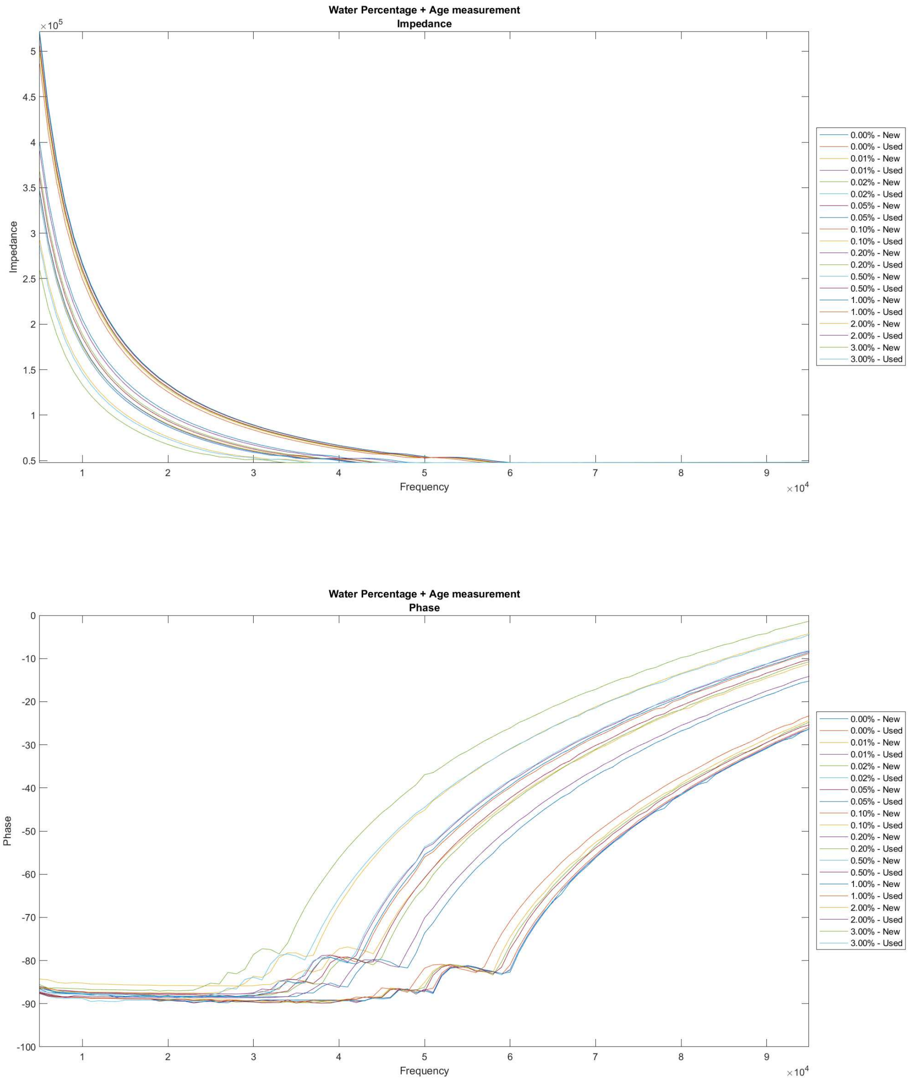
Figure 62: Temperature + Age - Frequency dependency of impedance and phase measurements.



Source: Own author.

