Measurement and modelling of earthing impedance in ships (DC-30MHz)

Master of Science Thesis

BY

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Abstract

Consequence of disturbance due to fault of earthing of on-board systems are not always clear. Second, the military EMC standards are outdated and the rationale behind these standards lacks. Therefore, research into rationale of standards and directives related to system earthing on board is necessary; in addition, develop appropriate on-board earthing models and appropriate method to measure on-board ship earthing impedance is necessary.

There are two objectives of the project. From industrial point of view, this focusses on: how to measure and install earthing on board of ships. While scientific objective is how to develop a measurement method from which the DC resistance and HF impedance (up to several MHz) can be measured and finally build a general model which represents the on-board ship earthing.

A test set up of measuring earthing impedance regarding to well-defined environment is built in order to get high reproducibly. In addition, for the measurement impedance from DC to 30 MHz, two approaches are done: first, in the company, current supply and voltage meter, LCR meter and spectrum analyser is used to measure DC, low frequency (20Hz to 100 kHz) and high frequency (100 kHz to 30MHz) separately. The loop areas, cross section of wire and length influence on the impedance are studied. In the university, current supply, voltage meter, and impedance analyser are chosen to measure ten groups of wire which one point earthing and multiply earthing are studied. Finally, a general model using curve fitting method and based on ten groups of measurement is built which can be used to further analysis.

Key words: measurement, modelling, earthing wire, external inductance, loop inductance, internal inductance
Acknowledgement

After finishing this thesis, there is a necessity to express my gratitude to those people who have contributed to this study.

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List of Abbreviations

EMC: Electromagnetic Compatibility
EMI: Electromagnetic Interference
EMP: Electromagnetic Pulse
COTS: Commercial Off The Shelf
E³: Electromagnetic Environmental Effect
HF: High Frequency
DC: Direct Current
dB: Decibel
CM: Common mode
Chapter 1 Introduction

1.1 Background

1.1.1 Project ‘EMC for future ships’

On naval ships, equipment needs to meet a series of military standards in order to work properly in a well-defined military environment. Until now, it is a common practice to test the equipment first before install it on naval ships in order to meet the requirement for performance, robustness, safety and continuity. Due to the strict military standards, Commercial off-the-shelf (COTS) product should not be installed on military ships without hardening.

In order to reduce the cost, the hardened COTS equipment should be minimised and it is preferable to integrate the COTS equipment widely into a military environment. However, COTS equipment which bought from market only designed for civil use and the Electromagnetic Environmental Effect (E³) in naval ships are much serious than civil ships. Therefore, using COTS equipment could have a high risk of not getting the desired performance, robustness, safety and continuity. So, the challenge is how to integrate any COTS equipment in the E³ naval military environment without influence the performance, robustness safety and continuity.

Furthermore, military EMC standards are outdated and not focus on state of art technical development. This can be explained in three aspects: First, most military standards in use now are based on experiences and empirical measurements gained from many decades ago and far behind the technology development. Following these standards will not guarantee success in reducing EMC and will more easily lead to overkill measures in particular situations. As a result, EMC standards should be tailored by knowledgeable people to meet today’s technical development. Second, most experts who know these findings in the past of EMC standards, has already retired or move to other technical field, so the rationale behind these standards lacks which cause difficulty to tailor the standards. Third is the use of strict military standards puts more restrictions on the choice of equipment used on board which limited the use of residential, official, industrial and medicine product which bought from market[1].

1.1.2 Objective of the project

Due to reasons as mentions above, Damen shipyards has initiated an EMC project (EMC for future ships) together with partners (Imtech Marine, Thales, Ministry of Defence, Lloyd’s Register and University of Twente) which focus on widely implementation of COTS equipment in naval ships.

The purpose of this project is to gain knowledge of EMC consequences of implementation of COTS equipment in naval ships. This implementation results in cost reduction because COTS equipment should not be adjusted to meet military EMC standards. In addition, considerable number of COTS equipment meets less strict civil EMC standards. Scientific research is part of the initiate EMC project in which a PhD student from University of Twente focuses on implementation of COTS equipment in different EMC zones of a ship.
1.2 Problem definition

In naval ships, military 

\( E^3 \) differs from civil environment (for instance, strong field strengths, high EMC requirements). COTS equipment works well in civil environment, but could suffer a high risk when applied in military standards.

In an effect to use COTS equipment on military environment, Separate EMC protection zones are created **below deck** in order to integrate residential, office, industrial, medical COTS into military environment. The special EMC zone is like an isolation area on board and outside the EMC zone is military environment which suffers from strong field interference, while inside of the zone is civil environment which suitable for civil equipment use. Red enclosed environment in figure 1-1 shows the suggested areas (red zone, below deck) for COTS equipment use.

![Figure 1-1 Red enclosed environment is suggested for COTS equipment use](image)

![Figure 1-2 schematic diagram of EMC protection zone](image)
1.2.1 Problem caused by improper Earthing

As mentioned above, in order to install COTS equipment in the naval ships, some special EMC protection zones (figure 1-3) are created. The mitigation methods such as screening, filtering [6] are chosen to create such a zone. The screen and filtering often associated with proper earthing to serve as a zero potential point or a path for interference signal flow. so a good analysis of earthing is one of the essential mitigation measures for creating such an EMC protection zone.

![Figure 1-3 EMC zones on-board ships](image)

Most conceptions and rules related to earthing theory were established in previous generations and on that the frequency is low which could not cause much EMI problems. The earthing on that time is more concerned about safety reasons: protect from hazards caused by high voltage/current, which may be a threat to life or cause damage to equipment. It should be working under normal or fault operating conditions and is principally associated with relatively low frequency applications, such as power and lightning current surge.

However, with the evolution of modern technology, the widely used radar system and VFD (Variable frequency Driver) on-board could raise the maximum frequency up to several GHz. The earthing impedance becomes significant due to the inductance of conductors, which zero-equipotential surface is not valid any more [5]. Consequences of disturbances due to faults of earthing of on-board not always clear and lack of knowledge and comprehension of science behind the rules of earthing may results in either inadequate design, faulty and lacking and possibly hazardous results, or worse still, overdesign and a costly solution[5].

In summary, a proper earthing which keep a balance between electromagnetic interference control, safety, and good engineering practice is a necessary. It is a necessary to do the measurement of earthing cable and thus develop a mathematical model which help gain knowledge of suitable earthing methods as well as two points listed below.

1. EMC standards
There are basically two levels of EMC requirements (by governmental agencies and by the product manufacture) which are imposed on electronic system. The requirements mandated by governmental agencies are legal requirements and generally cannot be waived. If an electronic product to be sold in a country, it must comply with these requirements. Otherwise, the product cannot be legally sold. The EMC requirements of the manufacture imposed on their products are intend to satisfy their customers.

Likewise, there are two EMC standards which are applied for naval ships and civil ships. Different countries has their own military standards, for instance, in Mil-Std-1310G-1996[2](US), it requires that earthing wire/bond strap should provide less than 25 ohms impedance at 30 MHz in addition, Defence Standard 59-411[3](UK) requires the impedance of earthing wire/bond strap should provide less than 8 ohms at 10 MHz. However, the rationale of these methods/standards lacks. Therefore develop appropriate on-board earthing models and appropriate method to measure on-board ship earthing impedance is necessary.

