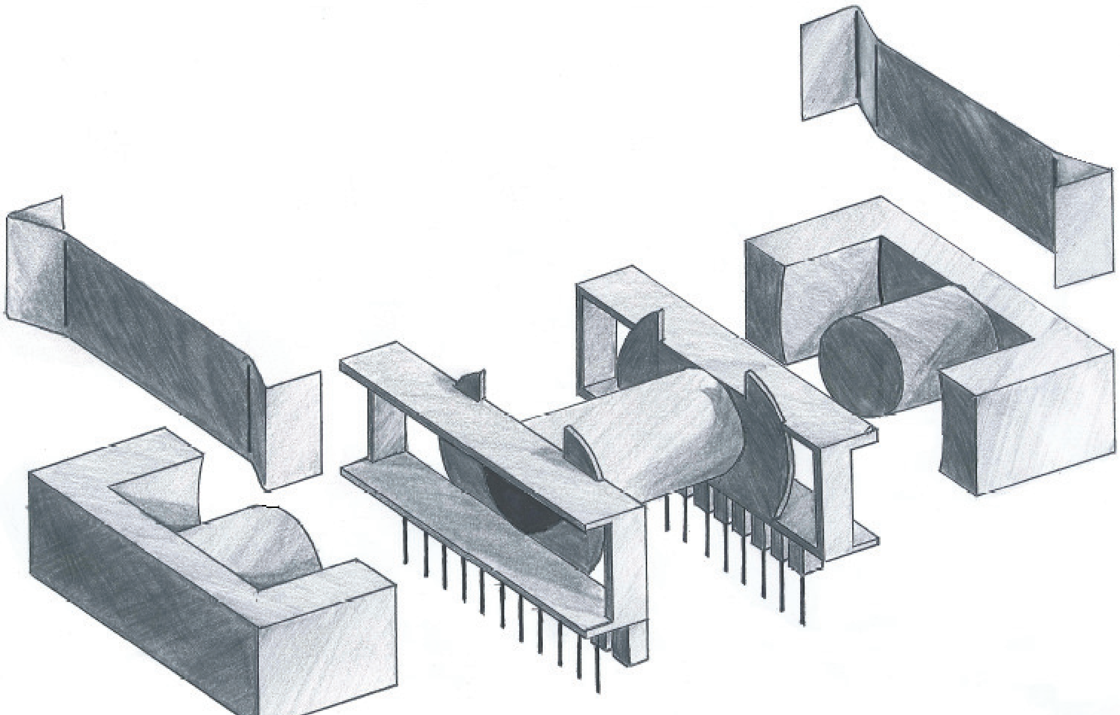

AC RESISTANCE EVALUATION OF FOIL, ROUND AND LITZ CONDUCTORS IN MAGNETIC COMPONENTS

Master of Science Thesis

HECTOR ORTEGA JIMENEZ

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

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ETD Transformer assembly.

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Abstract

In this work an evaluation of the AC resistance of various types of transformer's windings at different frequencies is made. The conductors utilized to build the transformers were the following ones: Foil, Round Magnetic Wire and Litz Wire.

Firs of all, it was necessary to assemble all the transformers with the predefined characteristics parameters. This was done in order to be able to analyze the effects of various characteristics. Then an accurate measuring procedure was chosen. After that the theoretical equations were collected with the purpose to compare the theoretical values with the measured ones.

The resistance of the foil winding was so low that not all the instruments were able to measure it with enough precision. Comparing the results that have been obtained for the research of different types of conductors, it is suggested that it would be valuable to continue future work utilizing foil windings.

Keywords: Ultra Low Impedance, Winding AC Resistance, Foil Conductor, Round Magnet Wire, Litz Wire.

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HECTOR ORTEGA JIMENEZ
Göteborg, Sweden, 2013

Contents

List of symbols

V_s the voltage in the secondary side.

N_s the number of turns in the secondary.

Φ the magnetic flux along the coil.

V_p the voltage in the primary side.

N_p the number of turns in the primary.

R_t the ratio of voltage from primary and secondary sides.

$P_{incoming}$ the power applied to the transformer.

$P_{outcoming}$ the power obtained from the transformer.

I_p the current thought the primary winding.

I_s the current thought the secondary winding.

R_p the primary winding equivalent resistance.

R_s the secondary winding equivalent resistance.

X_p the primary winding equivalent leakage inductance.

X_s the secondary winding equivalent leakage inductance.

R_c the iron core losses.

X_m the magnetizing reactance.

I_c the core losses current.

I_m the magnetizing current.

W_1 the wattmeter reading in the primary side or the full load copper loss.

θ_1 the impedance angle.

V_1 the applied rated voltage in the primary side.

I_1 the no-load current measured in the primary side.

Z_{oc} the exciting impedance.

R_{sc} the resistance as viewed from the primary.

X_{sc} the reactance as viewed from the primary.

Z_{sc} the total impedance as viewed from the primary.

δ the skin depth.

w the pulsation frequency of the waveform.

μ the permeability of the material.

σ the conductivity of the material.

f the frequency of the signal.

ρ the resistivity of the material.

R_{ac} the AC resistance of the winding.

R_{dc} the DC resistance of the winding.

ς_1 the skin effect factor.

ς_2 the proximity effect factor.

Δ represents the penetration ratio.

Δ' represents the modified penetration ratio.

η_w the porosity factor.

m the number or layers.

l_w the length of the middle layer.

h_w the width of the layer.

d_w the thickness of the foil or the equivalent thickness.

N the number of turns in one layer

d the diameter of the magnetic wire.

RF the resistance factor.

n_s the number of the strands in the bundle.

d_s the diameter of the strand.

d_a the diameter of the bundle.

r_s the radio of the strand.

r_b the radio of the bundle.

ζ the penetration ratio for litz wires.

$\psi_1(\zeta)$ the skin effect losses in round conductors.

$\psi_2(\zeta)$ the proximity effect losses in round conductors.

p_f the packing factor.

ϕ_1 the diameter of the core.

h_c the width inside of the core.

a the distance between the core and the first layer.

d_{HV} the distance between the external side of the last primary turn and the secondary layer.

L_p the distance between the core´s center to the middle length of primary side.

L_s the distance between the core´s center to the middle length of secondary side.

S_i the cross section; i type of wire.

Abbreviations

AC Alternating Current

ANSI American National Standards Institute

DC Direct Current

IEEE Institute of Electrical and Electronics Engineers

Chapter 1

Introduction

1.1 Problem background

Nowadays many studies have a focus on the efficiency of power generation systems, especially for wind power plants placed offshore. If the distance from the shore is more than 50 km, the energy should be sent through DC transmission lines [1] & [2]. One of the most important components of every power transmission is the electrical transformer. Its efficiency is typically related to the winding losses for a predefined frequency.

The optimization of the design is one of the aims of every new product. In order to do that, applications are being developed to simulate the products. One idea could be to increase the frequency as the voltage level is transformed. If this idea is implemented, new considerations for the design of the electrical equipment should be assumed. Working at higher frequency increases the losses significantly and accordingly new applications should be developed with the purpose to optimize the design of new high-frequency transformers.

1.2 Previous work

If the system frequency is increased, the winding losses would increase too. With the purpose to understand this effect some equations have been developed to verify their accuracy. The mathematical expressions are related to the type of conductor used to build the winding. This topic has been analyzed by some researches and they are collected in several technical documents. The most known researchers are: P.L. Dowell [3], F. Tourkhany and P. Viarouge [4], J. Biela [5], J. Mühlethaler [6], G. Ortiz [7] ... In their documents the equations to calculate the winding losses are included.

1.3 The purpose of this work

The goal of this thesis is to analyze the AC resistance of different types of windings in a defined frequency range (from 1kHz to 300kHz). This study was focused on three different types of conductors that could be used to manufacture the transformer's windings. The chosen conductors are the following: copper foil, round wire and litz wire.

First, the simulation equations were collected in order to calculate the AC resistance of the windings. Dowell's equations for foil and round wires windings were used. With the purpose to utilize a correct system for litz wire windings, several documents were checked. After verifying the different expression found in these technical reports, the Tourkhany and Viarouge equations for litz wire windings seemed to be the most accurate ones.

Secondly, with the intention to analyze the AC resistance, the theoretical results were compared with real values. These real values were measured from transformers. These ones were handmade in order to study some specific parameters.

Finally, as it was said before, the calculated values and the measured results were compared in order to verify the accuracy of the equations.

1.4 Project Layout

The organizing of the report is done as follows:

Introduction justifies the purpose of this project.

Chapter 2 includes the necessary theoretical background in order to be able to understand the results and the following tests.

Chapter 3 explains the procedure to manufacture the transformers winding and other components like the litz wires.

Chapter 4 shows the acquisition instrument used to measure and the configuration of this one.

Chapter 5 presents the results of the tests done, where the comparison between the theoretical values and the measured ones takes place.

Chapter 6 contains the conclusions of this project and the possible ideas for future researches.

Chapter 2

Technical background

2.1 Basics of electrical transformers

According to [ANSI/IEEE] ” the transformer is defined as a static electrical device, involving no continuously moving parts, used in electric power systems to transfer power between circuits through the use of electromagnetic induction”.

The transformer is based on the electromagnetism and electromagnetic induction principles. The electromagnetism principle is originated in the property to produce a magnetic field by the electric current. The electromagnetic induction is based on inducing a voltage across the coil due to a changing magnetic field.

These electrical devices can be considered as an ideal or as a real one. To be able to consider the transformer as ideal, the following assumptions must be accepted

- The windings of the transformer don’t have losses because the resistance of each one is zero.

- The leakage inductance in the transformer is zero because the coupling factor is one.

- The core of the transformer doesn’t store any energy and it never produces losses. It is because the permeability and the resistivity of the core are infinite.

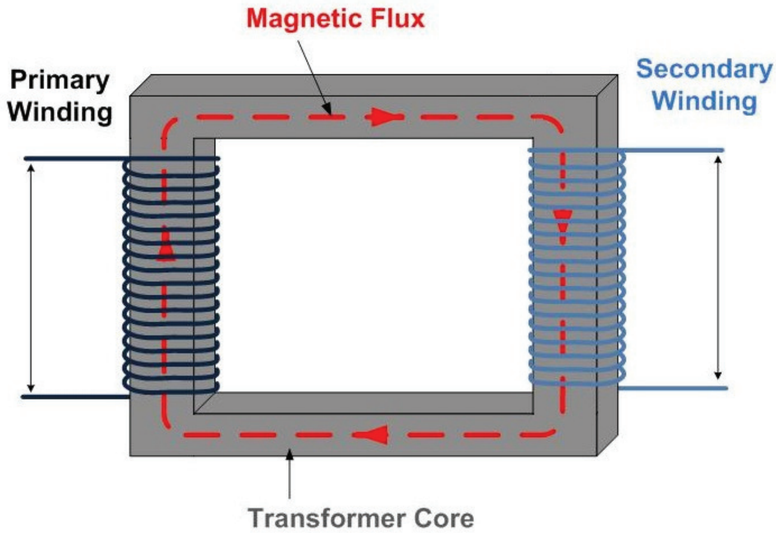

Fig. 2.1 An ideal transformer. [8].

The equivalent circuit of an ideal transformer is shown in Figure 2.1. In that figure the current which goes through the primary coil produces a magnetic field. The primary and secondary coils are wound around a core; therefore, the flux goes through both of them.

The voltage in the secondary side can be obtained from Faraday´s induction law,

$$V_\mathrm{s} = N_\mathrm{s}\frac{d\Phi}{dt} \tag{2.1}$$

where V_s is the voltage in the secondary side, N_s is the number of turns in the secondary and Φ is the magnetic flux along the coil. The magnetic flux is the same on both sides, so the voltage in the primary side equals,

$$V_\mathrm{p} = N_\mathrm{p}\frac{d\Phi}{dt} \tag{2.2}$$

taking the ratio of voltage from primary and secondary sides give,

$$R_t = \frac{V_\mathrm{s}}{V_\mathrm{p}} = \frac{N_\mathrm{s}}{N_\mathrm{p}} \tag{2.3}$$

If there is a load in the secondary side allowing current to flow, the energy transferred between both sides is ideally the same,

$$P_{incoming} = I_pV_p = P_{outcoming} = I_sV_s \tag{2.4}$$

giving the ideal transformer equation,

$$R_t = \frac{V_\mathrm{s}}{V_\mathrm{p}} = \frac{N_\mathrm{s}}{N_\mathrm{p}} = \frac{I_\mathrm{p}}{I_\mathrm{s}} \tag{2.5}$$

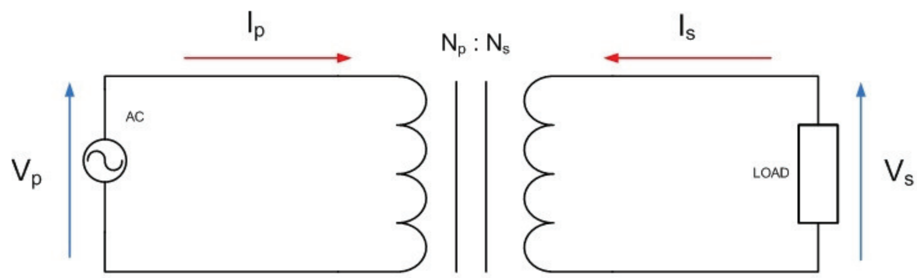

Fig. 2.2 The ideal transformer as a circuit element. [8]

If the previous suppositions haven't been accepted, the transformers must be considered as real. In that case, the losses of the windings are inherent to the resistivity of the material used to build them. They also can be affected by the temperature and the frequency. The efficiency of the transformers depends on the flux even if the windings is done carefully.

The finite permeability of the core means that some current and energy is needed to magnetize it. In order to do that, an unsuitable energy is stored and also dissipated in the core. Therefore, the transformer requires a cooling system in order not to get overheated.

Figure 2.3 shows the equivalent circuit with its corresponding losses and energy storing places.

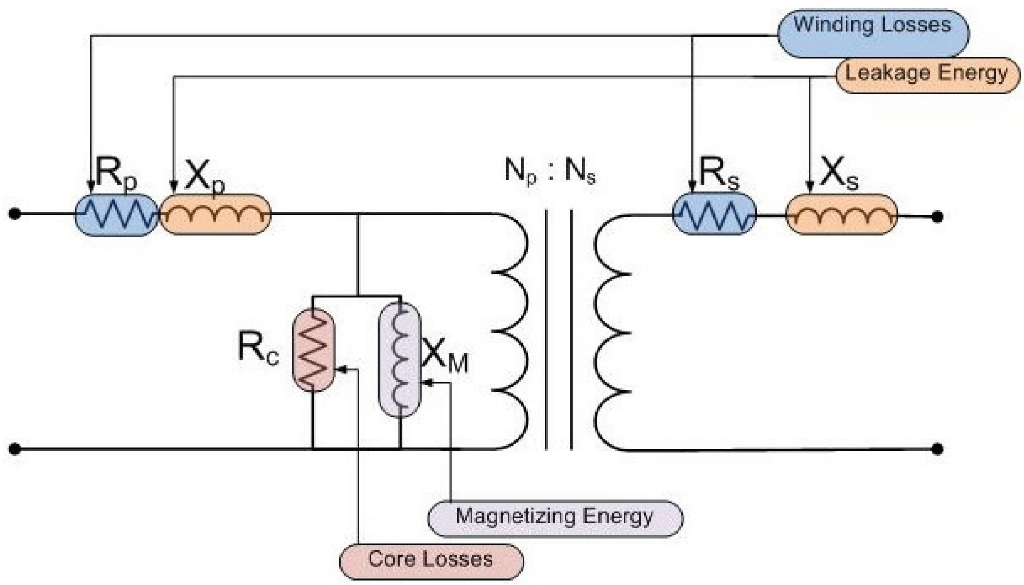

Fig. 2.3 Transformer equivalent circuit with corresponding loss and energy storing elements [9].