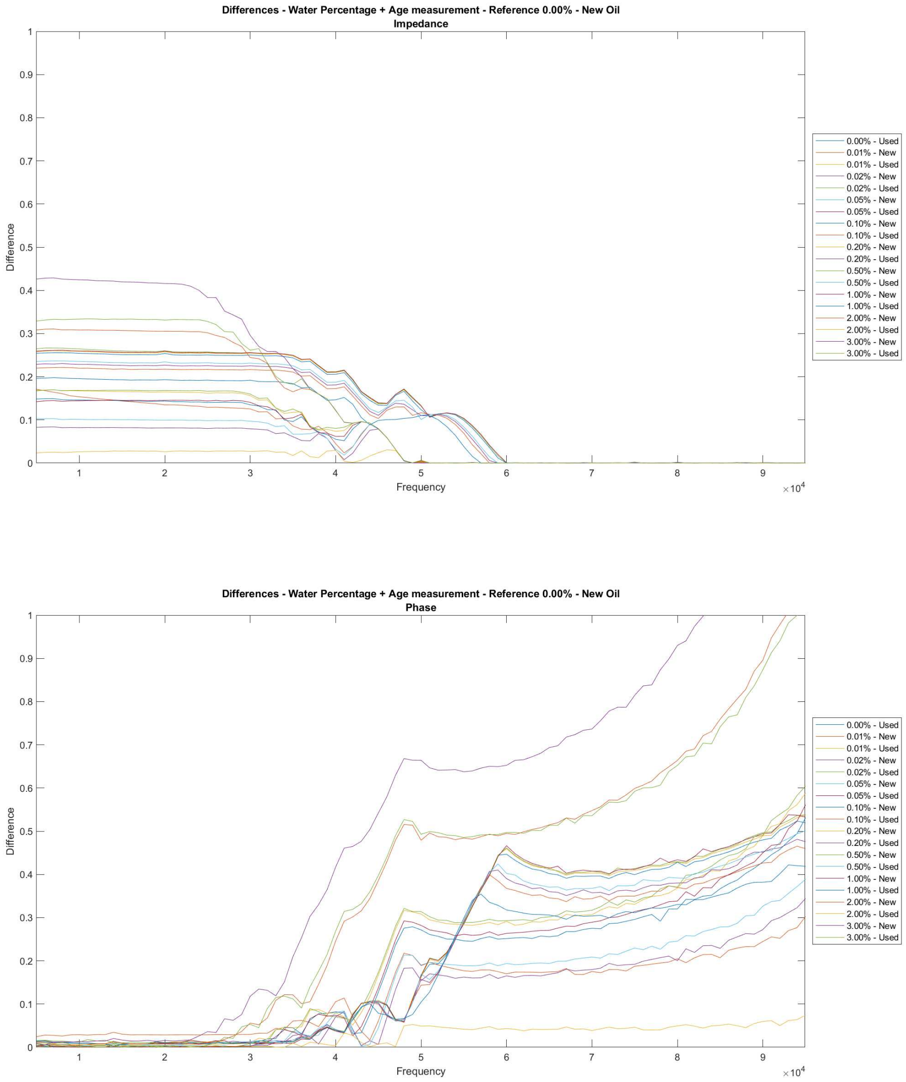
E.5 WATER PERCENTAGE + AGE

Figure 63: Water Percentage + Age - Impedance and phase measurements.



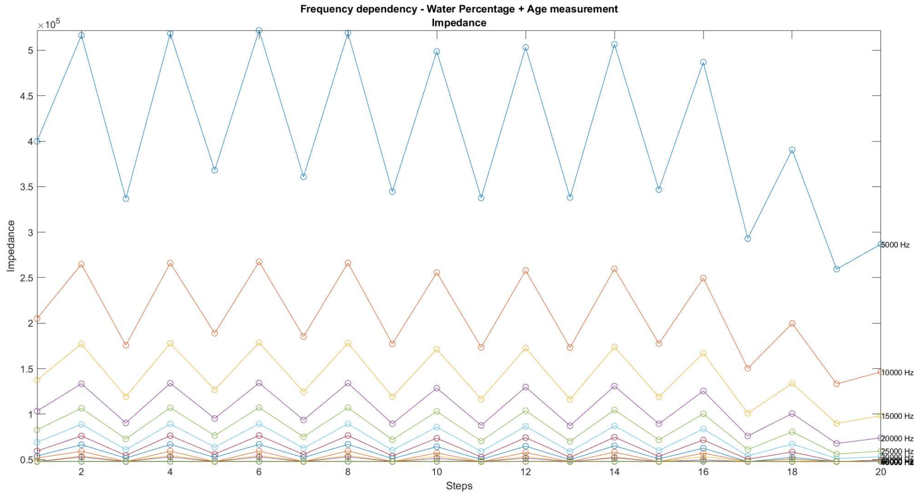
Source: Own author.