2. Signal Integrity

![Figure 1-4 loop with CM-current](image)

One commonly practical installation of earthing is shown in figure1-4, a high frequency interference near the cabinet A,B caused a common mode current flow through a loop which the earth system to the cabinet ,cable, metal plate then back. The CM-current which flow through the cable will influence the signal carried inside the cable. More details information will be explained in figure1-5 below. So a study of earthing system as well as loop area could help analysing the signal integrity of the system.
A simple model to simulate figure1-4 is shown in figure1-5. The system is characterised by a signal generator \( (V_g, R_g) \), a load \( R_L \), ground track impedance \( Z_a \), the metal plate impedance \( Z_r \) and a common mode interference \( V_{cm} \). The book ‘Analysys-method EMI-problem’ [8] only analysis the situation that the earthing wire as an ideal earthing, with no impedance, however, in high frequency, the earthing connection is not ideal any more. So neglecting the earthing analysis may cause inadequate analysis and thus cause EMI problem. In summary, a model of earthing system is quite necessary in analysis EMI problem on-board ships.

1.2.2 Frequency range

In ships, VFD (variable-frequency drive 500 kW - 10 MW), and HFSSB (High frequency single-sideband>100W) are two mainly emitters, which cause the high frequency interference on board.

HF SSB means High frequency Signal sideband. It is commonly used on-board ships to send and receive signals. The interference that the frequencies range of HF SSB is known, typically from 1700Hz to 30MHz [2].

Figure1-6 possible devices cause interference on-board ships
Equipment which could also cause interference on-board ships is Variable Frequency Driver (see figure1-6), which is widely used in driving motors. In VFD the high switching on/off of IGBT is the main cause of high frequency interference. For example, the switch on action, when the IGBT is switched on, the current grows very sharply in a very short time. The high di/dt will cause the electromagnetic interference to the environment. According to EMC-Practical Installation guidelines [3], the upper frequency range for VFD on board ships is 30MHz. So, the interest frequency range is generally chosen from DC to 30MHz, but this could vary with different situation.

1.3 Research content and Objectives of the project
As mentioned above, first, consequence of disturbance due to fault of earthing of on-board systems are not always clear. Second, the military EMC standards are outdated and the rationale behind these standards lacks. Therefore, research into rationale of standards and directives related to system earthing on board is necessary; in addition, develop appropriate on-board earthing models and appropriate method to measure on-board ship earthing impedance is necessary.

Multiple earthing methods are applied for system earthing on ship, for instance, green/yellow wire, litze wire or copper bar. Further, different measurements methods exist which are able to measure DC resistance and HF impedance of different on-board applied earthing method.

Researches and measurements will be done in laboratory environment which look into DC resistance and RF impedance measurement method. Analysis of the measurements results are necessary to build a model form which insight knowledge can be gained of a suitable earthing method (for both safety and signal earthing).

There are two objectives of the project. From industrial point of view, this focusses on: how to measure and install earthing on board of ships. While scientific objective is how to develop a measurement method from which the DC resistance and HF impedance (up to several MHz) can be measured and finally build a general model which represents the on-board ship earthing.

1.4 Approach and outline
Chapter1 explains first the introduction of my project, then the problem which is find the best practical earthing method on-board ships and a general model of the earthing system and finally the approaches to solve the problem.

Chapter2 first studied the earthing types on board, the length cross section and loop area influence on the impedance. Then, an overview of test methods and test equipment which can be used to perform the measurement is done. Finally, a well-defined test set up is built to get the measurement data more reproducible and trustful.

Chapter3 two approaches of performing the measurement are proposed and research based on the measurements data are done to analysis the loop area, cross section and length of test wire influence on impedance. Some practical installations of earthing wire are proposed.
Chapter 4 mainly involved ten groups of wire measured by impedance analyzer. Ten models base on the measurement data and using curve fitting method are built. A general model of these ten groups of wires is introduced.

Chapter 5 conclusion part and figure 1-7 gives the flow chat of the project.

| Goal | measurement and modelling of earthing on-board  
DC-30Mhz |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Research on measurement methods, equipment and test set up</td>
<td></td>
</tr>
<tr>
<td><strong>Approach 1</strong></td>
<td><strong>Approach 2</strong></td>
</tr>
<tr>
<td>Power supply + voltage meter (DC)</td>
<td>Power supply + voltage meter (DC)</td>
</tr>
<tr>
<td>LCR meter (20Hz-100kHz)</td>
<td>Impedance analyzer (40Hz-30MHz)</td>
</tr>
<tr>
<td>Spectrum analyzer (100kHz-30MHz)</td>
<td>LCR meter (verification 20Hz-100kHz)</td>
</tr>
<tr>
<td>Practical installation of earthing on-board</td>
<td>Model of ten groups of wire</td>
</tr>
<tr>
<td>conclusion</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1-7 flow chat of the project

1.5 Reference


[6] High frequency EMC mitigation techniques for telecommunication installations (Basic EMC Recommendation), ITU-T Recommendation K.37

[7] EMC and cable ducts, Gouda holland

Chapter 2 Overview of on-board earthing and test set up
This chapter consists three parts: first part is research on-board wires, which mainly discuss earthing types and impedance of internal and external of wire. Second part studied the measurement methods and measurement equipment which could be used on measuring earthing impedance in the lab environment. Finally, a test set up for measuring impedance wire from DC to 30MHz is proposed.

2.1 On-board Earthing

2.1.1 Earthing types

\[\text{(a) One point earthing} \quad \text{(b) multiple points earthing}\]

Figure 2-1 earthing type

Two earthing types are listed in figure 2-1. One point earthing is to connect one earth lead between cabinet and metal plate. And multiple points earthing is connect 2 or more earthing leads between cabinet and metal plate on ships. Usually, two earthed cabinets communicate with each other through cables, for instance, coaxial cable. If there are some high frequency interferences near the two cabinets, it will cause common mode current through the cable and will influence the signals carried by the cable, as shown in figure 2-2.

Figure 2-2
2.1.2 Earthing leads
As shown in table 2-1, green/yellow wire, earth strap (litze wire) and copper bar are three commonly used earthing leads on-board ships.

<table>
<thead>
<tr>
<th>Earthing type</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green/Yellow wire</td>
<td><img src="image" alt="Green/Yellow wire" /></td>
</tr>
<tr>
<td>Earth strap</td>
<td><img src="image" alt="Earth strap" /></td>
</tr>
<tr>
<td>Copper bar</td>
<td><img src="image" alt="Copper bar" /></td>
</tr>
</tbody>
</table>

Table 2-1 different type of earthing leads

Figure 2-3 shows practical situations of install green/yellow wire and earth strap on-board.

![Figure 2-3 earthing connection on-board ships](image)

2.2 Resistance and inductance of wires
For a round wire, it has an internal inductance, internal resistance as well as external inductance [4][5][6][7]. So internal resistance, inductance and external inductance are studied in the following part.
Some formulas from [4] [5] [6] [7] [8] [9] are used in theoretical calculation. These calculate values can function as a guideline in measuring the impedance of wire further.

Before the calculation, some parameters of wire should be well-defined. The term wire refers to conductors which consist of one or more solid, circular, cylindrical conductors. The wire has radius $r_w$ and conductivity $\sigma$. In practical, the most used conductor material is copper (Cu), which has conductivity $\sigma_{cu} = 5.8 \times 10^7 \, \text{S} / \text{m}$. In addition, the conductor is not ferromagnetic. So, its permeability

$$\mu = \mu_0 = 4\pi \times 10^{-7} \, \text{H} / \text{m}.$$ 

also the permittivity of virtually all conductors is equal to free space,

$$\varepsilon = \varepsilon_0 \equiv (1/ 36\pi) \times 10^{-9} \, \text{F} / \text{m}.$$ 

### 2.2.1 Internal resistance and inductance

#### 2.2.1.1 Calculation the internal resistance and inductance

The dc resistance of a round wire of radius $r_w$, conductivity $\sigma$, the total length $L$ is given by

$$R = \frac{L}{\sigma\pi r_w^2} \, \Omega$$ 

(Eq2-1)

As the frequency increased, most AC current tend to flow on the surface because of a phenomenon which known as skin effect. An important term ‘skin depth’ refers to the thickness which current concentrate in an annulus at the wire surface, which shown in figure2-4.