The physical limitations of the real transformer might be joined together in an equivalent circuit. Winding losses are related to current and are represented as resistances R_p and R_s. Leakage energy is part of the applied voltage lost without contributing to the mutual coupling; therefore is equivalent to leakage inductance X_p and X_s.

Core losses are produced by hysteresis and eddy current. The losses from the iron core can be represented by a resistance R_c in parallel with the ideal transformer. The core finite permeability is supported by a magnetizing current I_m that holds up the mutual flux. The flux inside the core produces a 90º lag from EMF (electromagnetic field) and this effect might be represented as a magnetizing reactance X_m in parallel with R_c. R_c and X_m are known as the magnetizing branch parameters.

It is common that R_s and X_s are moved to primary side; in order to do that, the impedance scaling factor $(N_p/N_s)^2$ or R_t^2 must be utilised.

2.2 Transformers equivalent circuit

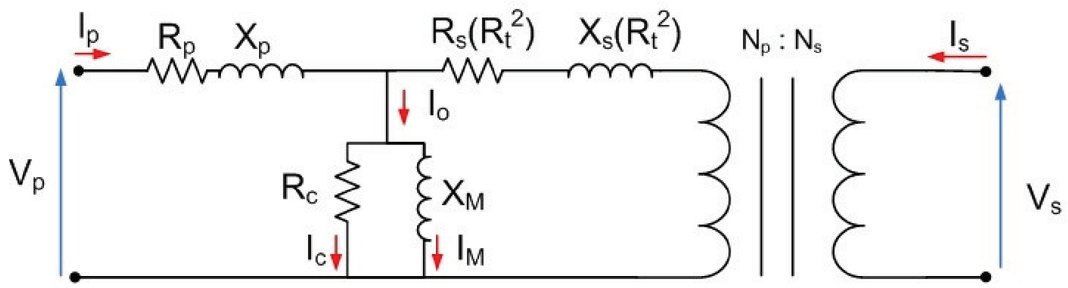

Fig. 2.4 Transformer equivalent circuit, with secondary impedance referred to the primary side [8].

The parameters of the equivalent circuit represented in Figure 2.4 can be obtained from the open-circuit and the short-circuit test.

2.2.1 The open-circuit test

The secondary side of the transformer is left open-circuited and a voltage is applied to the primary. Current, voltage and power are measured at the primary side to obtain the impedance and the power factor angle,

$$W_1 = V_1 I_1 \cos\theta_1 \tag{2.6}$$

the above equation can be rewritten as,

$$\cos\theta_1 = \frac{W_1}{V_1 I_1} \tag{2.7}$$

$$I_{\mathrm{m}} = I_1 \sin\theta_1 \tag{2.8}$$

$$I_{\mathrm{c}} = I_1 \cos\theta_1 \tag{2.9}$$

$$X_{\mathrm{m}} = \frac{V_1}{I_{\mathrm{m}}} \tag{2.10}$$

$$R_{\mathrm{c}} = \frac{V_1}{I_{\mathrm{c}}} \tag{2.11}$$

$$Z_{\mathrm{oc}} = R_{\mathrm{c}} + jX_{\mathrm{m}} \tag{2.12}$$

where W_1 is the wattmeter reading, θ_1 is the impedance angle, V_1 is the applied rated voltage, I_1 is the no-load current, I_m is the magnetizing component of the no-load current, I_c is the core loss component of no-load current, R_c is the resistance of the core, X_m is the magnetizing reactance and Z_{oc} is the exciting impedance.

2.2.2 The short-circuit test

The low voltage side of the transformer is short-circuited and a voltage is applied to the high voltage side; it is assumed to be the transformer's primary side. The core losses are too low so it can be neglected. Current, voltage and power are measured at the high voltage side to obtain the impedance and the power factor angle,

$$W_1 = I_1^2 R_{\mathrm{sc}} \tag{2.13}$$

The above equation can be rewritten as,

$$\cos\theta_{\mathrm{sc}} = \frac{W_1}{V_1 I_1} \tag{2.14}$$

$$R_{\mathrm{sc}} = \frac{W_1}{I_1^2} \tag{2.15}$$

$$Z_{\mathrm{sc}} = \frac{V_1}{I_1} \tag{2.16}$$

$$X_{\mathrm{sc}} = \sqrt{Z_{\mathrm{sc}}^2 - R_{\mathrm{sc}}^2} \tag{2.17}$$

where W_1 is the full load copper loss, θ_1 is the impedance angle, V_1 is the applied rated voltage, I_1 is the rated current, R_{sc} is the resistance as viewed from the primary, X_{sc} is the reactance as viewed from the primary and Z_{sc} is the total impedance as viewed from the primary.

2.3 Frequency effects in transformer

The transformer parameters began to vary as soon as the frequency tends to increase. It happens because of the change of magnetic field and current density that goes through the conductors. This depends on in which conductor the current flows, if it flows through its own conductor it is known as Skin Effect and if it goes within the neighbor's winding is called as Proximity effect. The magnitude of these effects depends on the frequency used, which modifies the AC resistance.

2.3.1 Skin Effect

As it is said before, the skin effect in a conductor is induced by the current going through itself. The magnetic field depends on the current magnitude, the distance from the conductor center and the frequency used.

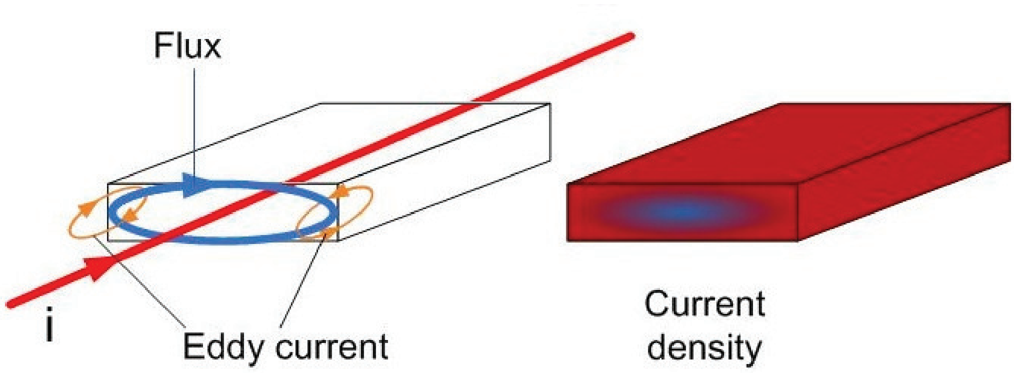

Fig. 2.5 The skin effect and current density in a single foil conductor [9].

Figure 2.5 illustrates the current within a foil conductor. This current causes a magnetic flux which goes around it. According to Lenz's law, the magnetic field induces an opposite current through the conductor. Therefore, the current tends to decrease in the center and grow in the surface. In addition to this effect, the total current through the conductor will be the same but not the density. Figure 2.6 shows the effect described before.

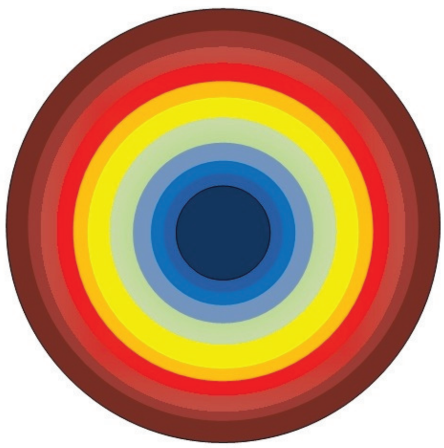

Fig. 2.6 Current density in a isolated round copper conductor [9].

The current density can be calculated using Maxwell´s equations. The value of this will be more pronounced with higher frequencies. This property of the materials used as conductors is known as skin depth δ, is defined as,

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad or \qquad \delta = \sqrt{\frac{\rho}{f\pi\mu}} \tag{2.18}$$

where w is the pulsation frequency of the waveform, μ is the permeability and σ the conductivity of the material, or f represents the frequency of the signal and ρ is the resistivity.

2.3.2 Proximity Effect

As was mentioned, the proximity effect in a conductor is induced by the current going through the neighbor≪s conductors. This current produces a magnetic field in the nearest conductors and induces a voltage on them, causing a current addition to the conductor. The magnitude of the penetration is related to the proximity of the external wire and the frequency. The total current density is still the same but the distribution is disturbed. So it will be decreased in the outer wire and increased in the other side. Finally if a new conductor is added inside the same outer field, it will be affected by this current even if there is no net current through it.

2.4 Winding Losses

The windings of the transformer are affected by skin effect and proximity effect. The skin effect of the conductor increases the resistance factor of the windings. The skin increases with frequency, causing a strange current reduction.

2.4.1 Resistance Factor. Dowell's Equation

Although Dowell [3] was the first one solving Maxwell equations for transformer windings, he also reached his own expression, the Dowell's equation for the AC resistance of a coil with layers using sinusoidal excitation. Dowell's equation is used to calculate the AC resistance of a foil conductor; moreover this equation can be adapted to obtain the value for round magnet wires as well. He includes another modification; he adapts his equations with the porosity factor coefficient η_w in order to apply the effect of the core window size used.

Foil conductor

The equation that Dowell provided for calculating the AC resistance of the foil winding can be written as follows.

$$R_{\mathrm{ac}} = \frac{l_\omega}{\delta\sigma h_\omega} m \left[\varsigma_1' + \eta_w^2 \frac{2}{3}(m^2 - 1)\varsigma_2' \right] \tag{2.19}$$

where

- ς_1' the skin effect factor

$$\varsigma_1' = \frac{\sinh(2\Delta') + \sin(2\Delta')}{\cosh(2\Delta') - \cos(2\Delta')} \tag{2.20}$$

- ς_2' the proximity effect factor

$$\varsigma_2' = \frac{\sinh(\Delta') - \sin(\Delta')}{\cosh(\Delta') + \cos(\Delta')} \tag{2.21}$$

- Δ represents the penetration ratio:

$$\Delta = \frac{d_w}{\delta} \tag{2.22}$$

- Δ' represents the modified penetration ratio.

$$\Delta' = \sqrt{\eta_w}\Delta \tag{2.23}$$

- η_w the porosity factor

$$\eta_w = \frac{h_w}{h_c} \tag{2.24}$$

- m the number or layers
- δ the skin depth
- l_w the length of the middle layer
- σ the material conductivity
- h_w the width of the layer
- h_c the core window size
- d_w the thickness of the foil

The DC resistance of a foil winding can be obtained with the following expression:

$$R_{\mathrm{dc}} = \frac{l_\omega}{d_\omega \sigma h_\omega} m \tag{2.25}$$

The formula that provides the resistance factor is obtained from the ratio R_{ac} and R_{dc} as

$$RF = \frac{R_{\mathrm{ac}}}{R_{\mathrm{dc}}} = \Delta' \left[\varsigma_1' + \eta_w^2 \frac{2}{3}(m^2 - 1)\varsigma_2' \right] \tag{2.26}$$

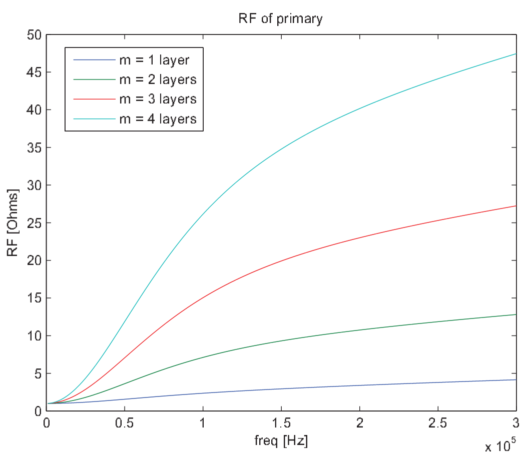

Fig. 2.7 Dowell resistance factor expression RF versus frequency.

In Figure 2.7 the resistance factors as a function of the frequency have been shown at four different number of layers. The total resistance grows quickly as soon as the frequency increases. For lower frequency values the resistance factor can be higher if there are several layers.

Round wires

Dowell's equation for foil winding can be adapted for being used with round magnet wires, so the total AC resistance of the round magnet wire is calculated with the following relation.

$$R_{\mathrm{ac}} = \frac{l_\omega}{\delta \sigma d_\omega} m N \left[\varsigma_1' + \eta_w^2 \frac{2}{3} (m^2 - 1) \varsigma_2' \right] \tag{2.27}$$

where

- η_w the porosity factor
$$\eta_w = \frac{d_w N}{h_w} \tag{2.28}$$
- N the number of turns in one layer
- d_w the equivalent thickness. In the case of round wires, the equivalent is defined as,
$$d_w = \sqrt{\frac{\pi}{4}} d \tag{2.29}$$
- d is the diameter of the magnetic wire.

  Figure 2.8 represents the equivalence between the foil and round conductors; it also shows some other technical information.

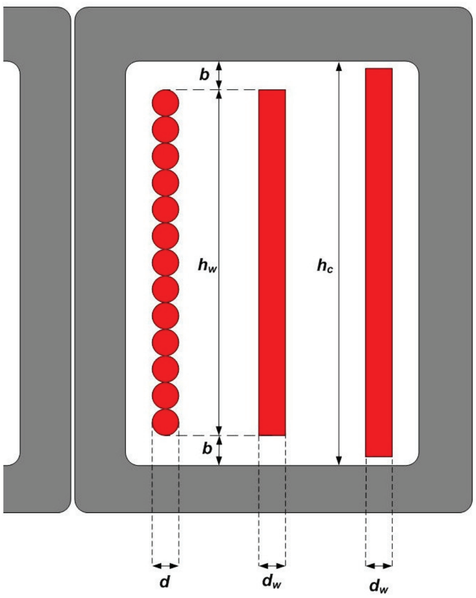

Fig. 2.8 Representation of the equivalent conductors [9].

The DC resistance of a round magnetic winding can be obtained as,

$$R_{\mathrm{dc}} = \frac{4l_\omega mN}{\pi\sigma d^2} = \frac{l_\omega mN}{\sigma d_w^2} \tag{2.30}$$

The formula that provides the resistance factor, as mentioned before, it is the ratio R_{ac} and R_{dc},

$$RF = \frac{R_{\mathrm{ac}}}{R_{\mathrm{dc}}} = \Delta' \left[\varsigma_1' + \eta_w^2 \frac{2}{3}(m^2-1)\varsigma_2'\right] \tag{2.31}$$

This equation is the same as for foil conductors, so Figure 2.7 is able to explain the effect of increasing the number of layers. If the number of turns per layer is increased, the Resistance Factor is not affected because their equation is not related to that parameter. The number of turns only concerns the DC Resistance and AC Resistance.

2.4.2 Litz Wires

The Skin and Proximity effects are significant when a coil is operating in medium-frequency applications, therefore, it is necessary a conductor with a proper section. If the chosen area is not the correct one, this may be too wide for the signal frequency due to eddy current effects. This effect can be decreased using stranded insulated and twisted wires. The skin depth effect is reduced because of the higher surface area of each strand. The Litz wire conductors are manufactured with several insulated strands twisted together.

The skin and proximity effect of round litz wire windings can be separated into Strand-level and Bundle-level. In Figure 2.9 are illustrated both effects.