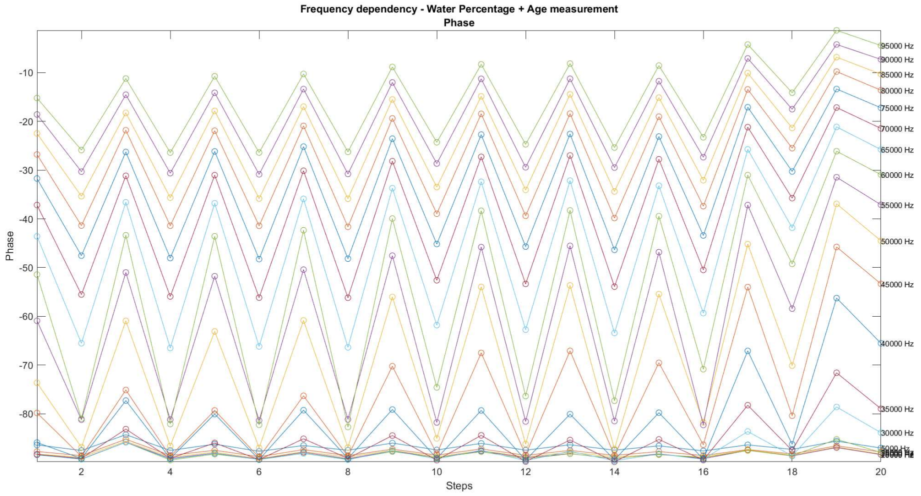
Figure 64: Water Percentage + Age - Differences in impedance and phase measurements - Reference 0.00% and new oil.



Source: Own author.

Figure 65: Water Percentage + Age - Frequency dependency of impedance and phase measurements.