![Figure 2-4 skin depth of a round wire](image)

The skin depth of a copper can be calculated by the equation below [4]:

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}} = \frac{6.6 \times 10^{-2}}{\sqrt{f}} \, \text{m}$$ 

(Eq2-2)

Table 2.2 shows the skin depth of a copper at different frequencies.

<table>
<thead>
<tr>
<th>F</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60Hz</td>
<td>8.5mm</td>
</tr>
</tbody>
</table>
Table 2-2 skin depth of copper at different frequency

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Skin Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>1KHz</td>
<td>2.09mm</td>
</tr>
<tr>
<td>10kHz</td>
<td>0.66mm</td>
</tr>
<tr>
<td>100kHz</td>
<td>0.21mm</td>
</tr>
<tr>
<td>1MHz</td>
<td>0.066mm</td>
</tr>
<tr>
<td>10MHz</td>
<td>0.021mm</td>
</tr>
<tr>
<td>30MHz</td>
<td>0.0121mm</td>
</tr>
<tr>
<td>100MHz</td>
<td>0.0021mm</td>
</tr>
</tbody>
</table>

Current will concentrate around the surface of the wire and the resistance and inductance will no longer the same as DC. Considering the skin effect:

For \( r_w << \delta \), \( r_{ij} = r_{dc} = \frac{1}{\sigma \pi r_w^2} \ (\Omega/m) \)  
\[(Eq 2-3)\]

For \( r_w >> \delta \), \( r_{ij} = \frac{1}{\sigma [\pi r_w^2 - \pi (r_w - \delta)^2]} \approx \frac{1}{\sigma 2 \pi r_w \delta} = \frac{r_w}{2 \delta} r_{dc} = \frac{1}{2r_w} \sqrt{\frac{\mu_0}{\pi \sigma}} \sqrt{f} \ (\Omega/m) \)  
\[(Eq 2-4)\]

Due to magnetic flux internal to the wire, the isolated wire has an inductance which called internal inductance, it also changed with frequency. The internal inductance is derived in [5] as

In low frequency, \( r_w << \delta \)

\[ L_{ij} = \frac{\mu_0}{8\pi} = 0.5 \times 10^{-7} H/m \]  
\[(Eq 2-5)\]

In high frequency, \( r_w >> \delta \)

\[ L_{ij} = \frac{2\delta}{r_w} L_{dc} = \frac{1}{4\pi r_w} \sqrt{\frac{\mu_0}{\pi \sigma}} \frac{1}{\sqrt{f}} \]  
\[(Eq 2-6)\]

2.2.1.2 Model of skin effect

In high frequency, the current in the conductor tend to on the surface of the conductor. It will cause the internal inductance decrease with frequency (Eq2-6), in the same time, the high frequency resistance become significantly large. Some skin effect model has been come up by[6][7][8] and the current flow at different frequencies of M rings as shown in figure 2-5(a). the equivalent circuit consist of M resistors and M-1 inductors is shown in figure 2-5(b).

.........

(a) Round wire divided into M rings

\[ R_i = \frac{1}{Ai\sigma} \]  
\[ (Eq2-7) \]

\[ L_i = \frac{\mu(r_{i-1} - r_i)}{2\pi r_i} \]  
\[ (Eq2-8) \]

In the practical computation, the value of M can be a number, for example 3, or 5 and a constant resistor ratio \( R_i \) is maintained. The more the rings divided, the more precise the results. A model of four ladder compact model is proposed by [10].

### 2.2.2 External inductance

#### 2.2.2.1 Calculation of Loop inductance

External inductance always follows with the concept ‘loop’. Current come from the source to the wire and need a return path to flow back to the source which form a ‘loop’. If the loop area is S, the total magnetic flux penetrating the loop \( \psi \) and the inductance L can be calculated by [5]

\[ L = \frac{\psi}{I} \]  
\[ (Eq2-9) \]
Where,  

\( \psi = \int_B \cdot d\hat{s} \)  

(Eq2-10)

B is magnetic flux density and s is the loop area. It can be seen the inductance proportional to the loop area.

\[ B \psi \]

\[ \text{Figure2-6 external inductance} \]

Computing the loop inductance of a structure requires that the complete current loop need to be identify. For ‘intentional’ inductors this current loop is quite obviously. For example, if we wind several turns around a ferromagnetic toroid core, the loop area of the current that the magnetic flux passes through is evident. So it is quite easy to calculate the intentional inductors using loop inductance for it is virtually ‘by design’.

However, in some cases, as explained in [5], it is impossible to determine the complete loop(figure2-6) due to today’s currents having ever-increasing spectrum content. In addition to that, the completer path for current flow depends also on frequency. For one frequency, the return current will take a particular path. However, in a higher frequency, the path of the return current may be entirely different. In the same time, since the loop inductance is a property of the entire loop, so it is impossible to associate the loop inductance with any particular segment of the loop.

2.2.2.2 Partial inductance

Due to the reasons list in chapter2.2.2.1,’ It is useful to develop a lumped-circuit model of a closed current loop wherein the segments of the perimeter of the loop area are represent with a self-inductance as well as that segment and other segments of this and other adjacent current loops, the concept partial inductance allows us to do that in a unique way’ explained in the book [5].
An alternative way to calculate the inductance is by using vector magnetic potential $\vec{A}$, which is defined by

$$B = \nabla \times A$$

(Eq2-11)

Hence, the total magnetic flux through the surface $S$ is

$$\psi = \int_S \mathbf{B} \cdot d\mathbf{s} = \int_S (\nabla \times \mathbf{A}) \cdot d\mathbf{s} = \oint_c \mathbf{A} \cdot d\mathbf{l}$$

(Eq2-12)

So, an alternative way to calculate the inductance of current loop is

$$L = \frac{\oint_c \mathbf{A} \cdot d\mathbf{l}}{I}$$

(Eq2-13)

$C$ is the closed contour that bounds the open surface $S$. So the equation2-11 could be decomposed into the line integral along unique segments of the closed loop as

$$L = \frac{\oint_{c_1} \mathbf{A} \cdot d\mathbf{l}}{I} + \frac{\oint_{c_2} \mathbf{A} \cdot d\mathbf{l}}{I} + \cdots + \frac{\oint_{c_n} \mathbf{A} \cdot d\mathbf{l}}{I}$$

(Eq2-14)

Where the closed path $c$ is segmented into $n$ contiguous segments $c_i$ so that $c = c_1 + c_2 + \cdots + c_n$, and $A_i$ is the total $A$ along contour $c_i$.

So the partial inductance $L_i$ is defined as:

$$L_i = \frac{\oint_{c_i} \mathbf{A} \cdot d\mathbf{l}}{I}$$

(Eq2-15)

And the total loop inductance is the sum of each part:

$$L = L_1 + L_2 + \cdots + L_n$$

(Eq2-16)

Assume the current of the current $I$ is distributed uniformly over the cross section for the purpose of computing the $B$ and $A$ field and thus calculate the self-partial inductance. Self-partial inductance of a length of $l$ and radii $r$ (figure2-7) is given in book [5].
Figure 2-7 one single wire

\[ L_p = \frac{\mu_0}{2\pi} I \left[ \ln \left( \frac{l}{r_w} \right) + \sqrt{\ln \left( \frac{l}{r_w} \right)^2 + 1} - \sqrt{1 + \left( \frac{r_w}{l} \right)^2 + \frac{r_w}{l}} \right] \]  
(Eq2-17)

If \( l \gg r_w \), the equation 2-17 can be approximated to

\[ L_p \approx 2 \times 10^{-7} I \ln \left( \frac{2l}{r_w} \right) - 1 \]  
(Eq2-18)

The calculation of mutual partial inductance between parallel wires (figure 2-8) also can refer to [5].