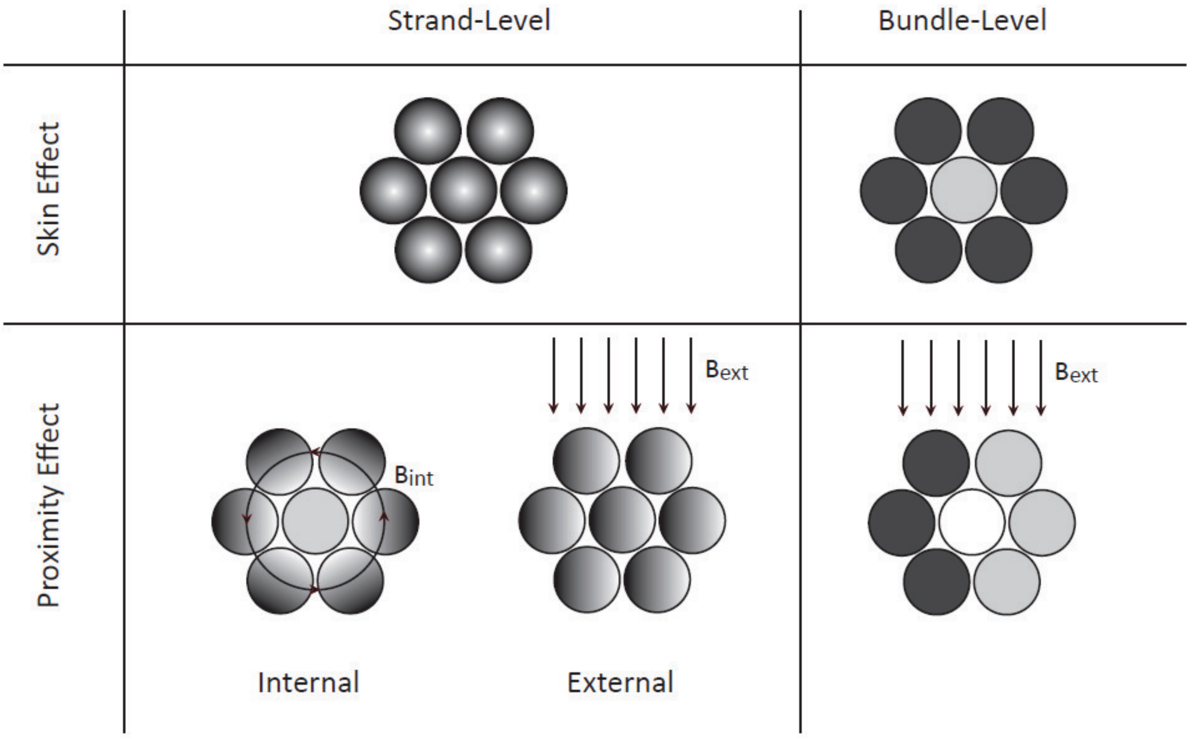

Fig. 2.9 Type of eddy currents in round litz conductors. Illustration introduced in. [10]

Bundle-level effects are related to current going through different paths. These trajectories involve multiple strands. These effects can be solved by the correct manufacturing of the litz wire. Simple twisting can resolve Bundle-level proximity loss, whereas complex structures control Bundle-level skin effect. Proximity effect at Strand-level dominates over skin effect in a winding with many layers; therefore, Strand-level skin effects are negligible.

Strand-level proximity effect can be divided into internal proximity effect and external proximity effect. Internal proximity effect are concerned with the currents effect through the bundle, and external proximity effect is related to the losses generated from current in the other bundles.

The resistance factor equation used in the following experiments is taken from Tourkhani and Viarouge [4]. They have developed an analytical model of winding losses for Round Litz Wires Windings.

$$RF = \frac{R_{ac}}{R_{dc}} = \frac{\zeta}{\sqrt{2}} \left[\psi_1(\zeta) - \frac{\pi^2 n_s p_f]}{24} \left(16m^2 - 1 + \frac{24}{\pi^2} \right) \psi_2(\zeta) \right] \tag{2.32}$$

where:

- R_{ac} is the ac resistance of the winding.
- R_{dc} is the dc resistance of the winding.

$$R_{dc} = \frac{4mNl_w}{n_s \sigma \pi d_s^2} \tag{2.33}$$

- m the number of layers in the winding.
- N the number or turns of litz wire in a layer.
- l_w the length of the middle layer.
- n_s the number of the strands in the bundle.
- d_s the diameter of the strand.
- d_a the diameter of the bundle. This value can be estimated with the next equation. It is taken from J. Biela [5].

$$d_a = 135 * e - 6 \left(\frac{n_s}{3} \right)^{0.45} \left(\frac{d_s}{40e - 6} \right)^{0.85} \tag{2.34}$$

- ζ the penetration ratio.

$$\zeta = \frac{d_s}{\delta \sqrt{2}} \tag{2.35}$$

- δ the skin depth.

- $\psi_1(\zeta)$ the skin effect losses in round conductors.

$$\psi_1(\zeta) = \frac{ber_0(\frac{\zeta}{\sqrt{2}})bei'_0(\frac{\zeta}{\sqrt{2}}) - bei_0(\frac{\zeta}{\sqrt{2}})ber'_0(\frac{\zeta}{\sqrt{2}})}{ber'_0(\frac{\zeta}{\sqrt{2}})^2 + bei'_0(\frac{\zeta}{\sqrt{2}})^2} \tag{2.36}$$

- $\psi_2(\zeta)$ the proximity effect losses in round conductors.

$$\psi_2(\zeta) = \frac{ber_2(\frac{\zeta}{\sqrt{2}})ber'_0(\frac{\zeta}{\sqrt{2}}) - bei_2(\frac{\zeta}{\sqrt{2}})bei'_0(\frac{\zeta}{\sqrt{2}})}{ber_0(\frac{\zeta}{\sqrt{2}})^2 + bei_0(\frac{\zeta}{\sqrt{2}})^2} \tag{2.37}$$

- p_f the packing factor.

$$p_f = n_s \left(\frac{d_s}{d_a}\right)^2 \tag{2.38}$$

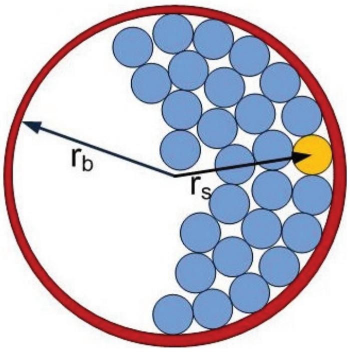

Fig. 2.10 Litz wire´s filling or packing factor [9].

The equation for skin effect (eq 2.36) and proximity factor (eq 2.37) are written as Bessel functions. These values can be obtained by a Taylor-series expansion as Tourkhani and Viarouge [2001] suggested. For the theoretical implementation the following equations are used,

$$\psi_1(\zeta) = 2\sqrt{2}\left(\frac{1}{\zeta} + \frac{1}{32^8}\zeta^3 - \frac{1}{32^{14}}\zeta^5 + ...\right) \tag{2.39}$$

$$\psi_2(\zeta) = \frac{1}{\sqrt{2}}\left(-\frac{1}{2^5}\zeta^3 + \frac{1}{2^{12}}\zeta^7 + ...\right) \tag{2.40}$$

Chapter 3

Manufacturing procedure

The aim of the experiments is to measure the AC resistance of the device as function of frequency. In this chapter, the procedure to build the needed transformers for the experiment, as well as other necessary components is explained. The electrical devices have been manufactured following the supervisor's instructions. These parameters are related to the number of turns on each side, the kind of electrical conductor and the dimensions of the transformer.

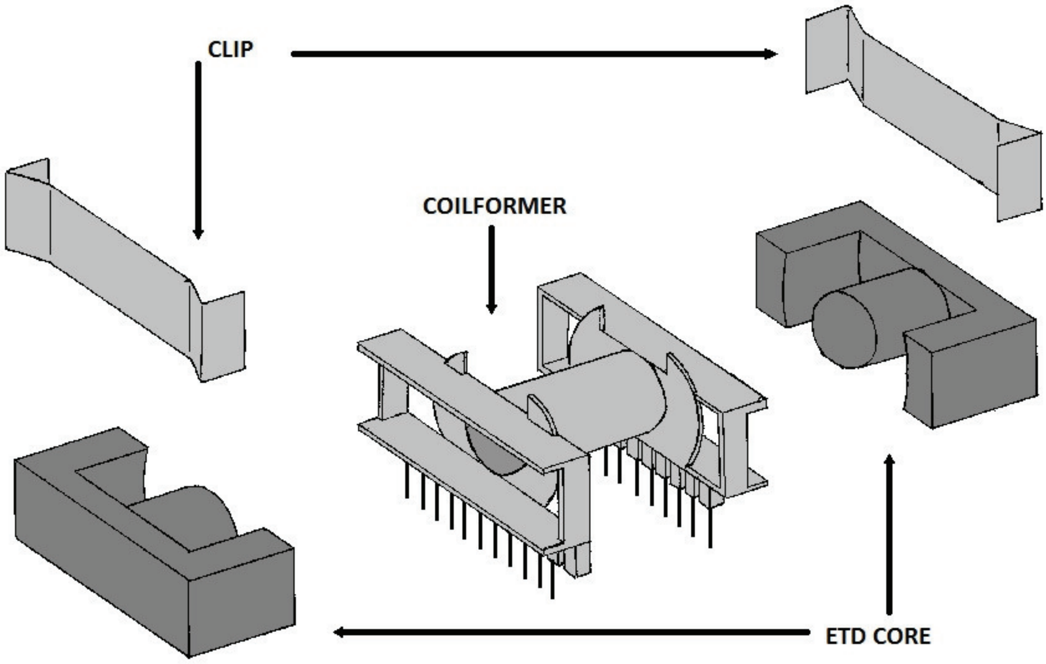

Fig. 3.1 ETD core with coil-former and clips.

The electrical devices have been built using precast components. The premanufactured components used to mount the devices are the following: the core, the coil-former and the clips. In Figure 3.1 is shown how to assemble all these components are assembled, the clips are the ones who keep fixed the core to the coil-former.

In addition to the previously mention precast components, different kind of conductors has bee used. These conductors are manufactured with cooper, all of them built in various formats like: foil, round magnet wire and litz wire. In the table 3.1 the bill of material used to manufacture the electrical transformers are listed.

Table 3.1 Bill of materials

Product	Model
Coil-former	CPH-ETD59-1S-24P
Core	ETD59
Clip	CLI-ETD59
Foil 0.5 mm	DURATOOL 7097189
Foil 0.9 mm	DURATOOL 7097207
Wire 0.4 mm	BELDEN 8053
Wire 1 mm	BELDEN 8049
Wire 1.8 mm	BELDEN 8073

3.1 Characteristic parameters of the materials

In the following subsections the most important manufacturing characteristics of each one of the components from the bill of materials are shown .

3.1.1 Coil-former

The CPH-ETD59-1S-24P is the coil-former model used to build the electrical transformers. The dimensions of this component are illustrated in Figure 3.2.

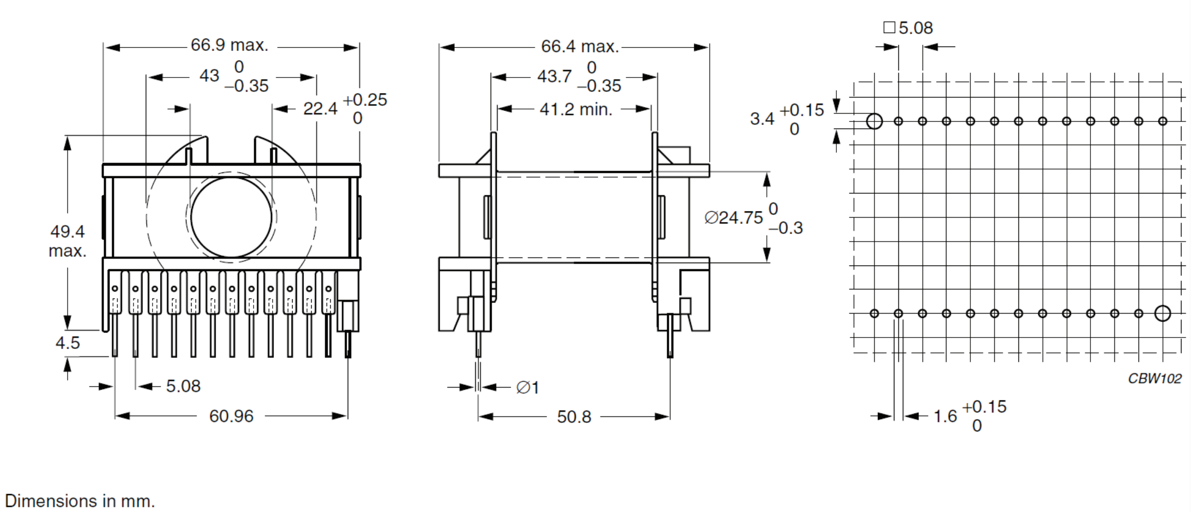

Fig. 3.2 ETD 59 Coil-former [11].

The external diameter and the internal width are the most important parameters of this component. The value of the external diameter is 24.75mm and the internal coil former width (h_w) is 41.2mm (figure 2.8).

3.1.2 Core

The ETD59 is the model of the core employed to manufacture the devices. Figure 3.3 displays the technical blueprints of the half core.

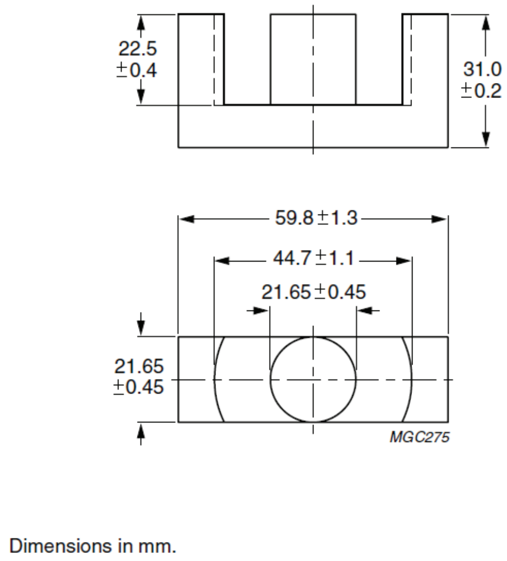

Fig. 3.3 ETD 59 Core [11].

The most important parameters shown in the contour map are the core diameter (ϕ_1) and the internal width (h_c). The value of ϕ_1 is 21.65mm and the measure of h_c is 44.7mm.

3.1.3 Clips

The clips are employed to fix the core to the coil-former as was mentioned before. The dimensions of this component are presented in Figure 3.4.

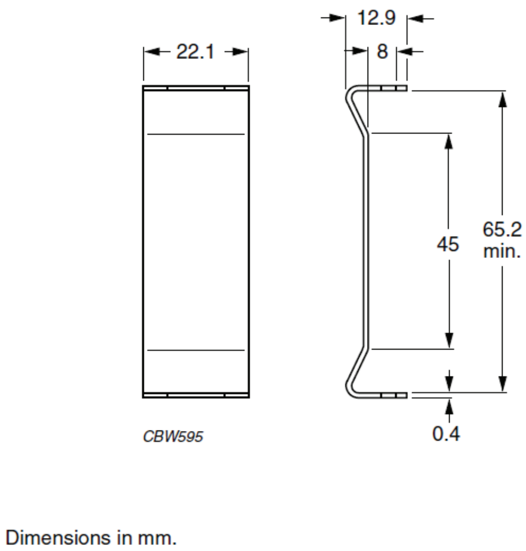

Fig. 3.4 ETD 59 Clips [11].