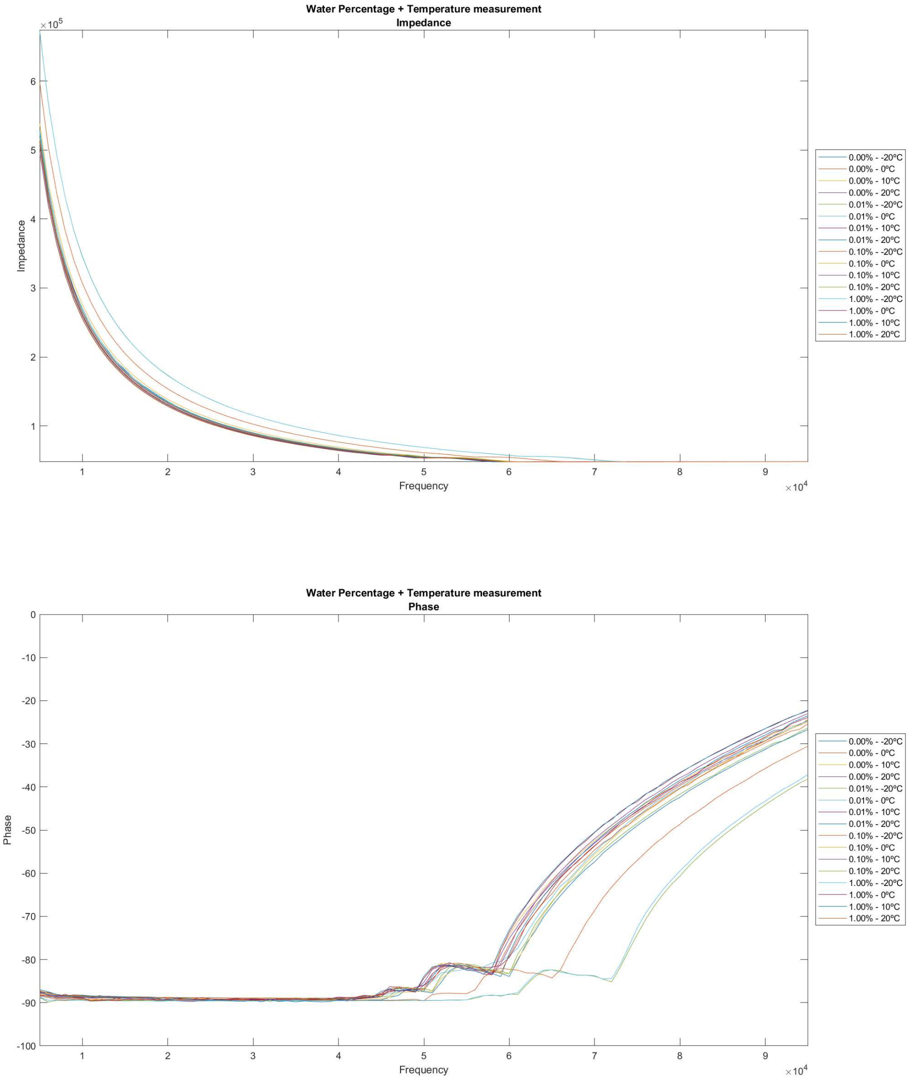




Source: Own author.

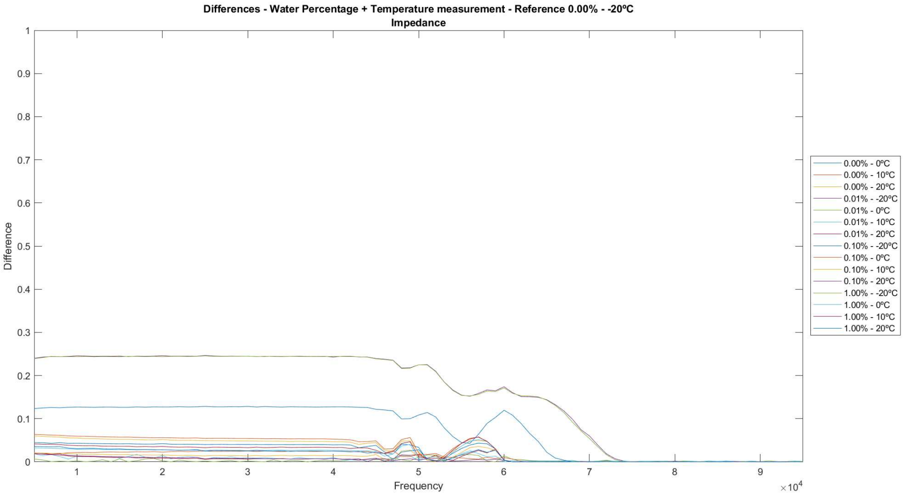
E.6 WATER PERCENTAGE + TEMPERATURE

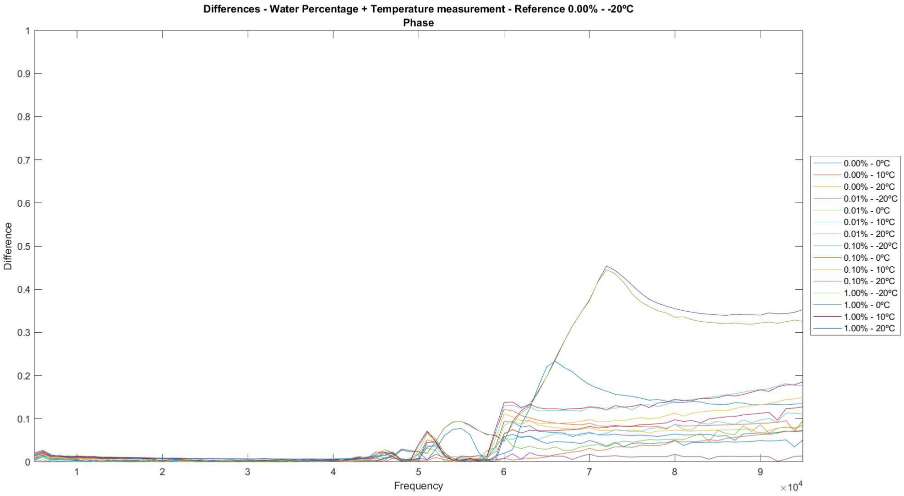
Figure 66: Water Percentage + Temperature - Impedance and phase measurements.