Figure 2-8 two wires in parallel

The mutual inductance is defined as figure 2-19.

\[ M_{ij} = \frac{\int A_i \cdot dl}{I_j} \]  
(Eq2-19)

The mutual partial inductance between two wires with a distance \( d \) is:

\[ M_p = \frac{\mu_0}{2\pi} I \left[ \ln \left( \frac{l}{d + r_w} \right) + \sqrt{\left( \frac{l}{d + r_w} \right)^2 + 1} - \sqrt{1 + \left( \frac{d + r_w}{l} \right)^2 + \frac{d + r_w}{l}} \right] \]  
(Eq2-20)

And if \( d \gg r_w \), the mutual inductance is approximated to

\[ M_p \approx 2 \times 10^{-7} I \left[ \ln \left( \frac{l}{d} + \sqrt{\left( \frac{l}{d} \right)^2 + 1} \right) - \sqrt{1 + \left( \frac{d}{l} \right)^2 + \frac{d}{l}} \right] \]  
(Eq2-21)
If \( l >> d \), the \( M_p \) is approximately to:

\[
M_p \approx \frac{\mu_0}{2\pi} l (\ln \frac{2l}{d} - 1)
\]  

(Eq2-22)

If two wire in parallel with each other as shown in figure2-9 and the inductance can be represented as figure2-10.

![Figure2-9 two wires in parallel](image)

![Figure2-10 two wires in parallel](image)

So \( L_{net} \) can be calculated as

\[
L_{net} = \frac{L_{p1}L_{p2} - M_p^2}{L_{p1} + L_{p2} - 2M_p}
\]  

(Eq2-23)

If the two wires have identical lengths and radii, \( L_{p1} = L_{p2} = L_p \) and ...reduce to
The mutual partial inductance between wires at an angle (Figure 2-11) to each other is

\[ M_p = \frac{\mu_0 \cos \theta (l \ln \frac{R + m - l \cos \theta}{l - l \cos \theta} + m \ln \frac{R + l + m}{R + m - l})}{4\pi} \]  

(Eq2-25)

2.2.3 Proposed model

The model consisting external and internal inductance and internal resistance concerning of skin effect is proposed by [7], and the external inductance can be calculated by partial or loop inductance from [5] and internal inductance and resistance can be calculated by [6][8].
2.2 Impedance and measurement methods

2.2.1 Background of impedance

Impedance: impedance is quite an essential parameter used in electrical engineering and it is generally defined as the total opposition a device or circuit offer to the flow of an alternating current (AC) at a given frequency. The impedance (Z) is usually presented as a complex quantity, which consists of a real part (resistance R) and an imaginary part (reactance X) as shown in figure 2-13. It also can be represented by a magnitude and phase angle: $|Z| \angle \theta$.

![Figure 2-13 impedance (Z)](image)

So, in summary:

$$Z = |Z| \angle \theta = R + jX \quad \text{(Eq2-26)}$$

$$R = |Z| \cos(\theta)$$

$$X = |Z| \sin(\theta) \quad \text{(Eq2-27)}$$

Reactance takes two forms: inductive ($X_L$) and capacitive ($X_C$). By definition, $X_L = 2\pi fL$,

$$X_C = \frac{1}{2\pi fC}, \text{ where } f \text{ is the frequency, } L \text{ is inductance and } C \text{ is capacitance.}$$

Furthermore, the quality factor (usually be called as Q factor) is quite an factor which represents a measure of reactance's purity, which means how close it is to being a pure reactance. It is expressed as

$$Q = \frac{X}{R}. $$

2.2.2 Measuring impedance

In order to get value of the impedance, we need at least two values for impedance is a complex quantity. Many modern impedance measuring instruments measure the real part and imaginary parts of an impedance vector and convert them into the desired parameters, for instance, $|Z|$, $\theta$, $R$, $X$, $L$, and $C$. 
The only thing is to connect the unknown component to the instrument. But determine a parameter value from measurement equipment, one thing that need take into special attention is that the difference among the ideal value, the real value and the measured value. The differences can be explained by taking capacitor as an example.

The ideal value of a capacitor is a purely capacitor which can be calculated by formulas from test book. It is not dependent on frequency. It is only for academic use.

The real value of a capacitor is much complex, it has some unwanted resistance, inductance as well as parasitic capacitance. In reality, the equivalent circuit of a real capacitor is showed in figure 2-14.

The measured value is the value obtained by measurement equipment. The measured value is dependent not only the value of the real word component but the inaccuracy of the test equipment and residuals of test fixture.

The goal of measurement is to have the measured value as close as possible to the real value. So some compensation, for instance, open/short/load compensation need to be done in order to get the precisely value.

2.2.3 Measurement equipment
Considering the frequency range and measurement methods list above, two approaches are proposed to measure the impedance of test wire. One approach is carried out by three measurements equipment: power supply and voltage meter to measure DC resistance, LCR meter to measure impedance from 20Hz
to 100 kHz and spectrum analyzer to gain impedance from 100 kHz to 30MHz. Another approach can be completed using power supply and voltage meter for DC and impedance analyzer from 40Hz to 30MHz.

The measurement method used by LCR meter and impedance analyser is auto-balance bridge method and will be explained in more detail. Further, the working principle will also be explained in the following part.

2.2.2.1 DC measurement

![Figure 2-16 DC measurement](image)

Thomason (Kelvin) Bridge test method is used to measure the DC impedance. As can be seen from figure 2-16, a power supply injects constant current (I) to the DUT and the voltage meter cross the DUT can measure the voltage (V). So the resistance of DUT can be got from

$$R_{DUT} = \frac{V}{I} \quad \text{(Eq2-28)}$$

Because the resistance is very small, the higher current injected, more precise.

2.2.2.2 Working principle of LCR meter

LCR meter is a piece of electronic test equipment which commonly used in measuring the inductance(L), resistance(R), impedance(Z) and phase angle(Θ) and other desired parameters.

A simplified model of auto-balancing method (below 100 KHz) is showed in figure 2-17,
Three critical parts ensure the proper working of LCR meter.

First part is signal source section, which generates the test signal applied to the Device under Test (DUT), frequency range and resolution is dependent on the test equipment used.

Second part is auto-balancing bridge section balances the current comes from Rs with the DUT current as well as maintain a zero potential at low terminal (right side of DUT). Figure 2-17 shows the auto-balancing bridge section for frequency below 100 kHz. For frequency above 100 kHz, please refer to Impedance measurement book [1].

Third part is Vector ratio detector (VRD) section, which measures the ratio of vector voltage across DUT (Vx) and across the range resistor (Vr). In order to avoid tracking error, Vx and Vr are measured by same voltage meter. In addition, the VRD also consists of a phase detector, an A-D converter which helps convert the analogy signal into digital signal.