3.1.4 Conductors

Three different kinds of copper conductors has been used in the manufacturing, these are composed of foil, round magnet wire and Litz wire.

Foil

The transformers have been built using two kinds of foils. The thickener foil was 0.5mm and the thicker one was 0.9mm. Figure 3.5 shows the two types of copper foil utilized.

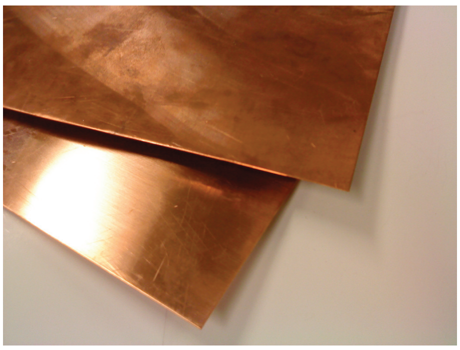

Fig. 3.5 Copper Foils.

Round magnet wire

There were three round magnet wires with various diameters available. The diameters were 0.4mm, 1mm and 1.8mm. Figure 3.6 displays a visual comparison between them.

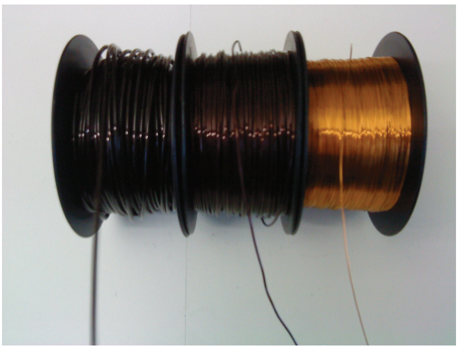

Fig. 3.6 The three types of round magnet wires.

Litz wire

The litz wire has been manufactured by the available round magnet wires. The procedure to build this type of conductor is explained in section 3.4. The diameter of the bundle can be estimated by (2.34). Figure 3.7 shows one of the litz wires manufactured for the research.

Fig. 3.7 Litz wire.

3.2 Design parameters of transformers

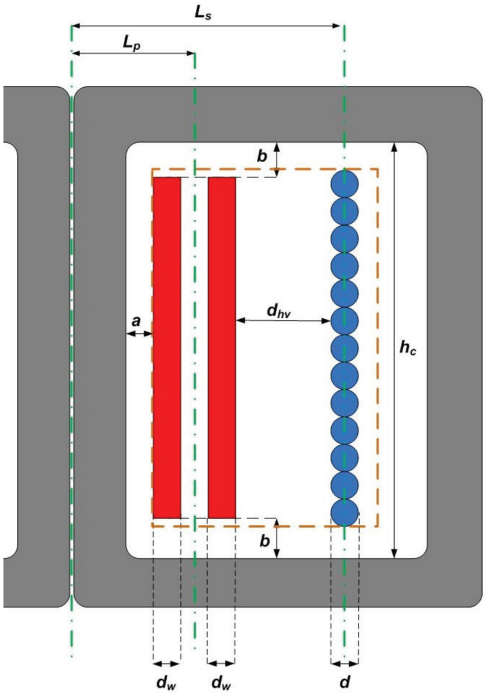

Fig. 3.8 Transformer blueprint.

Figure 3.8 is the blueprint of the transformer. The figure shows the main characteristics used in the manufacturing procedure and also in the theoretical calculations, they are:

- h_c is the width inside of the core.
- $b = \%h_c$ (a defined percent of h_c value)
- a is the distance between the core and the first layer.
- d_{HV} is the distance between the external side of the last primary turn and the secondary layer.
- L_p is the distance between the core´s center to the middle length of primary side.
- L_s is the distance between the core´s center to the middle length of secondary side.

3.3 Transformers manufacturing

In this section the process to build the electrical transformers for the experiments is explained. In the present project three different types of transformers have been manufactured. The winding types are listed in table 3.2,

Table 3.2 List of transformers types

TRANSFORMER TYPE	PRIMARY WINDING	SECONDARY WINDING
A	Foil Conductor	Foil Conductor
B	Foil Conductor	Wire Conductor
C	Wire Conductor	Wire Conductor

3.3.1 Foil-Foil transformer manufacturing

The first type of transformers have been manufacture with cooper foils in both windings. The conductor has been bent around the coil-former. The bill of material used to build these types of devices is formed by: coil-former, core, clips, foil of 0.5mm thickness and insulation material.

The procedure followed to build the transformers is composed by the next steps.

STEP 1 Measure the coil-former external diameter and add the necessary insulation material up to get the correct dimensions. $\phi_1 + 2a = 25.5mm$. The insulation material used in this case is composed of paper and tape, it can be seen in Figure 3.9.

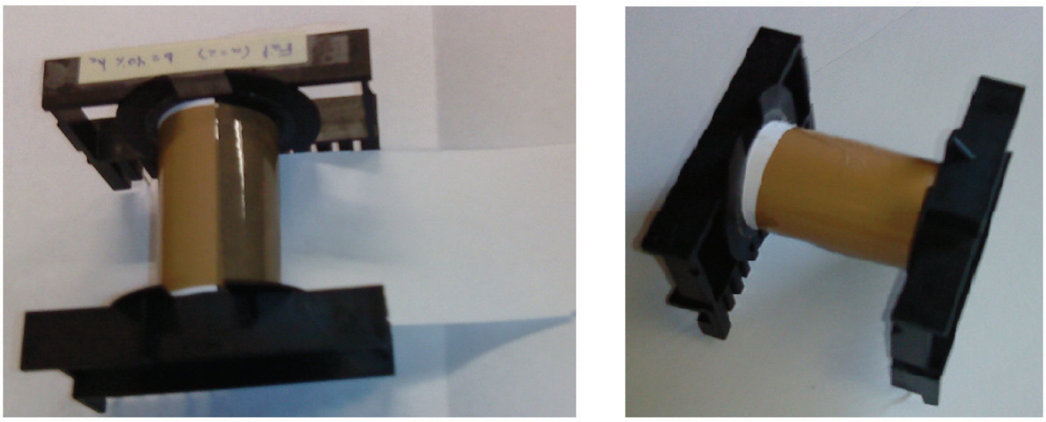

Fig. 3.9 Adding insulation material.

STEP 2 Measure, mark and cut the copper foil using the available tools in the laboratory as it is shown in Figure 3.10.

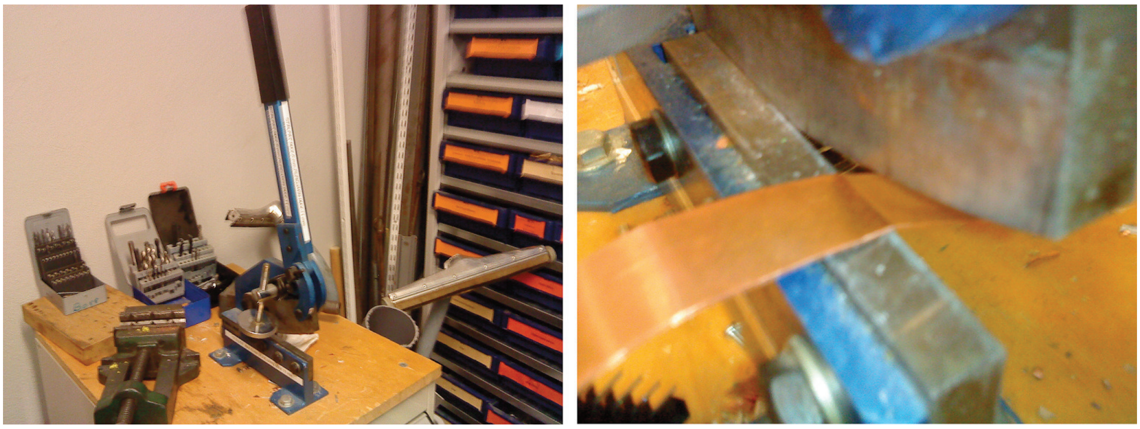

Fig. 3.10 Cutting the copper foil.

STEP 3 Cut two leads and then weld them to the copper foil, each one in the conductor ends. Figure 3.11 displays that process.

Fig. 3.11 Welding the leads.

STEP 4 Bend the copper foil around the coil-former like it is done in Figure 3.12. Of course, some insulation material must be added between the turns.

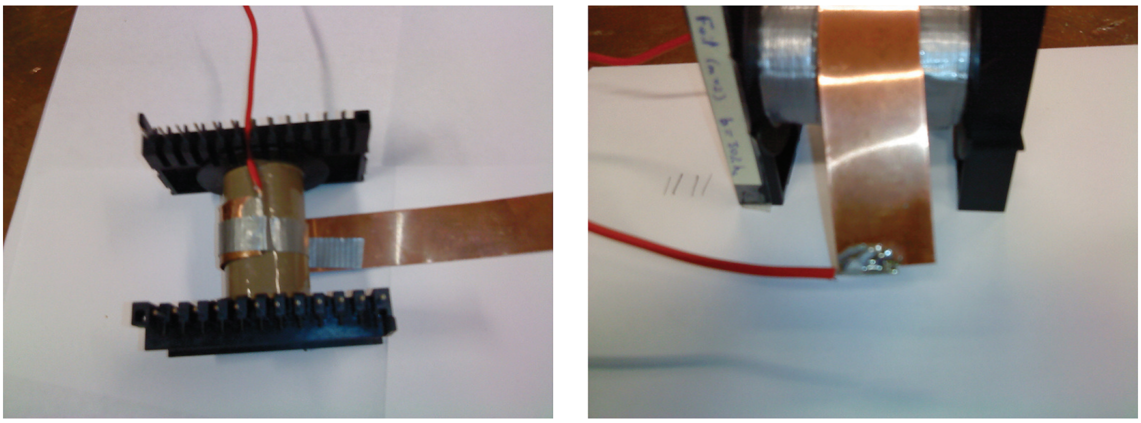

Fig. 3.12 Bending the copper foil.

STEP 5 Add insulation tape up to get enough space between both sides of the transformer(d_{HV}). Figure 3.13 shows how to add the tape.

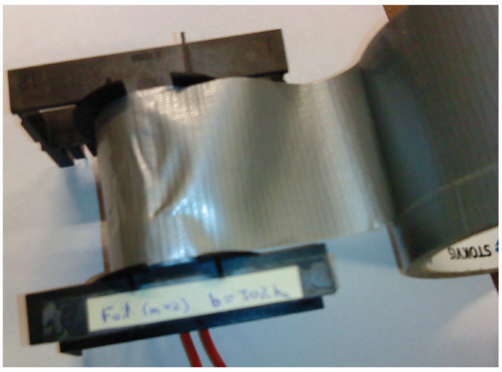

Fig. 3.13 Adding the insulation material between the primary and secondary sides.

STEP 6 Repeat steps 2, 3 and 4. (NOTE: If there is only one layer in the secondary side; step 3 can be canceled and be replaced by welding together the conductor ends after doing steps 2 and 4. This option reduces the losses and improve the short-circuit of this side)

Picture 3.14 shows the transformer after adding the core and having fixed it with the clips.

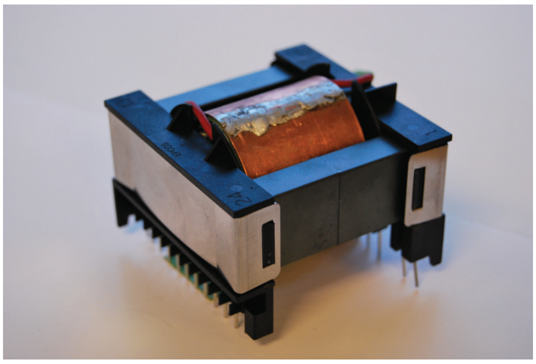

Fig. 3.14 Picture of Transformer Type A.

3.3.2 Foil-Wire transformer manufacturing

These types of electrical devices have been built using a copper foil for the primary side and a round magnet wire for the secondary side. The foil has been bent along the coil-former and the wire has been wound around the coil-former. The bill of material used to build these types of transformers consist of: coil-former, core, clips, foil of 0.5mm or 0.9mm thickness, round magnet wire of 1mm diameter and insulation material.

The procedure to assemble the transformers is similar to the type explained before. The way to build this model is the following.

STEP 1 Measure the coil-former external diameter and add the necessary insulation material up to get the correct dimensions. $\phi_1 + 2a = 25.5mm$. The insulation material used in this case is composed of paper and tape. Figure 3.9 displays this procedure.

STEP 2 Measure, mark and cut the copper foil using the available tools in the laboratory. Figure 3.10 shows how to cut the foil.

STEP 3 Cut two leads and then weld them to the copper foil, each one in the conductor ends. Figure 3.11 displays how to weld them to the foil's ends.

STEP 4 Bend the copper foil around the coil-former. Remember that some insulation material must be added between the turns. This procedure is shown in Figure 3.12.

STEP 5 Add insulation tape up to get enough space between both sides of the transformer(d_{HV}). Figure 3.13 displays this step.

STEP 6 Coil the round magnet wire around the coil-former. Figure 3.15 has been taken during the coiling procedure.

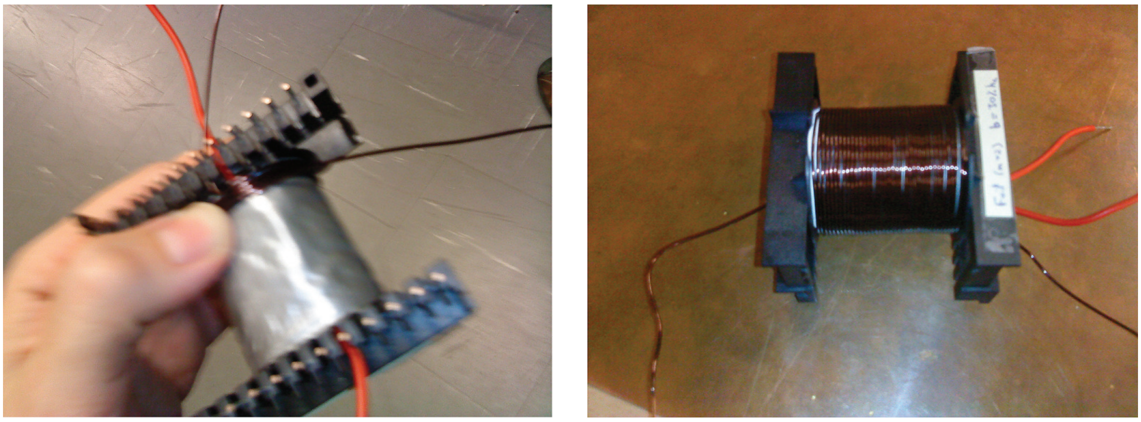

Fig. 3.15 Coiling the round magnet wire.

Figure 3.16 shows the transformer after adding the core and fixing it with the clips.

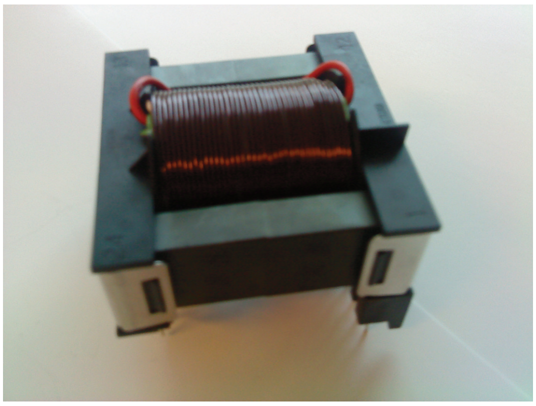

Fig. 3.16 Picture of Transformer Type B.