Source: Own author.

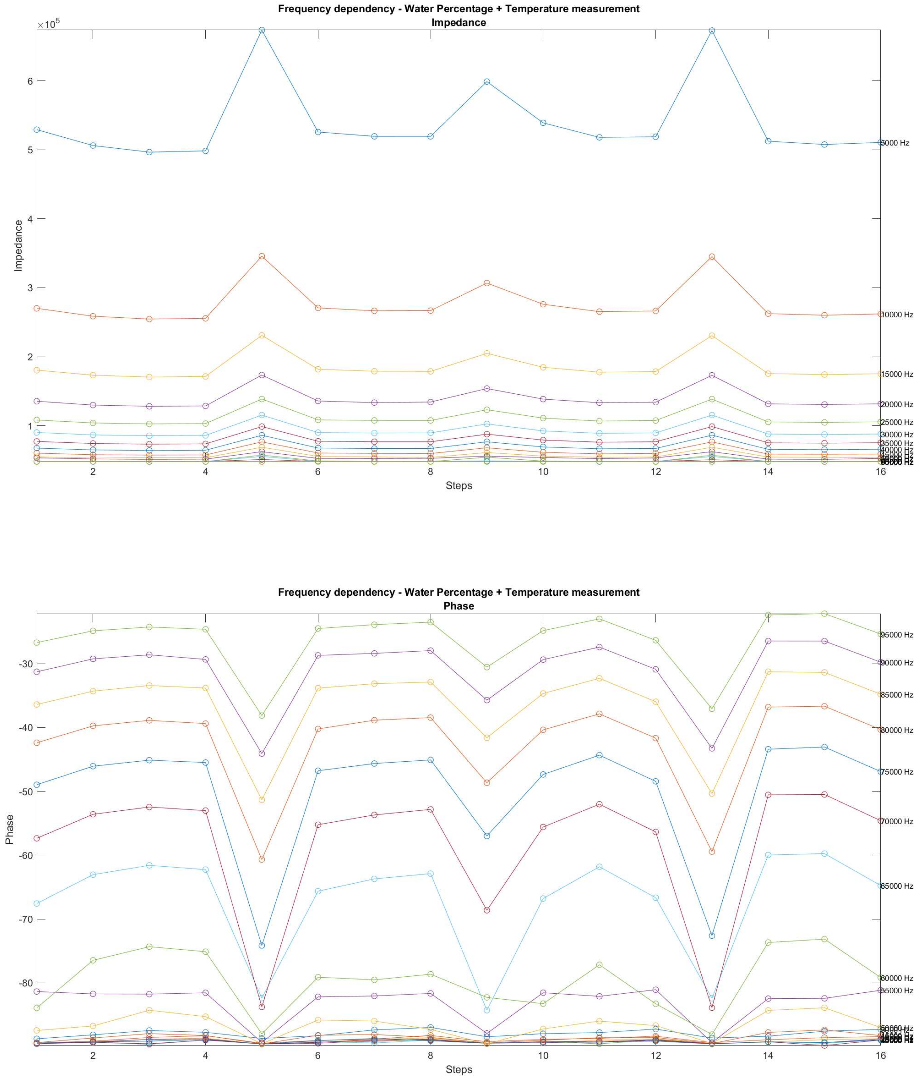
Figure 67: Water Percentage + Temperature - Differences in impedance and phase measurements - Reference 0.00% and -20 °C.





Source: Own author.

Figure 68: Water Percentage + Temperature - Frequency dependency of impedance and phase measurements.



Source: Own author.