In order to measure Vx and Vr, these vector signals are resolved into real and imaginary part, 

\[ V_x = a + jb , \quad V_r = c + jd, \] 

which shown in figure2-10. So the \( \frac{V_x}{V_r} \) can be represented by:

\[
\frac{V_x}{V_r} = \frac{a + jb}{c + jd} = \frac{ac + bd}{c^2 + d^2} + j\frac{bc - ad}{c^2 + d^2}
\]

(Eq2-29)
The VRD working as follows: the input selector S (shown on figure2-17) is set to Vr position, the phase detector is driven with 0 degree to 90 degree and imaginary and real part of Vr can be extracted. The A-D converter outputs Vr with digital data a and jb. Further, S is set to Vr position and the imaginary part and real part of Vr can be extracted for the same procedure.

In the previous appendix A, from EqA-1 and EqA-2

$$Z_x = R_x \frac{V_x}{V_r} = R_x \left[ \frac{ac + bd}{c^2 + d^2} + j \frac{bc - ad}{c^2 + d^2} \right]$$  \hspace{1cm} \text{(Eq2-30)}

In addition, $Z_x = R_x + jX_x$

The resistance and reactance of the DUT can be calculated as

$$R_x = R_r \frac{ac + bd}{c^2 + d^2}, \quad X_x = R_r \frac{bc - ad}{c^2 + d^2}$$  \hspace{1cm} \text{(eq2-31)}

Various impedance parameters can be calculated from the measured Rx and Xx.
Figure 2-19 Programmable LCR Bridge HM8118

Figure 2-19 shows a picture of HM8118 and it is made by Rohde & Schwarz Company, has a basic accuracy of 0.05%, can measure L, C, R, |Z|, Θ and other electrical parameters. The measurement frequency range is from 20Hz to 200 kHz. 30 minutes warm up and open/short calibrations need to be done before use. More information can refer to impedance handbook [1] and manual [2].

2.2.2.3 Principle of Spectrum analyser

A spectrum analyser is a very important test equipment for analysing high frequency signals. It has some similarities with an oscilloscope which can produce a visible graphical display of amplitude and time on the screen. But unlike the oscilloscope, the spectrum analyser gives a display of frequency against the amplitude usually in dB.

Figure 2-20 Block diagram of spectrum analyzer

Figure 2-20 shows a simplified block diagram of a super heterodyne spectrum analyser. Heterodyne means to mix. That is, to translate frequency and super refers to super-audio frequencies, or frequencies above the audio range. Referring to the block diagram, we see that an input signal passes through a low-pass filter to a mixer, where it mixes with a signal from the local oscillator. Because the mixer is a non-linear device, its output includes not only the two original signals but also their harmonics.
and the sums and differences of the original frequencies and their harmonics. If any of the mixed signals falls within the pass band of the IF filter, it is processed, essentially rectified by the envelop detector, digitized and applied to the vertical plates of a cathode-ray tube to produce a vertical deflection on the screen. For more information can refer to [6].

The FSH3 (figure 2-21) can measure the power of the different types of signals by using a power sensor, cable losses as well as two ports measurements using tacking generator. By using a tracking generator to inject different frequency signals to DUT and measure the output power by SA, then by doing some calculation, the Impedance of DUT can be got. However, one disadvantage is that it can only provide the absolute value of impedance without getting phase angle. More detailed calculation will be found in the next section. The measurement Frequency range of FSH3 Spectrum analyzer is from 100 kHz to 3GHz.

From the above analysis, the HM8118 LCR meter can measure impedance from 20Hz to 200 kHz and FSH3 spectrum analyzer could measure from 100 kHz to 3GHz. A combination of these two measurement equipment, the impedance from 20Hz to 3GHz can be got.
2.2.2.4 Impedance analyser

The working principle of impedance analyzer is almost the same as LCR meter which use auto-balancing method. The only different is that the auto-balancing bridge section (shows in figure2-17), it has more complex circuit which can measure quite high frequency up to 110MHz which suitable for high frequency measurement.

The impedance analyser can measure quite a lot of impedance parameters. Take Agilent 4292A Impedance analyzer (figure2-22, the one I use it in my measurements) as an example, it can measure $|Z| - \Theta$, R-X, Ls-Rs, Ls-Q, etc. As a matter of fact, what interests most is $|Z| - \Theta$, which represents absolute value of impedance and phase angle. The measurement frequency range of impedance analyzer is from 40Hz to 110MHz and it corves most of interest frequency (DC-30MHz). So by using 4292A impedance analyzer, I could finish all my measurement except DC measurement, which is quite a good choice.

2.3 General test set up for measurement

Test set up is quite important in measuring the impedance of the earthing wire. Three different test set ups are proposed and compared (test set up-1 and test set up-2 can be found in appendix B). The best measurement test set up is found considering reproducibility, minimum error and easy to operate in low frequency and high frequency. Two following conditions should take consideration:

1. Define the environment

Because the impedance of the earthing impedance is quite small (less than 1mΩ) and a little interference from the outside will has significant influence on measuring the impedance in low frequency. In high frequency, coupling and also stray capacitance will also have more or less influence on measuring results. So it is quite important to have a well-defined measuring environment to make
the measurement data reproducible in a large frequency range (from DC to 30MHz). in addition, current may flow different path... low impedance/ maybe what measured is not the impedance of wire.....

2. Reproducible

Test set up-1 and test set up-2(see appendix) have some two critical disadvantages: first, the measurement data got from LCR meter is unstable. The second is the test set up could not do high frequency measurement. And third, it could not investigate multiple point earthing. These three advantages means measurement data from low frequency to high frequency could not be got rightly and not to mention build a model for it.

Due to the advantages list above, a third measurement test set up is proposed. It can be divided into three parts: first part is the metal plate. The main function of the metal plate is to reduce the interference from outside and thus make the measurement data more reproducible and accuracy. Second part is the BNC connector part, which can connect high frequency measurement equipment to the test wire. Third part is called adjustment part, which means the height of the test cable can be adjusted with the reference to the metal plate. In addition, in combination with the metal plate, it can also measure test cables with different length.

2.3.1 Metal plate

The metal plate (shown in figure2-23 below) is used in naval ships. The dimension of the metal plate is 90cm (length)*60cm (width)*8mm (thickness). In the middle of the earth plate, a rectangle tray is placed which can hold cabinet. In addition to that, on the surface of the metal plate, some nuts (M8) are welded to the metal plate in order to connect the earth wire to it. Three lengths of wires can be measured are highlighted by yellow colour. The lengths of wire are 23cm, 55.5cm and 72cm separately which showed on figure2-23.

There are three reasons of choosing this metal plate. First, serve as a return path of current flowing back to the measurement equipment. The measurement equipment injects current to the test cable, then, through the metal plate and finally goes back to the equipment. The loop flow determines the external current which can be measured by test equipment. Second, in ships, the earthing wire is direct connects to the metal plate, this metal plate serve as an’ physical earth’ in this aspect. In the other words, this metal plate can simulate the environment on-board ships. Third reason could be screening the interference below the metal plate, which can make measurement data more stable.
2.3.2 BNC connector

Figure 2-23 metal plate

Figure 2-24 Draft of BNC connector
Figure 2-24 shows the draft of BNC connector, and figure 2-25 below is the pictures of real product, which is made according to the draft of figure 2-24.

The BNC connector in figure 2-25(b) can be connect to the FSH3 spectrum analyzer and for low frequency measurement. The function of BNC connector is to fix the test cable, to keep the test cable as the same loop area, make the measurement data more producible.

2.3.3 Adjusting part
Adjustment part is used for change the height to the metal plate, as can be seen from figure 2-26, two M8 galvanic tape about 30cm long are used to change the height and screw nuts are used to set the wire in the certain position.
For low frequency measurement, the red fixture connects to the one side of earth wire and the other side to the galvanic, as shown in figure 2-27.
For high frequency measurement, Generator output inject high frequency signal to the test cable and then goes back to RF input, as shown in figure 2-28.