3.3.3 Wire-Wire transformer manufacturing

The windings of the third type of transformers have been assembled with round magnet wires or litz wires. The cable has been coiled along the coil-former. The materials employed to mount these transformers consists of: coil-former, core, clips, the available magnet wires and insulation material. As it is explained in the previous transformer's manufacturing procedures, the way to build all of them has some common steps. The procedure to make this one is shown below.

STEP 1 Measure the coil-former external diameter and add if it is necessary insulation material up to get the correct dimensions as it is displayed in Figure 3.9. The insulation material might be tape.

STEP 2 Coil the wire around the coil-former in order to build the primary side of the transformer.

STEP 3 Add insulation tape up to get enough space between both sides of the transformer (d_{HV}). Figure 3.13 shows how the tape is added over the primary winding.

STEP 4 Coil the wire along the coil-former in order to build the secondary winding. Figure 3.17 displays the litz wire coiling procedure.

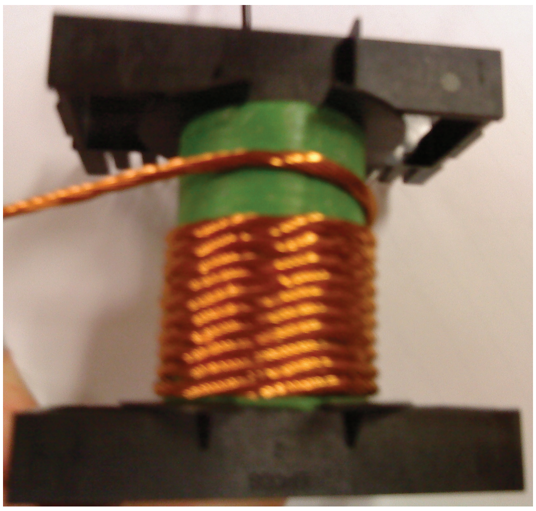

Fig. 3.17 Coiling a litz wire.

NOTE If there is a need for more than one layer, insulation must be added in between.

Figure 3.18 displays the transformer after having added the core and fixed it with the clips.

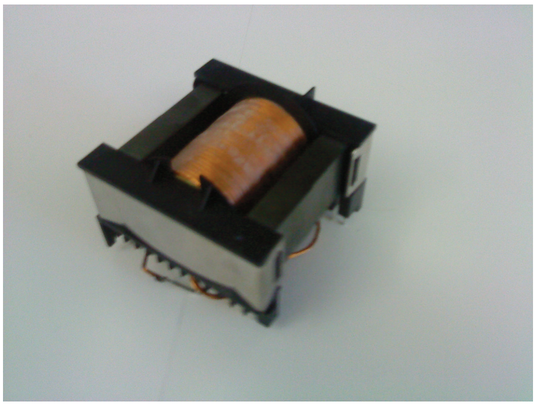

Fig. 3.18 Picture of Transformer Type C.

3.4 Litz wire manufacturing

In this part the procedure to manufacture the litz wire is explained. This type of conductor has been used to manufacture some transformers. As was said before, this kind of conductor is composed by several strands, all of them twisted together.The procedure to assemble this conductor is the following:

- First of all, cut the necessary amount of round wires to build the litz wire. All the strands must have the same length.
- After cutting the strands, the isolation of every strand ends must be removed . Then, the wires are welded together in order to keep them fixed.
- When the previous work is done, the wires could be twisted. This step consists of keeping one of the bundle ends fixed and turning the other, and at the same time apply tension to the wire. This procedure is shown in Figure 3.19.

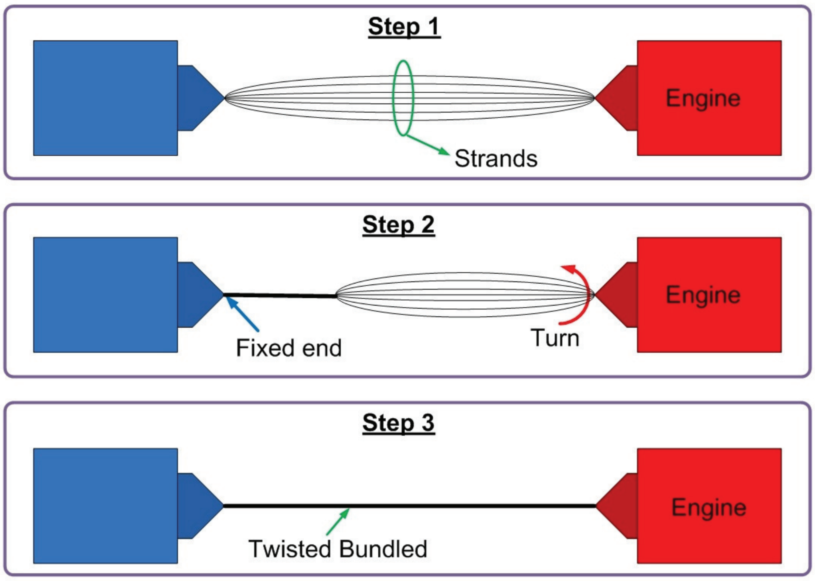

Fig. 3.19 Schematic of the twisted procedure to manufacture the Litz wires.

The fixed point can be done in many ways, the one used to manufacture the litz wire is displayed in the Figure 3.20.

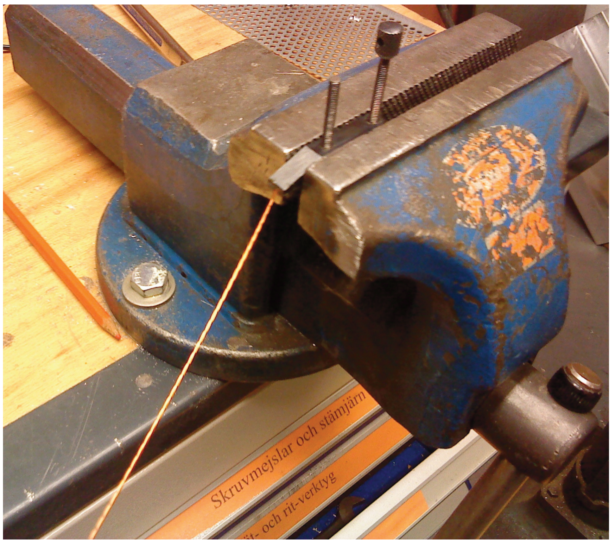

Fig. 3.20 Photograph of the fixed point.

Chapter 4

Measurement procedure

In this chapter the method to measure the impedance of the transformers winding is explained. In the laboratories of the department there are lots of equipments but just one is efficient for this experiment. The Network Analyzer Bode 100 manufactured by OMICRON LAB is the only one accurate enough to be able to measure the very low.

4.1 Bode 100 (Network Analyzer)

The Bode 100 is a multifunctional equipment that can work as a vector network analyzer, impedance meter, gain phase meter, frequency response analyzer and work as a function generator.

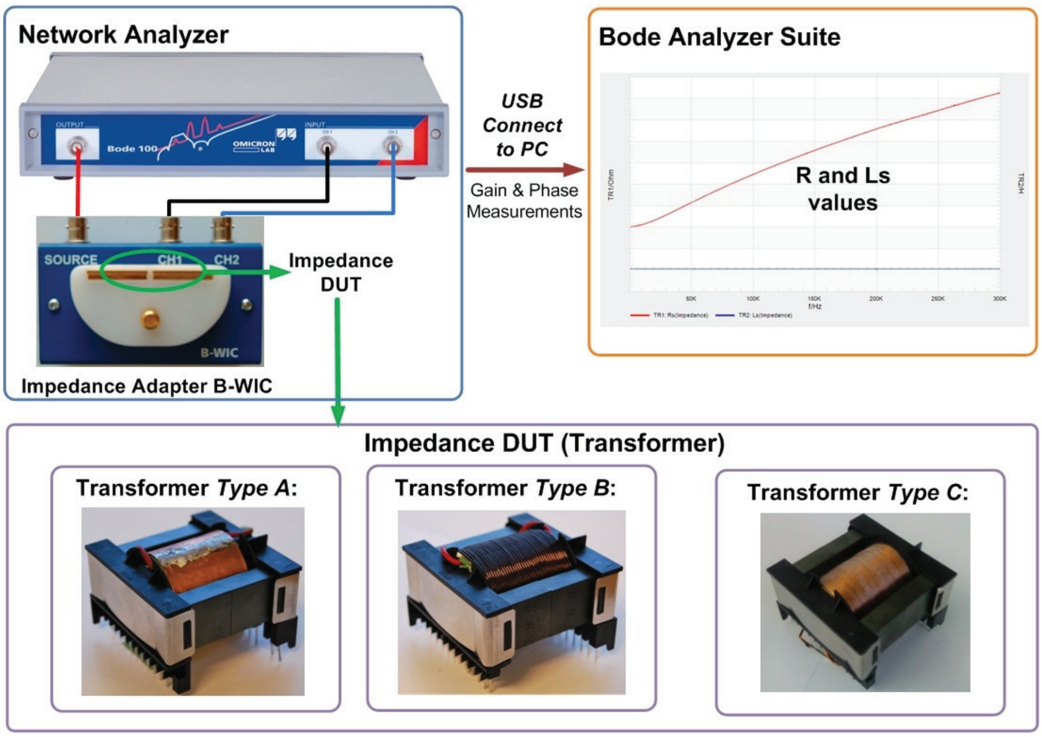

Fig. 4.1 Schematic of the measuring connection.

The instrumental equipment has been configured to measure the impedance as function of frequency. Figure 4.1 shows the schematic connection. This configuration allows the acquisition of the values with such precision that is useful to evaluate the winding resistance. This was the most accurate method available. An error is produced by the necessary tools required to connect the transformer to the equipment, because of that reason; the B-WIC impedance adapter is used to take the measures.

Before getting the first measures, the range of the frequency sweep and other parameter of the Bode 100, like the type of graph and the number of measures should be defined. Figure 4.2 shows the mentioned software settings.

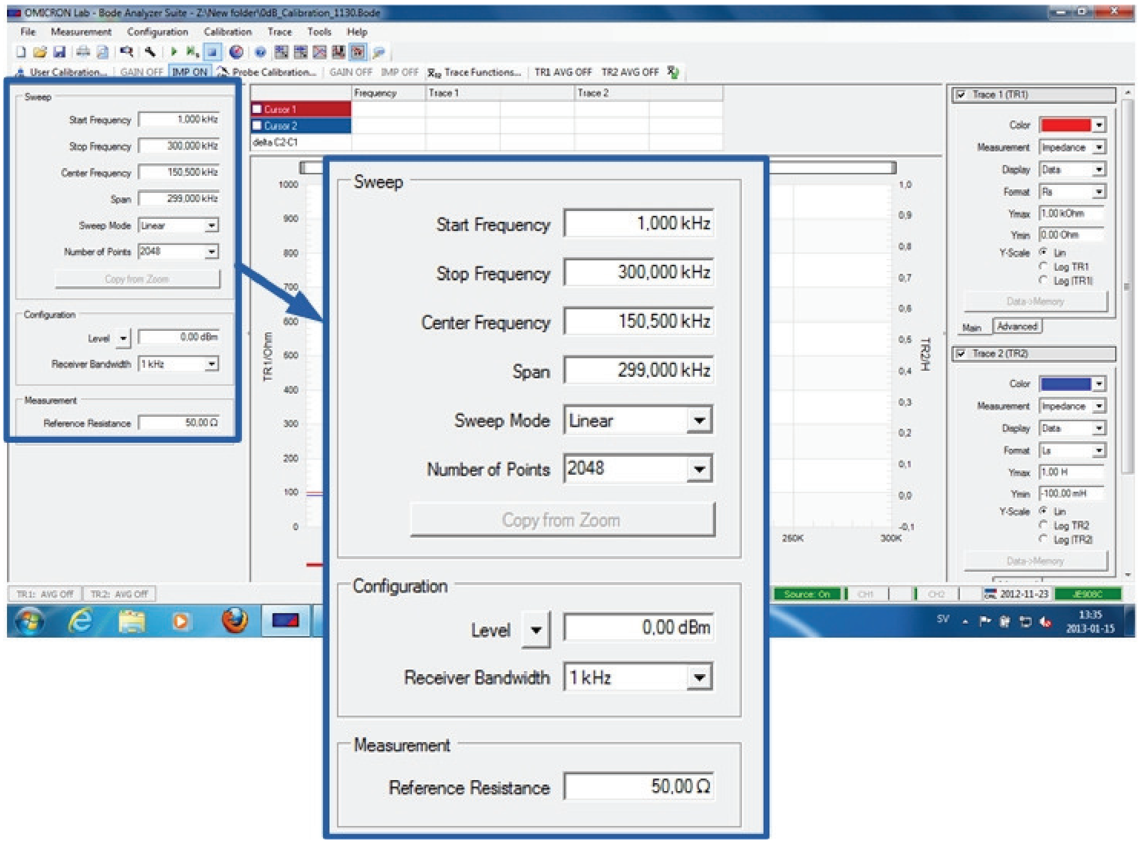

Fig. 4.2 Zoom of part of the Bode Analyzer Suite to show the measuring parameters.

After choosing the configuration parameters, the measuring equipment needs to be calibrated. Doing that calibration gives more accuracy to the instrument. The chosen one is the user calibration, because it is more accurate than the normal one. The calibration subtracts the effect of using the instrument's wires and the other equipment to measure. The instrument is calibrated after doing three different tests from the calibration menu as is shown in Figure 4.3 .

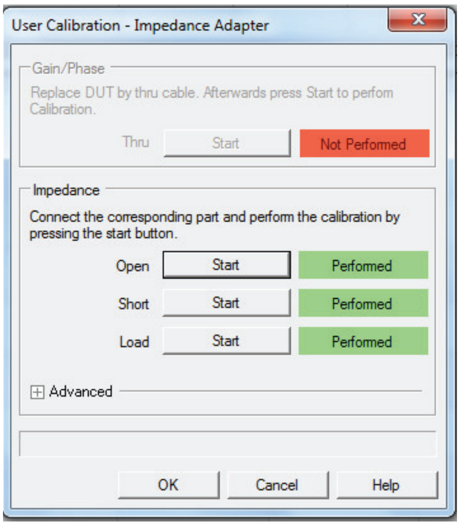

Fig. 4.3 Capture of the user calibration menu.

The calibration test consists of doing three measures, as shown next.

- The first is the open circuit test.
- The second is the short-circuit test.
- The third is the load test.

Figure 4.4 shows the way of doing the tests.

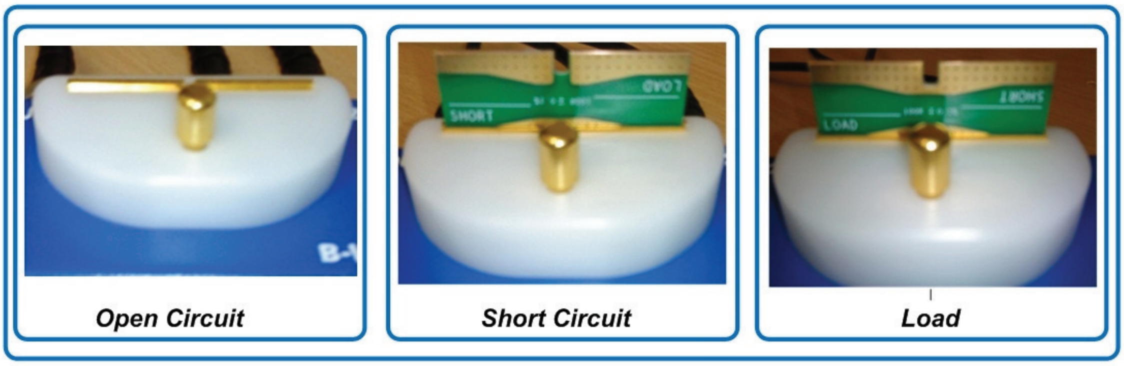

Fig. 4.4 Tests connections.