2.4 summary

1. On-board earthing can use green/yellow wire, litze wire and copper bar. In addition, the earthing type could be one point earthing and multiple points earthing. Further, Inductance and resistance of wire are studied, it includes two parts, internal inductance and external inductance. Internal inductance influenced by skin effect, which inductance decrease with frequency, while resistance increase with frequency. External inductance rely on the loop which the formed with surroundings as well as length and the cross section of the wire.

2. Two measurement approaches are proposed considering the measurement methods and the test equipment in the company and TU Delft lab separately. First in the company environment, a combination of power supply, voltage meter, LCR meter and spectrum analyser are chosen for DC, low frequency and high frequency measurement. In the TU Delft lab, power supply, voltage meter and impedance analyser are chosen to do the measurement.

3. Due to the reason that the impedance of external inductance rely on the loop it flows, so a test set up which help define the loop flow is built. In addition, the test set up also beneficial to the reproducibility of measurement. This test set up can be used to connect LCR meter, spectrum analyser and also impedance analyser.
2.5 Reference


[2] HF SSB Use’s guide & Professional Products Catalog, SGC


[4] Introduction to EMC


Chapter 3 Practical measurement
This chapter mainly consist two parts.

First part was performed in the company, which power supply, voltage meter, LCR meter and spectrum analyser are used to measure the test wire from Dc to 30MHz, further, by analysis the data got from equipment, the influence of loop area, cross section and length of test wire on impedance are studied.

Second part lab work was performed at TU Delft lab, which power supply, voltage meter and spectrum analyser is used as measurement equipment. Some practical installation of cable is proposed in the end of this chapter.

3.1 Part 1 DC+LCR meter + Spectrum analyser measurement
This part measurement is performed at Damen shipyard Gorinchem and Imtech marine Rotterdam. Power supply and voltage meter is used to measure the resistance of DC. Further, LCR meter is used to measure the impedance and phase angle of test wire from 20Hz to 10 kHz. In addition, the spectrum analyser, which can be used to measure the impedance of test wire from 100 kHz to 30MHz.

3.1.1 Test procedure of DC measurement
3.1.1.1 Test methods:

![Diagram of DC measurement](image)

Figure 3-1 schematic diagram of DC measurement

Thomason (Kelvin) Bridge test method is used to measure the DC impedance. As can be seen from figure 3-1, a power supply injects constant current (I) to the DUT (test cable) and the voltage meter cross the DUT can measure the voltage (V). So the resistance of DUT can be got from Eq3-1:

\[ R_{DUT} = \frac{V}{I} \quad (Eq3-1) \]

Figure 3-2 shows the power supply and voltage meter used to measure the resistance.
3.1.1.2 Test procedure:
1. Connect the test wire to the power supply and voltage meter as shown in figure 3-1.

2. Turn on the power supply, set the test current 10A, record the data from voltage meter.

3. Repeat above 2 steps five times and take average value of five data measured.

3.1.2 LCR meter (20Hz—100 kHz)

3.1.2.1 Test set up
Figure 3-3 shows HM8118 LCR meter and it connects to the general test set up (figure 3-4). It measures the impedance of test cable $Z_{\text{wire}}$, impedance of rod $Z_{\text{rod}}$, impedance of metal $Z_{\text{metal}}$. 

(a) Voltage meter Fluke 289

(b) Delta power supply

Figure 3-2 test equipment for DC
Figure 3-3 HM8118 LCR meter

Figure 3-4 test set up
3.1.2.2 Test procedure:

1. Connect the test fixture to the LCR meter, install cable to the test set up, and adjust the height. Turn on the LCR meter, 30 minutes warm up.
2. Perform open/short calibration from 20Hz to 100kHz.
3. Connect the test fixtures to the coaxial cable as shown in figure 3-4, choose 'auto' option.
4. Measure $Z - \theta$, $L - R$ at frequency (20, 40, 72, 100, 200, 400, 720)Hz, (1, 2, 4, 7.2, 10, 20, 40, 72, 100)kHz
5. Record the measurement data.
6. Repeat above five steps five times.
7. Data analysis, delete the maximum and minimum value and take average value of the remaining 3 measurements.
3.1.3 Test procedure of Spectrum analyser (100kHz-30MHz)

Figure 3-6 test set up for FSH3 spectrum analyzer

![Test setup image]

Figure 3-7 Schematic diagram for SA

The Schematic diagram is given in figure 3-6 and figure 3-7 provides the equivalent circuit of this test set up. The spectrum analyser has an inner impedance of 50Ω which in parallel with the unknown impedance Z and further in series with the inner impedance of spectrum analyser 50Ω.

3.1.3.1 Theoretical calculation
In order to do the calculation, some parameters need defined as shown in figure 3-8(a). First, the tracking generator has a voltage $V_t$ and the inner impedance $R_t = 50\, \Omega$. Second, the spectrum analyzer itself is the road $R_s$, which is also $50\, \Omega$ and the voltage across it is $V_s$. Third, the output of Spectrum analyzer $S_{output}$ is calculated by:

$$S_{output} = 20\log\left(\frac{V_s}{V_{ref}}\right) \quad (Eq3-2)$$

One thing should take special attention is that, $V_{ref}$ is defined as when tracking generator directly connect to the spectrum analyzer, the output of spectrum analyzer is $S_{output} = 0\, dB$, so
\[ V_{ref} = \frac{1}{2} V_t \]  
(Eq.3-3)

\[ V_{ref} \] is a constant value, equals \( \frac{1}{2} V_t \).

Then, come back to (a) again. The values of \( S_{output} \) are shown on the screen, and they are known.

Assume the impedance of test wire is \( Z \), \( V_s \) and \( V_t \) can be calculate by Kirchhoff’s circuit laws, which is:

\[ V_s = \frac{\frac{50Z}{50Z + 50} \cdot 2V_t}{\frac{50Z}{50} + 50} \]  
(Eq3-4)

Combine eq3.2 and eq3.3, so impedance can be solved by:

\[ Z = \frac{25 \cdot \frac{S_{output}}{10^{20}}}{1 - 10^{20}} \]  
(Eq3-5)

By measuring \( S_{output} \) and using Eq3-5, the impedance can be obtained.

3.1.3.2 Test procedure

1. Preparation work

Install cable and adjust the cable to suitable height, turn on the spectrum analyzer.

2. Calibration:

Disconnect the BNC connector from T-Piece. Set Start Frequency 100 kHz, Stop Frequency 30MHz. set level Tracking Generator to maximum. Adjust Ref level of SA to 0dB level on screen. Disconnect Tracking Generator. Check the level on Tracking Generator screen, Reconnect Tracking Generator.

3. Verification:

Connect to 25Ω, 30Ω, 50 Ω, 75 Ω and 100 Ω to the spectrum analyzer, record the data and compare them with the calculated value. Further, these recorded data can verify next time measurement.

4. Testing:
Connect BNC connector. Connect the ground wire (DUT). Open FSH viewer (a software which used to collect data from spectrum analyser to the computer), connect spectrum analyser to the computer. Collect these data and imagine from computer.

5. Repeat step 1 to step 4 four times
6. Data analysis, delete the maximum and minimum value and take average value of the remaining 3 measurements.

3.2 Research on loop area, cross section and length influence on test cable
In real world test, testing of wires always follows with loop area, in the other words, the measured impedance include two parts, one part is the impedance of wire and the other is impedance formed by loop, as said in chapter 2. Refer to equation 2-9 and 2-10. The inductance of wire depends on the loop area which it flows. Also refer to equation 2-17 and 2-18, the partial inductance of wire also has some relation with cross section area and length of cable.

In order to investigate how loop area and cross section influence on the impedance of test Green/yellow wire, three tests from 20Hz to 200 kHz are performed by LCR meter in table 3-1. Comparing Group 1 and group 2, the cross section and cable length is the same while the loop area is different. Compare G2 and G3, the only difference is cross section of wire.

3.2.1 Research on loop area and cross section influence on impedance using LCR meter
Some measurements of green/yellow wires are performed by LCR meter first. As shown on figure 3-15, assume the test wire length is Length, the cross section of test wire is Area, Hm is the distance between the big metal plate and the small metal plate, H1 is the height above the metal plate. Further, the current flows from the red fixture of LCR meter to the test green/yellow wire and finally return back to the black fixture to through H1 and the metal plate. So the impedance measured is the loop impedance of test cable, the galvanic tap and the metal plate.
3.2.1.1 Check reproducibility

The impedance of earthing cable is quite small (ten to hundreds mΩ) in low frequency and it can be easily influenced by the environment as well as the contact resistance between the wire and metal plate. So check the reproducibility is e

Some precaution works, such as fasten the bolt to decrease the contact resistance and calibrate LCR meter are performed in order to get the measurement data repeatable.
(a) Impedance (upper, mΩ) an phase angle( lower, degree) comparisons

(b) Inductance(upper, uH) and resistance(lower, mΩ)

Figure3-10 test of reproducibility

Figure3-10(a) shows three independent measurements of different date and it shows that the impedance is almost the same while the phase angles are different. The reason can be found in figure3-10(b), which shows that the inductance it almost the same of these three measurement while the contact resistance has some differences. This shows reproducibility is quite acceptable.

3.2.1.2 Loop area

As said in chapter2, the loop area which current flow determines the external inductance. Group 1(Big loop in figure3-11) has a loop area of 555mm*140mm while group 2(small loop in figure3-11) has an area of 555*80, which showed in table3-2. The ratio of these two loops is 1.75. The measurement data comparisons are shown in figure3-17 below.

<table>
<thead>
<tr>
<th>Group</th>
<th>Area (mm²)</th>
<th>Length (mm)</th>
<th>H m (mm)</th>
<th>H1 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. G/Y wire</td>
<td>35</td>
<td>555</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>2.G/Y wire</td>
<td>35</td>
<td>555</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

Table 3-2

(a) *Impedance (upper, mΩ) an phase angle (lower, degree) comparisons*
We can see from figure 3-11(a), the bigger the loop, the higher the impedance. The impedance of the highest frequency is around 950 mΩ while the small loop is about 700 mΩ. Further, the impedance of the large small loop ratio is 1.35 compared to the loop ratio of 1.75. This means that the loop area will influence the impedance value greatly.

Guideline on installing earthing wire on-board is to keep the loop area which is created by current flow as small as possible to decrease the impedance.

3.2.1.3 Cross section of wire

<table>
<thead>
<tr>
<th>Group</th>
<th>Area (mm²)</th>
<th>Length (mm)</th>
<th>H m (mm)</th>
<th>H1 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.G/Y wire</td>
<td>35</td>
<td>555</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>3.G/Y wire</td>
<td>6</td>
<td>555</td>
<td>60</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 3-3

If loop area keeps constant and what will wire cross section influence the impedance measured? Table 3-3 compared one 6 mm² green/yellow wire with 35 mm².
(a) Impedance (upper, mΩ) an phase angle (lower, degree) comparisons

(b) Inductance (upper, uH) and resistance (lower, mΩ) comparisons

Figure 3-12 cross section comparisons

Figure 3-12 (a) compares absolute value of impedance and phase angle of 35 mm$^2$ green/yellow wire with 6mm2 green/yellow wire. At highest frequency, the impedance of 35 mm$^2$ green/yellow wire is
790mΩ while 6mm² is 700ohm. The cross section change about six times ($\frac{35\text{mm}^2}{6\text{mm}^2}$) while the impedance only change 1.1 ($\frac{790\text{mΩ}}{700\text{mΩ}}$) times. This means that the cross section also determines the impedance, but not as significant as loop area.

3.2.2 Research on length and cross section influence on impedance (Spectrum analyser)

<table>
<thead>
<tr>
<th>Group</th>
<th>Area (mm²)</th>
<th>Length (mm)</th>
<th>H m (mm)</th>
<th>H1 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>35</td>
<td>555</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>2.</td>
<td>6</td>
<td>555</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>3.</td>
<td>35</td>
<td>230</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>4.</td>
<td>6</td>
<td>230</td>
<td>25</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 3-4

Table 3-4 measures four different groups of green/yellow wire with different cross section and length. The loop area is kept the same in order to find the best earthing wire with minimal impedance.

In order to verify the results got from spectrum analyser and the calculation are trustful, some verifications with known 25Ω, 30Ω, 50Ω, 70Ω load are test first. An example of 50Ω load is presented in figure 3-13.
Figure 3-13 verification of 50ohm load (300kHz-16MHz)

Figure 3-14 four measurements comparisons (300 kHz-16MHz)

Four groups of green/yellow wire with different cross sections and lengths wires are measured from 300 kHz to around 15MHz in figure 3-14.
It shows that: the 6mm², 555mm green/yellow wire has the largest impedance which labelled in red. The second highest is the green yellow wire with a length of 555mm and cross section of 35mm². The third one is the green/yellow wire with 230mm length and a cross section of 6mm², and the lowest one is the wire with a length of 230mm and cross section 35mm².

So this means, in order to obtain a lower impedance of earthing wire, the most important thing is to keep the wire short and then increase the cross section.

3.3 Part2 DC+IA+LCR meter
These part measurements are performed in the lab of TU Delft. Power supply and voltage meter are chosen to measure the DC resistance. The impedance analyzer can measure the impedance from 40Hz to 30MHz, so it can replace LCR meter and spectrum analyzer to do the measurement.

3.3.1 DC
DC measurement can refer to 3.1.1.1.

<table>
<thead>
<tr>
<th>Group</th>
<th>DC resistance (mΩ)</th>
<th>DC calculation(mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1 litze wire 1 (30cm)</td>
<td>0.618</td>
<td>0.1293</td>
</tr>
<tr>
<td>G2 litze wire 2 (24.5cm)</td>
<td>0.488</td>
<td>0.1056</td>
</tr>
<tr>
<td>G3 G/Y 25cm 35mm²</td>
<td>0.515</td>
<td>0.1232</td>
</tr>
<tr>
<td>G4 G/Y 25cm 6mm²</td>
<td>1.252</td>
<td>0.7184</td>
</tr>
<tr>
<td>G5 3*6mm² 10cm apart</td>
<td>0.528</td>
<td>0.2395</td>
</tr>
<tr>
<td>G6 3*6mm² 5cm apart</td>
<td>0.523</td>
<td>0.2395</td>
</tr>
<tr>
<td>G7 2*6mm² 5cm apart</td>
<td>0.7564</td>
<td>0.3592</td>
</tr>
<tr>
<td>G8 2*6mm² 10cm apart</td>
<td>0.7894</td>
<td>0.3592</td>
</tr>
<tr>
<td>G9 2*6mm² close together</td>
<td>0.680</td>
<td>0.3592</td>
</tr>
<tr>
<td>G10 3*6mm² close together</td>
<td>0.5442</td>
<td>0.2395</td>
</tr>
</tbody>
</table>

Table 3-5 DC resistance measurement and calculation

Table3-5 compares the resistance of DC measurement and theoretical calculation. It can be seen the resistance measured is quite larger (2 to 5 times ) than the calculation. The reason is may due to first the DC current inject to the test cable is small or equal to the disturbance of the surroundings, second, the oxide layer also has some influence on the measurement.