After doing that, the Bode 100 is ready and is possible to begin measuring. The experiment is aiming at determining the winding AC resistance, so the secondary or the primary of every transformer is shorted circuit; it depends on the transformer configuration. The not short-circuit side of the transformer is connected between the terminals of the B-WIC as is shown in Figure 4.5.

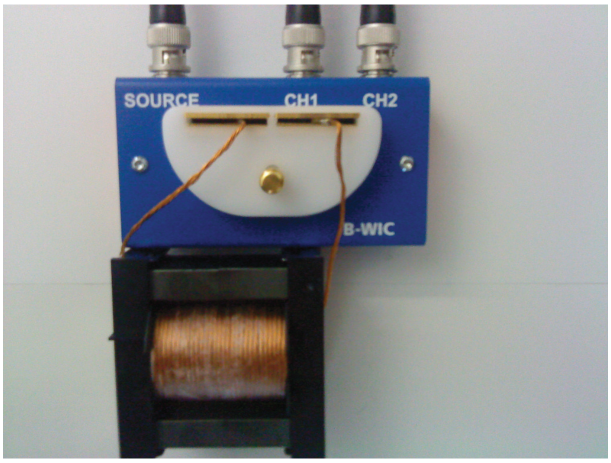

Fig. 4.5 Transformer connected to the impedance adapter B-WIC.

Then the single sweep mode is selected and when it has finished the values are saved in a file. This file must be processed, especially in the case that the winding is manufactured with foil, because the leads used to connect the foil conductor to the B-WIC increase the measured value. In order to subtract this error, the wire must be measured and saved. Using a Matlab script, the files are processed with the intention to eliminate the effect of the leads whenever needed.

Chapter 5

Results

The results that are shown in this chapter are the theoretical values and the measurements that have been obtained in this study. As it has been mentioned in the previous chapters. In this work three different types of transformers has been manufactured . In Appendix A.1 a list of all the electrical transformers that have been assembled for this thesis is attached . All the devices differ in the type of conductor and/ or other characteristics. In order to show the results that have been measured in the experiments, some cases are studied.

- Validate the measurement procedure for ultra low impedance.
- Influence of using copper foil conductor to manufacture the winding.
- Influence of using round magnetic wire to manufacture the winding.
- Influence of using litz wire to manufacture the winding.
- Comparing a litz wire winding with a round magnetic wire winding.
- Checking the DC resistance of the wires

5.1 Validate the measurement procedure for ultra low impedance.

The aim of the project is to evaluate the AC resistance of different types of windings, so a measuring procedure must be proven that is suitable for this research. In chapter 4, the measuring procedure and the equipment configuration were explained.

The transformer used to validate the acquisition method has been assembled with four layers in the primary winding and one foil layer in the secondary winding, so it is type A. The secondary side has been assembled with a fixed short circuit in order to decrease the losses that add others components.

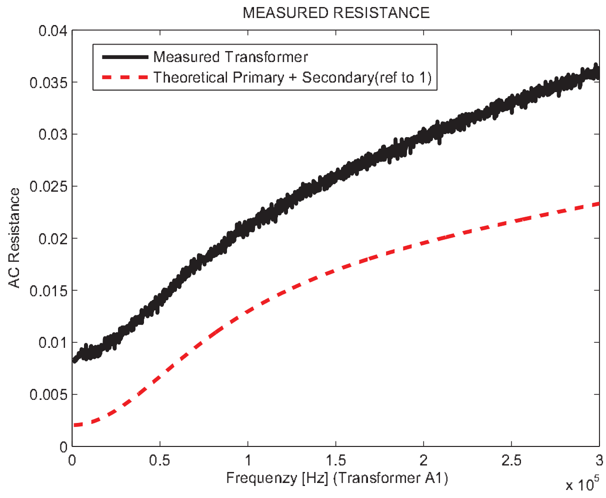

Fig. 5.1 Measuring results for transformer Type A

Figure 5.1 shows the results of measuring the windings from this device, as well as the estimated resistance for this case. Analyzing the displayed values, it is noticed that the acquired values are higher than the expected. So the manufacturing of this transformer was rechecked. It is found that two leads are welded at the primary's ends with the purpose to connect the winding to the Impedance Adapter. Because of that, an identical lead in the same sweep range as the transformer must be measured. After that, the effect of these leads was subtracted.

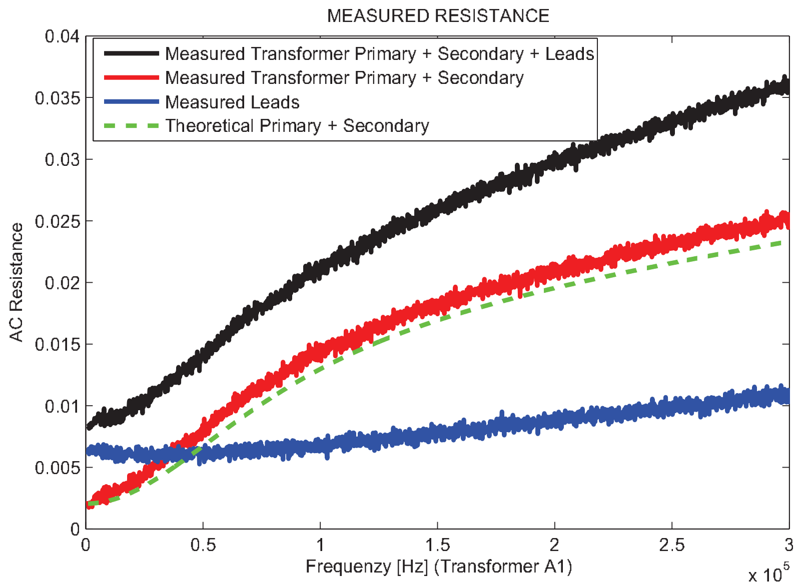

Fig. 5.2 A comparison between theory and measures.

As it is possible to see in the upper comparison, the values are more similar after discounting the leads; so the measuring procedure is validated.

5.2 Influence of using copper foil conductor to manufacture the winding.

The aim of using copper foil conductor to manufacture the device is related to the maximum current that can flow through the conductor. Different types of transformers have been assembled in order to study the effect of some parameters. In the foil winding experiment's two types of transformers are used: type A and type B. The foil winding research has been carried out in three ways.

- Validate the foil Resistance Factor equation.
- Analyze the effect of the winding's layer width.
- Analyze the effect of increasing the number of foil layers in the winding.

5.2.1 Validate the foil Resistance Factor equation.

The equation for calculating the foil resistance factor (2.26) has been used to obtain the resistance of both windings. In this part, the accuracy of this equation is shown with the intention to accept it to estimate the results. In order to do that, the measures from the transformer A1 have been used. That one has been processed and then the resistance measured from the primary have been separated into the primary and the secondary winding resistance.

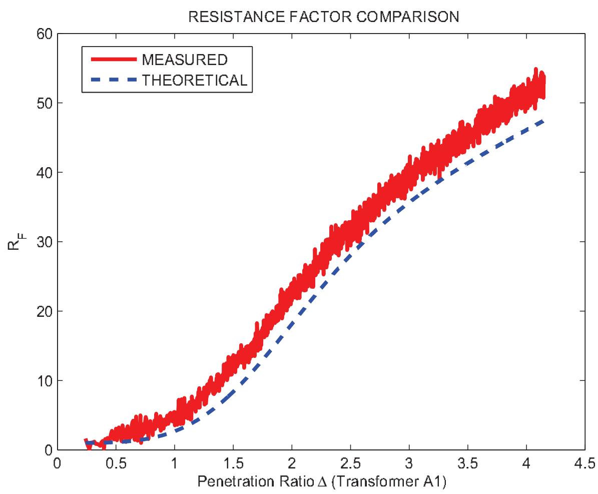

Fig. 5.3 One layer foil winding.

Figure 5.3 shows the resistance factor of one layer winding. The displayed values are closer, so the equation is valid.

5.2.2 Analyze the effect of the winding's layer width.

The layer's width is related to the cross-section of the foil conductor. The current goes through this section; so depending on the layer's width, the resistance of the winding is lower for higher values of width and higher for lower values of width.

In Figure 5.4 the theoretical resistance factor for different foil windings are shown. It has been estimated for various windings widths using (2.24). The AC Resistance values has also been calculated for the transformers of type B by using (2.19).

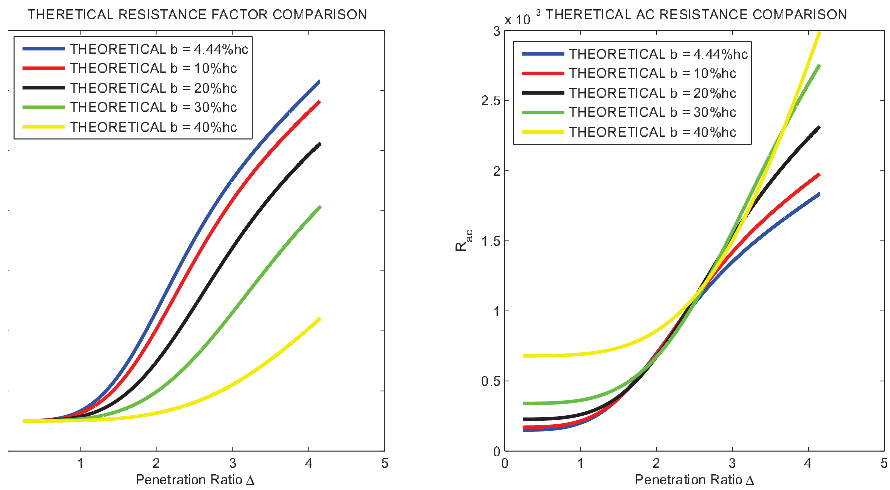

Fig. 5.4 Resistance factor for different widths

The following pictures represent the results of the transformers that have been measured to check the calculated values shown in Figure 5.4. These graphs show the comparison between the acquired and the estimated ones. It must be noticed that the results are composed of the primary and the secondary winding resistance, because of that, they are shown as function of frequency.

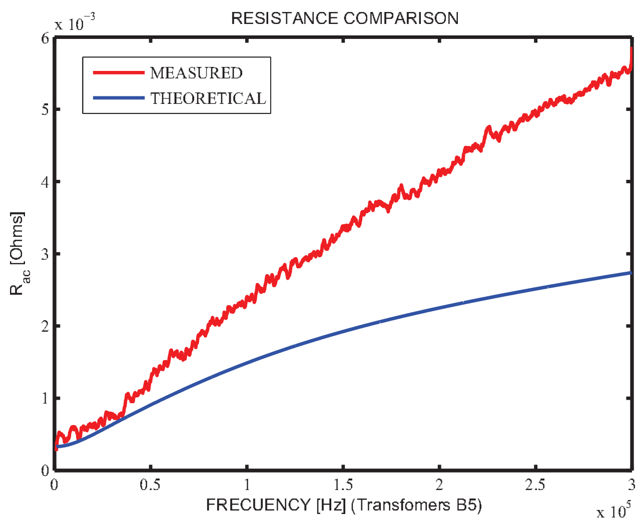

Fig. 5.5 A comparison between theoretical and measured values of transformer B5.

Figure 5.5 is the case where $b = 4.44\%h_c$ each measurement are related to transformer B5. As it is seen, the accuracy of the results in this case is not as good as expected. A probable cause is the low value of the foil winding resistance and the imprecisions of the manufacturing.

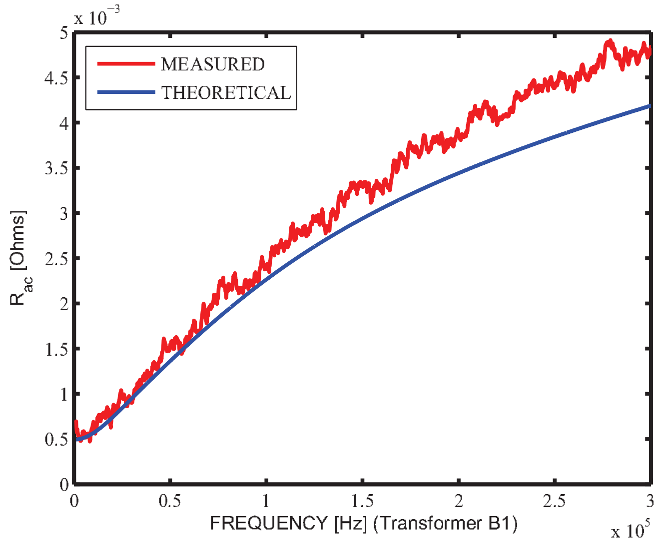

Fig. 5.6 A comparison between theoretical and measured values of transformer B1.

Figure 5.6 corresponds to case $b = 10\%h_c$, transformer B1. The acquired results of this device are closer to the calculated one, so the precision is checked and the proposed effects of the previous case are accepted.

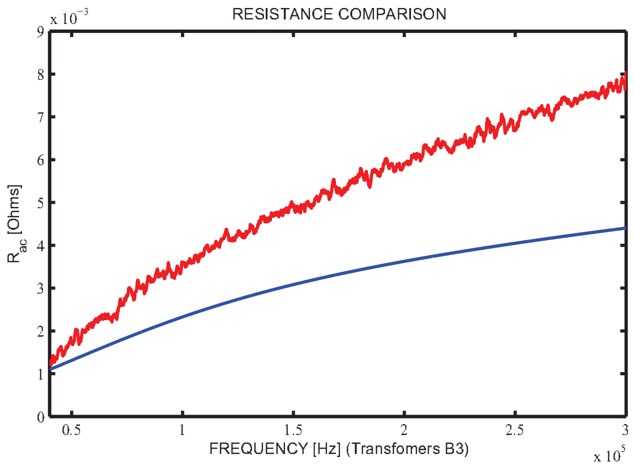

Fig. 5.7 A comparison between theoretical and measured values of transformer B3.

Figure 5.7 is related to $b = 30\%h_c$, transformer B3. As in the first device, the acquired values are higher than the calculated, so the reasons gave for $b = 4.44\%h_c$ are steel valid for this one too.

5.2.3 Analyze the effect of increasing the number of layers.

In order to have a deeper knowledge of the foil windings, a comparison between the different foil windings with the same width has been done. In that case the effect of increasing the number of layers employed to assemble the winding is analyzed .

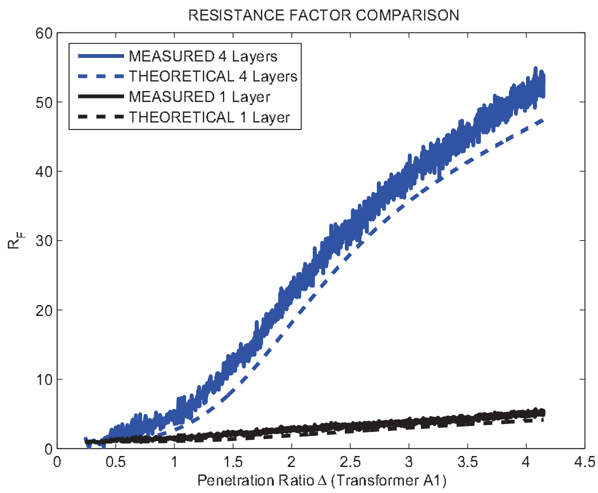

Fig. 5.8 A comparison between the theoretical values and the measured values of multilayers windings

Figure 5.8 the results of the theoretical and the measured values for one layer and four layers windings are shown. As it is can be seen, the expected factor is closer to the acquired one, but differs because of the effect of the wires used to connect the foil winding to the instrumental equipment and the consequence of being handmade.

5.3 Influence of using round magnet wire to manufacture the winding.

The most typical transformer´s windings are manufactured with round magnet wires, this type of conductor is the most common for assembling that devices. So in this subsection the theoretical resistance factor and the one obtained from the processed measures are shown. The representation of these two parameters allows to make the comparison and shows the accuracy of the equation to estimate these values as function of Δ.

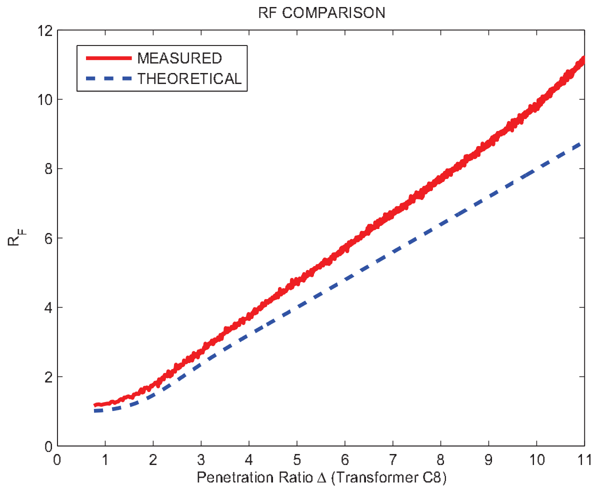

Fig. 5.9 A comparison between theoretical value and measured value of a 1.8mm round magnetic wire

In Figure 5.9 the resistance factor of a winding manufactured with 18 turns of 1.8mm magnetic wire is displayed. The results show that (2.31) is more accurate for lower values of Δ than for the higher ones.

5.4 Influence of using litz wire to manufacture the winding.

This experiment is done to analyze the effect of using Litz wire to manufacture the transformer´s winding and check the theoretical equation used to calculate the resistance factor. The transformers assembled for this research (type C) have been manufactured with different configurations in order to analyze the influence of parameter variationy. So it has been carried out in three ways:

- Validate the resistance factor equation for Litz wire winding.
- Compare litz wire winding manufactured with different number of strands.
- Compare several windings with different number of layers.

5.4.1 Validate the resistance factor equation for Litz wire winding.

Several documents have been checked in order to use the closest theoretical equation to the acquired values. So before utilizing (2.32), its accuracy must be verified . In order to have the lower influence of another kind of conductors in the winding the transformer for that test is assembled with litz wire windings in both sides.

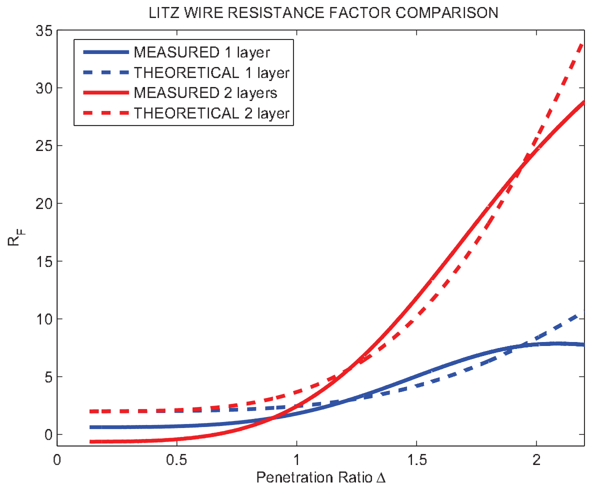

Fig. 5.10 A resistance factor comparison using the transformers C5

Figure 5.10 represents the calculated values and the measures values of the resistance factor. The diagram shows that during most of the time the measured results are a bit lower than the estimated ones, but for the other range happen the opposite. In general, the values for both cases are closer to the calculated ones, so the resistance factor equation is valid.

5.4.2 Compare litz wire winding manufactured with different number of strands.

The litz wires are built with several strands as was mentioned in the previous chapters. Some strands have been twisted with the aim of understanding the effect of the bundle number.

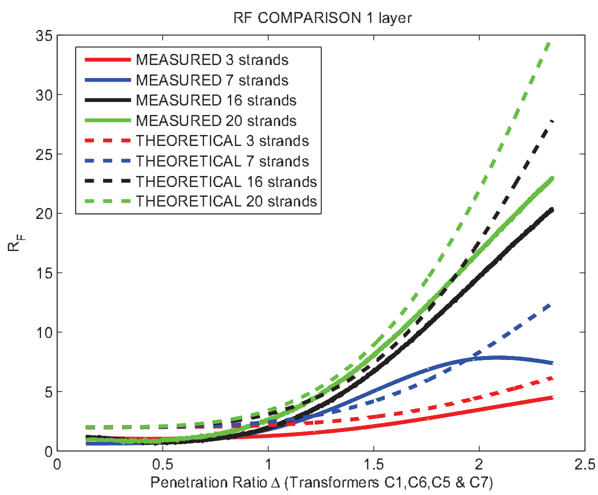

Fig. 5.11 A resistance factor comparison using the transformers C1, C5, C6 & C7

Figure 5.11 the resistance factor of four different types of litz wire used to manufacture the transformers winding are shown. It can be seen that the bundles with more number of strands present a higher resistance factor value. The reason for that effect comes from the dependency on the strands number of some coefficients of the resistance factor equation for litz wires (2.32). As it is done in the previous subsection, the theoretical values are checked but the results are only acceptable for some range of penetration ratio where the measured and the calculated factor are closer. Outside this range the theoretical results are higher than the measured ones, so it is still correct using this equation in order to overestimate the results instead of underestimating them; it must be noticed that some assumptions have been made for the resistance factor equation.

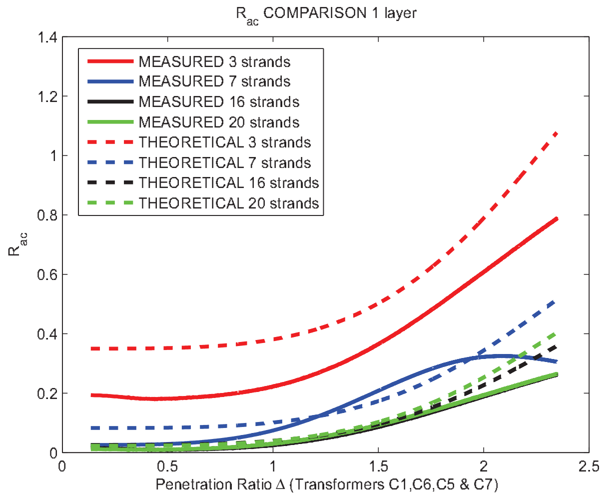

Fig. 5.12 An AC resistance comparison using the transformers C1, C5, C6 & C7

The diagram displayed in the figure 5.12 represents the AC resistance of the same litz wires used to analyze the resistance factor. It is also shown that the estimated values are closer to the acquired ones. It must be noticed that the winding's width is the same for all of them, so the number of turns per layer is different in all of them. In that case, the order of the result is the opposite of the previous one; the reason for that effect is found in the DC resistance of the litz wire. The DC resistance is lower for the litz wires with higher number of strands (2.33). The AC resistance of the sixteen strands litz wire winding and the twenty strands one is closer because of the bundle is similar and also the number of turns in a layer.

5.4.3 Compare several windings with different number of layers.

Transformer windings usually consist of several layers of conductors. In order to understand the effect of the number of layers in the winding's configuration some transformers have been built.

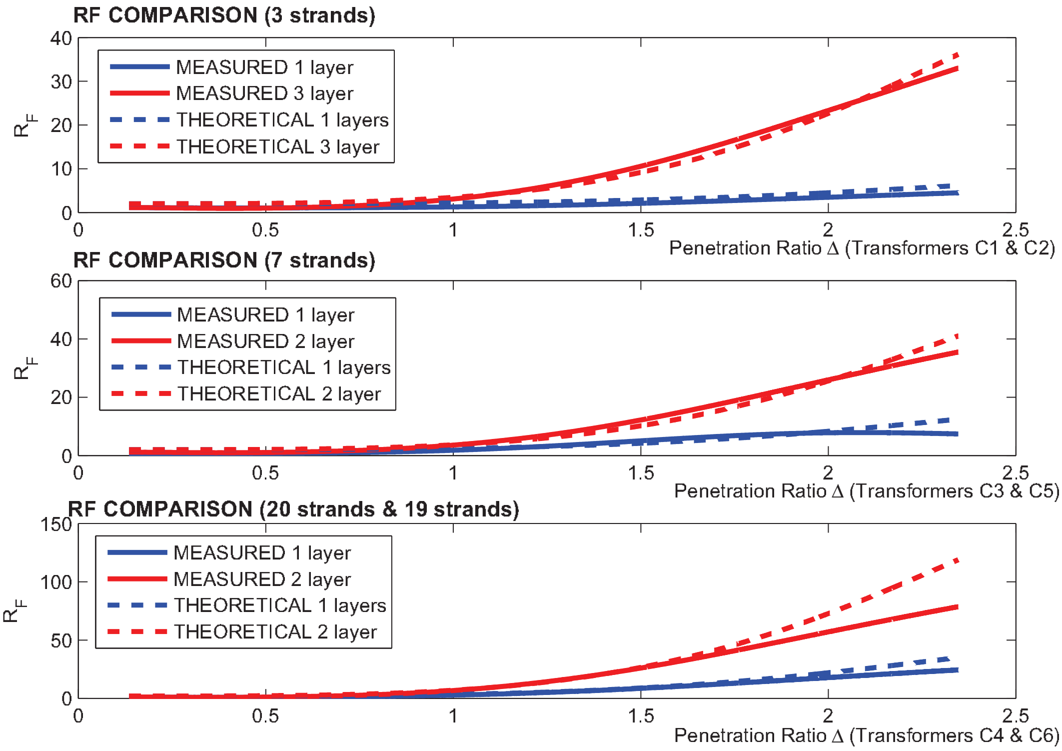

Fig. 5.13 A resistance factor comparison using the transformers C1 & C2 in the upper graph, C3 & C5 in the middle graph and in the down one C4 & C6

The graphs displayed in Figure 5.13 show the resistance factor or three types of litz wire windings. The upper graph displays the values for two types of windings manufactured with a three strands bundle. This comparison is done between a one layer winding an a three layers' one. The theoretical results in both cases are closer to the measured ones. The same findings can be made in the other two graphs. The middle one compares a one layer and two layers windings manufactured with a seven strands litz wire. The bottom graph shows the comparison between a one layer winding built with twenty strands bundle and a two layers winding manufactured with a nineteen strands one. The last comparison has been done since the number of strands is similar.

The resistance factor is similar at the beginning of each case. It is because just one of the parameters of (2.32) depends on the number of layers. So this coefficient does not influence so much during this period.

5.5 Comparing a litz wire winding with a round magnetic wire winding..

In this part, two types of windings have been considered. The comparison between the Litz wire and the magnet wire has been done in the range of the penetration ratio with the purpose of determining which type of that wires is better. The comparison has been carried out it two ways:

- Wires windings with the same cross section.
- Different wire windings with the same number of turns.

5.5.1 Wires windings with the same cross section.

In order to compare a litz wire with the most similar cross section of a magnetic wire some mathematical operations are needed. The following equations demonstrate how equal the cross section values of these wires are.

$$S_i = \frac{\pi d_i^2}{4} \tag{5.1}$$

$$S_{Bundle} = n_{Strands} * S_{Strand} \simeq S_{Wire} \tag{5.2}$$

$$n_{Strands} = \frac{S_{Wire}}{S_{Strand}} = \frac{\frac{\pi d_{Wire}^2}{4}}{\frac{\pi d_{Strand}^2}{4}} = \frac{d_{Wire}^2}{d_{Strand}^2} = \frac{(1.8mm)^2}{(0.4mm)^2} = 20.25Strands \simeq 20Strands \tag{5.3}$$

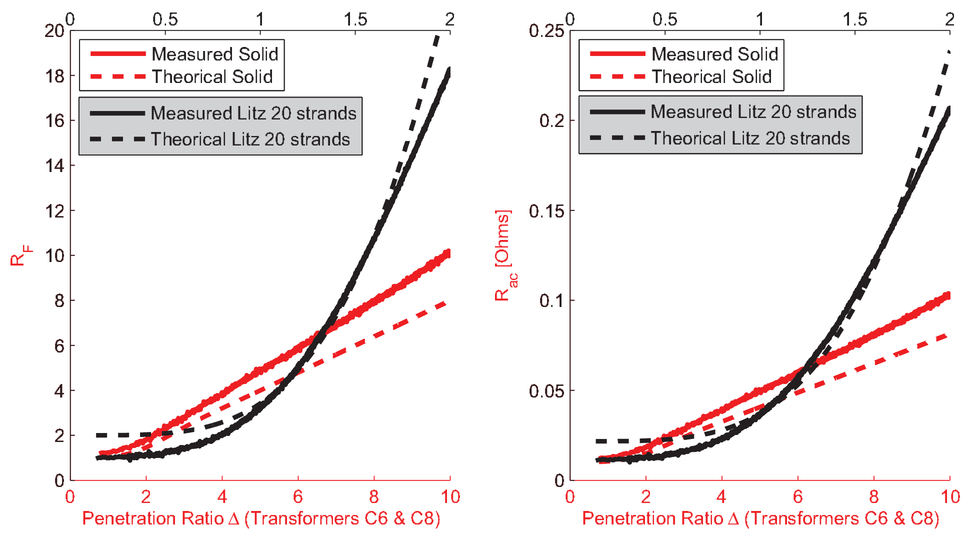

Fig. 5.14 A comparison between litz wire and magnet wire with the same cross section.

As can be seen in the figure 5.14, the Litz wire's resistance factor is lower during most of the magnetic wire penetration range. The same observation can be done for the wires AC resistance. The reason to employ Litz wire instead of using magnet wires is that the proximity effect and skin effect is lower.

5.5.2 Different wire windings with the same number of turns

A second comparison has been done between litz wires and round magnet wires. This one has been carried out with the same number of turns per layer. The litz wire used for this experiment is the closest one in order to have the same amount of turns in both devices, so in that case the diameter of the bundle and the magnet wires is similar. The number of strands is estimated using (2.34).

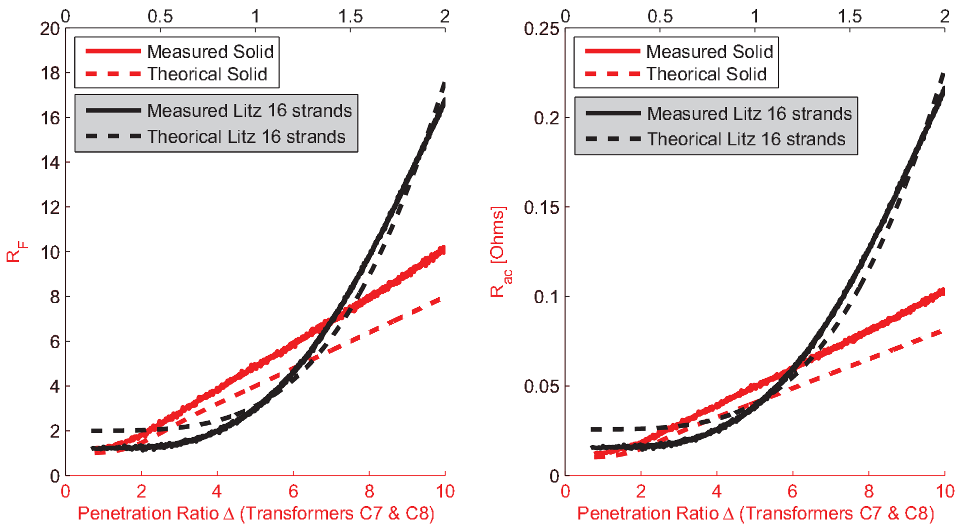

Fig. 5.15 A comparison between litz wire and magnet wire with the same number of turns per layer (same diameter).

The results display in Figure 5.15 are similar to the cross-section comparison (fig. 5.14), so the conclusions for the previous case are steel valid.

5.6 Checking the DC resistance of the wires

The DC resistance of some wires has been checked. This evaluation has been done in order to know the accuracy of the equipment for lower values of frequency because of the AC resistance values obtained in this frequency range (from 1Hz to 100 Hz) can be considered as DC resistance. This assumption could be done since the frequency influence on the resistance is very low.

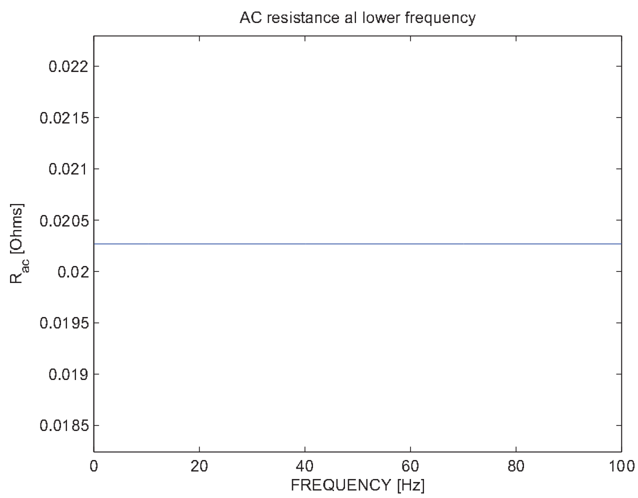

Fig. 5.16 The AC resistance of 1mm diameter magnet wire.

Figure 5.16 displays the calculated AC resistance of a round magnet wire. As it can be seen the AC resistance value is the same as the theoretical DC resistance for the round magnet wire shows in Table 5.1, so the previous assumption is valid for the conductors.

Table 5.1 DC comparison

Type of Wire	No strands	Theoretical R_{dc}	Measured R_{dc}	Length
Round Wire $(d = 1mm)$	-	$20.3m\Omega$	$20m\Omega$	0.925m
Litz Wire $(d_s = 0.4mm)$	3	$107.7m\Omega$	$109.8m\Omega$	2.36m
Litz Wire $(d_s = 0.4mm)$	7	$17.9m\Omega$	$16.4m\Omega$	0.915m
Litz Wire $(d_s = 0.4mm)$	16	$5.3m\Omega$	$4.6m\Omega$	0.62m
Litz Wire $(d_s = 0.4mm)$	20	$4.5m\Omega$	$3.7m\Omega$	0.65m

Table 5.1 displays the results of several types of wires that have been measured. In all the cases, the expected results are close to the measured ones; so the equipment proves that is able to measure with good accuracy ultra-low impedance also at a lower frequency range. The previous theoretical values have been calculated with (2.30) in the case of round conductors and with (2.33) if they are Litz wire. The measured values are the average of the results obtained in this frequency range.

Chapter 6

Conclusions

6.1 Conclusions of the present thesis work

In this thesis, an analysis of transformer's winding AC resistance in a defined frequency range (from 1kHz to 300kHz) has been carried out. The electrical devices have been manufactured with three different types of conductors: foil, round magnet wire and litz wire.

First of all the necessary transformers for the research were built. In order to do that, the transformers listed in Appendix A.1 together with other components like the litz wire have been assembled. The procedures to manufacture all these components are shown in the chapter 3. It must be noticed that all these items are handmade so the results of the research could be affected.

Secondly a measuring procedure was implemented, which is necessary to validate before obtaining the first results. The accuracy of several equipments available in the Electrical Laboratories like: the Aritsu MS460B (Network Analyzer), the PicoScope 6000 Series from picotech, the Pearson Current Monitor model 2877 and finally the Bode 100 from Omicron Lab have been checked. The only one, found to be accurate to measure ultra-low impedance (in the range of milliohms) from the ones listed above is the Bode 100. This equipment perform the measurement task if the impedance adapter B-WIC is used. So it has been confirmed that all the equipments are not useful in the available configurations to measure ultra-low impedances.

Thirdly the classical theoretical equations are collected. The mathematical expression have been obtained from several documents. The foil and round wire equations have been obtained from Dowell's [3].The mathematical expression for litz wires is the one that takes more time to be validated. In order to find an accurate equation, several documents have been checked but just one is acceptable; Tourkhani and Viarouge [4].

Then, the evaluation of the theoretical equations has been carried out. With the purpose of admitting the expressions, the comparison with the real values should be done. So the transformers manufactured for that intention are measured. After checking the results of the acquired values and the calculated ones, it is possible to see that the equations are acceptable to be used in most of the range with good accuracy. The accuracy error depends on the impedance magnitude and the frequency. The discrepancy between measured and theoretically obtained values at the acquired measurements is $\pm 40\%$ or even worse at medium frequency range and $\pm 10\%$ at higher frequencies. The discrepancy is higher in medium frequency because of the ultra-low impedance magnitude is closer to the equipment's resolution. It should be noticed that the measurements have been acquired outside the resolution range validated by OMICRON LAB, the manufacturer of the Bode 100.

Finally, it also has been found that the measurements can be affected with external components necessary to manufacture the transformers, so it is suggested that the effect of these components must be subtracted.

6.2 Future work

The present work is the beginning of a large research effort, so there are lots of topics that can be carried out: the themes could be analyzing the interleaving effect, the type of core ... In order to keep on these topics more transformers should be assembled with different configurations to analyze these effects. Moreover, a thermal study of each transformer to determine the optimal design would be very valuable.

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Appendix A

TECHNICAL DOCUMENTATION

A.1 Transformers List

TRANSFORMERS LIST

TYPE	
A	FOIL-FOIL
B	FOIL-WIRE
C	WIRE-WIRE

NOTE: hc = 45mm

TYPE	NAME	PRIMARY SIDE						SECONDARY SIDE						Others	
		m1 (layers)	N1 (turns in a layer)	Type of conductor	D1_start (mm)	D1_end (mm)	Lp (mm)	m2 (layers)	N2 (turns in a layer)	Type of conductor	D2_start (mm)	D2_end (mm)	Ls (mm)	d_HV (mm)	a (mm)
A	A1	4	1	FOIL d_w = 0.5 mm b = 10%hc (hw = 36 mm)	24,75	32,25	14,25	1	1	FOIL d_w = 0.5 mm b = 10%hc (hw = 36 mm)	35	36	17,75	1,375	1,75
B	B1	2	1	FOIL d_w = 0.5 mm b = 10%hc (hw = 36 mm)	25,5	31	14,125	1	37	MAGNETIC WIRE d = 1 mm	35	37	18	2	2,25
B	B2	2	1	FOIL d_w = 0.5 mm b = 20%hc (hw = 27 mm)	25,5	31	14,125	1	37	MAGNETIC WIRE d = 1 mm	35	37	18	2	2,25
B	B3	2	1	FOIL d_w = 0.5 mm b = 30%hc (hw = 18 mm)	25,5	31	14,125	1	37	MAGNETIC WIRE d = 1 mm	35	37	18	2	2,25
B	B4	2	1	FOIL d_w = 0.5 mm b = 40%hc (hw = 9 mm)	25,5	31	14,125	1	37	MAGNETIC WIRE d = 1 mm	35	37	18	2	2,25
B	B5	2	1	FOIL d_w = 0.5 mm b = 4.44%hc (hw = 41 mm)	25,5	31	14,125	1	37	MAGNETIC WIRE d = 1 mm	35	37	18	2	2,25
B	B6	2	1	FOIL d_w = 0.9 mm b = 30%hc (hw = 41 mm)	25,5	32,5	14,5	1	37	MAGNETIC WIRE d = 1 mm	35	37	18	1,25	2,25
C	C1	1	20	MAGNETIC WIRE d = 1.8 mm	24,75	28,5	13,3125	1	40	LITZ ns = 3 strands; ds = 0,4 mm	29,5	31,5	15,25	0,5	1,75
C	C2	1	20	MAGNETIC WIRE d = 1.8 mm	24,75	28,5	13,3125	3	42	LITZ ns = 3 strands; ds = 0,4 mm	29,5	34,5	16	0,5	1,75
C	C3	1	20	MAGNETIC WIRE d = 1.8 mm	24,75	28,5	13,3125	2	29	LITZ ns = 7 strands; ds = 0,4 mm	29,5	34	15,875	0,5	1,75
C	C4	1	20	MAGNETIC WIRE d = 1.8 mm	24,75	28,5	13,3125	2	16	LITZ ns = 19 strands; ds = 0,4 mm	29,5	37	16,625	0,5	1,75
C	C5	1	26	LITZ ns = 7 strands; ds = 0,4 mm	24,75	27	12,9375	2	29	LITZ ns = 7 strands; ds = 0,4 mm	28	32,5	15,125	0,5	1,75
C	C6	1	20	MAGNETIC WIRE d = 1.8 mm	24,75	28,5	13,3125	1	16	LITZ ns = 20 strands; ds = 0,4 mm	29,5	33,5	15,75	0,5	1,75
C	C7	1	18	LITZ ns = 16 strands; ds = 0,4 mm	24,75	28,5	13,3125	1	18	MAGNETIC WIRE d = 1.8 mm	29,25	32,5	15,4375	0,375	1,75
C	C8	1	18	MAGNETIC WIRE d = 1.8 mm	24,75	28,5	13,3125	1	18	MAGNETIC WIRE d = 1.8 mm	29,5	33	15,625	0,5	1,75

Fig. A.1 List of all the transformers built for the reseach

Appendix B

MATLAB SCRIPTS

B.1 DC Resistance Functions

B.1.1 Copper Foil DC Resistance

```
function [Rdc] = Calc_Foil_Rdc(l_w,d_w,h_w,m)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Calculate the DC Resistance of a conductor.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Inputs:
%       l_w:    length of the middle layer      [m]
%       d_w:    thickness of the conductor      [m]
%       h_w:    width of the layer              [m]
%       m:      number of layers                []
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Outoputs:
%       Rdc:    Resistance value
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Cooper parameters
sigma = 58.108*10^6; %copper conductivity [S/m]
mu = 1.256629*10^-6; %copper permeability [H/m]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Rdc = l_w .* m ./(d_w .* sigma .* h_w);

end
```

B.1.2 Round Magnetic Wire or Litz Wire DC Resistance

```
function [Rdc] = Calc_Rdc(l_w,d,m,ns,N)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%   Calculate the DC Resistance of a conductor.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Inputs:
%       l_w:    length of the middle layer      [m]
%       d:      diameter of the conductor       [m]
%       h_w:    width of the layer              [m]
%       m:      number of layers                []
%       N:      number of turns in one layer    []
%       ns:     number of strands if there are more than one []
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Outoputs:
%       Rdc:    Resistance value
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Cooper parameters
sigma = 58.108*10^6; %copper conductivity [S/m]
mu = 1.256629*10^-6; %copper permeability [H/m]


Rdc = 8 *l_w *m *N /(sigma *ns * (d.^2));

end
```

B.2 Resistance Factor Functions

B.2.1 Copper Foil Resistance Factor

```
function [RF] = Calc_Foil_RF(d_w,freq,m,hw,hc)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Calculate the DC Resistance of a conductor.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Inputs:
%       d_w:    thickness of the conductor      [m]
%       freq:   frequency range                 [Hz]
%       m:      number of layers                []
%       h_w:    Foil width                      [m]
%       h_c:    Winding available width         [m]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Outoputs:
%       RF:     Resistance Factor               []
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Cooper parameters
sigma = 58.108*10^6; %copper conductivity [S/m]
mu = 1.256629*10^-6; %copper permeability [H/m]

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
delta = sqrt(1./(pi.*mu.*sigma.*freq));

Delta = d_w./delta;
nu_w = hw/hc;
Delta = sqrt(nu_w).*Delta;
```

```
T1 = (sinh(2.*Delta) + sin(2.*Delta))./(cosh(2.*Delta) - cos(2.*Delta));
T2 = (sinh(Delta) - sin(Delta))./(cosh(Delta) + cos(Delta));

RF = Delta.*(T1 + (2/3).*(m.^2 - 1).*T2);


end
```

B.2.2 Round Magnetic Wire Resistance Factor

```
function [RF] = Calc_RF(d_w,freq,m,hc,N)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Calculate the DC Resistance of a conductor.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Inputs:
%       d_w:    thickness of the conductor      [m]
%       freq:   frequency                       [Hz]
%       m:      number of layers                []
%       hc:    Winding available width         [m]
%       N:      number of turns                 []
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Outoputs:
%       Rac:    Resistance value
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Cooper parameters
sigma = 58.108*10^6; %copper conductivity [S/m]
mu = 1.256629*10^-6; %copper permeability [H/m]



delta = sqrt(1./(pi.*mu.*sigma.*freq));

Delta = d_w./delta;
nu_w = N*d_w/hc;
Delta = sqrt(nu_w).*Delta;

T1 = (sinh(2.*Delta) + sin(2.*Delta))./(cosh(2.*Delta) - cos(2.*Delta));
T2 = (sinh(Delta) - sin(Delta))./(cosh(Delta) + cos(Delta));

RF = Delta.*(T1 + (2/3).*(m.^2 - 1).*T2);


end
```

B.2.3 Litz Wire Resistance Factor

```
function [ RF ] = Tourkhani_and_Viarouge(layers,N_strands,d_strand,d_wire,freq)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% TOURKHANI_AND_VIAROUGE Method RF for Litz Wires
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Index
% ---------------------------------------------------------------------
% d_wire = Diameter of a conductor [m]
% d_strand = Diameter of a strand [m]
% freq = Frequency [Hz]
% N_strands = Number of conductors in the bundle
% layers = Number of layers


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   COPPER PARAMETERS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sigma = 58.108*10^6; %copper conductivity [S/m]
mu = 1.256629*10^-6; %copper permeability [H/m]


delta_w =  1./sqrt(pi.*mu.*sigma.*freq);

xi = d_strand./(sqrt(2).*delta_w);




% Packing factor
pf = N_strands.*((d_strand./d_wire).^2);



F1 = 2.*sqrt(2).*((1./xi)+((xi.^3)/(3.*(2.^8)))-((xi.^5)/(3*(2^14))));
F2 = (1/sqrt(2))*(-((xi.^3)./(2^5))+((xi.^7)/(2^12)));


% RESISTANTE FACTOR
RF = (xi./sqrt(2)).*(F1-((pi.^2).*N_strands.*pf./24).*(16.*(layers.^2) -1+(24./(pi↩
    .^2))).*F2);


end
```