3.3.2 test procedure of impedance analyzer
In order to connect the test set up to the impedance analyser, a coaxial cable is added showed in figure3-15. The length of the coaxial cable is 10cm, and the impedance schematic is shown in figure3-16. So the impedance analyser measures not only the impedance of test cable, metal plate but also the impedance of coaxial cable.
Figure 3-15 test set up

Z coaxial cable

Z wire

Z rod

Z metal

measurement

Figure 3-16 impedance schematic
3.3.2.1 Test procedure

1. preparation work

The whole test set up is shown in figure3-17.

Connect 82357b USB/GPIB between computer and impedance analyser, install Agilent connection expert to record the data from impedance analyser to computer.

Connect four terminal ports 16048G to the impedance analyser; install cable to the test set up

Turn on the machine and 30 minutes warm up, press button pre-set on the machine, set measurement parameters (|Z|–Θ), format (log), bandwidth(5), sweep(log), start frequency (40Hz) and stop frequency(30MHz)

2. calibration

Perform open/short/load calibration of the 1 meter four-terminal pair port adapter 16048G

Perform open/load calibration of test fixture 16047E

3. verification

Connect to the coaxial cable, one side to the test equipment and the other to the known load. Use 25 Ω, 30 Ω, 50Ω, 75 Ω, and 100 Ω load to verify the measurements

4. test

Connect the test fixture to the test set up. Record the data in the computer.
Disconnect the cable and repeat this measurement 4 times.

5. Data analysis
After the measurement, 5 data are got from the impedance analyser, in order to reduce error, the maximum and minimum value are excluded from the data and average value are taken of the remaining three. Determine the standard deviation ($\delta$), determine the measurement uncertainty with test equipment specification.

6. Validate practical results with a model

3.3.3 LCR meter (20Hz-100 kHz)
LCR meter in this part plays a function as verified equipment in low frequency, also refer to 3.1.2

3.4 Research on one point earthing and multiple points earthing
Chapter 3.2 investigate the loop area, length and cross section influence on the impedance, this parts mainly investigate earthing with one wire and earthing with two or three wire of the same length(250mm). Three commonly used wire type(6mm2,35mm2 green/yellow wire, litze wire) are measured in order to solving the questions mentioned below:

1. For these three types of wire, if the loop area, length is the same, what is best earthing wire regarding to the smallest impedance?
2. If two 6mm2 green/yellow wire in parallel, considering the proximity effect, the distance between the two wires will influence the impedance, how? Will the impedance of two 6mm2 green/yellow wire smaller than one 35mm2 green/yellow wire? Further, consider three 6mm2 green/yellow wire also.
3. Is there a general model of the earthing wire?

Ten groups of wire are measured to get the answers above, which listed in table 3-5.
### Table 3-6 Ten groups of measurements

<table>
<thead>
<tr>
<th>Group</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>Litze wire, length 30cm, width 2cm, thickness 2mm</td>
</tr>
<tr>
<td>G2</td>
<td>Litze wire, length 24.5cm, width 2cm, thickness 2mm</td>
</tr>
<tr>
<td>G3</td>
<td>Length 25cm, 35mm² Green/yellow wire</td>
</tr>
<tr>
<td>G4</td>
<td>Length 25cm, 6mm² Green/yellow wire</td>
</tr>
<tr>
<td>G5</td>
<td>Wire 3*6mm², 10cm apart</td>
</tr>
<tr>
<td>G6</td>
<td>3*6mm², 5cm apart</td>
</tr>
<tr>
<td>G7</td>
<td>2*6mm², 10cm apart</td>
</tr>
<tr>
<td>G8</td>
<td>2*6mm², 5cm apart</td>
</tr>
<tr>
<td>G9</td>
<td>2*6mm² close together</td>
</tr>
<tr>
<td>G10</td>
<td>3*6mm² close together</td>
</tr>
</tbody>
</table>

Note: G5 to G10 all test 6mm² green/yellow cables.

### 3.4.1 Verification

3.4.1.1 LCR meter low frequency
The data got from LCR meter is used to verify the data got from Impedance analyser so that the data got from impedance analyser can be used to build the model.
In figure 3-18, the green plot represents testing with impedance analyser from 40Hz to 100 kHz and the blue plot is testing with LCR meter. It can be seen that in low frequency, the measurement data is almost the same and differs at high frequency.

3.4.1.2 Test with known load
Test the impedance analyser with known load, 25 Ω, 30 Ω, 50Ω, 75 Ω loads. Here gives an example of test impedance analyser with 50ohm, the other could be found in appendix C.
4.4.1 Different types of wires

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>length 30cm, width 2 cm, thick: 2mm litze wire</td>
</tr>
<tr>
<td>G2</td>
<td>length 24.5cm, width 2cm and thick 2mm litze wire</td>
</tr>
<tr>
<td>G3</td>
<td>length 25cm, 35mm2 Green/yellow wire</td>
</tr>
<tr>
<td>G4</td>
<td>length 25cm, 6mm2 green/yellow wire</td>
</tr>
</tbody>
</table>

Table 3-7 different types of wires comparison

(a) Impedance comparison of four measurements

(b) Phase angle of four measurements
Figure 3-20 four different wire measurements

Figure 3-20 shows impedance and phase angle of four different types of wire from 40Hz to 30MHz.

G1, G2 both are both earth strap but with different length. From figure3-20(a), it can be known that for litze wire with the same cross section, the longer the length, the larger the impedance.

G2, G3, G4 are earthing wire with the same length but different cross section. Comparing them, it can be seen that the impedance of litze wire with cross section of 40mm² has the lowest impedance, flowing by 35mm² green/yellow wire and the highest impedance exists in 6mm² green/yellow wire.

In summary, for litze wire of the same cross section, the longer the length, the higher the impedance. For earthing wire with the same length, the bigger the cross section, the lower the impedance.

4.4.2 3*6mm², different distance

<table>
<thead>
<tr>
<th>G5</th>
<th>3*6mm², 10cm apart from each other</th>
</tr>
</thead>
<tbody>
<tr>
<td>G6</td>
<td>3*6mm² 5 cm apart from each other</td>
</tr>
<tr>
<td>G10</td>
<td>3*6mm² close together</td>
</tr>
<tr>
<td>G3</td>
<td>35mm² G/Y wire</td>
</tr>
</tbody>
</table>

Table 3-8 3*6mm² green/yellow wire with different distance apart

(a) Impedance comparison of 4 measurements
(b) Phase angle of four measurements

Figure 3-21 comparisons

Figure 3-21 compares three 6mm2 green/yellow wire in parallel of different distance between with the 35mm2 green/yellow wire.

It can be seen that connecting three 6mm2 green/yellow wire in parallel, the impedance is lower than one 35mm2 green/yellow wire.

Comparing G5 (10cm apart from each other), G6 (5cm apart), G10 (close together), it can be seen that the longer distance the wires apart from each other, the lower impedance. This can be explained by proximate effect.

4.4.3 2*6mm2, different distance

<table>
<thead>
<tr>
<th>G7</th>
<th>2*6mm2 10 cm apart from each other</th>
</tr>
</thead>
<tbody>
<tr>
<td>G8</td>
<td>2*6mm2 5 cm apart from each other</td>
</tr>
<tr>
<td>G9</td>
<td>2*6mm2 close together</td>
</tr>
<tr>
<td>G3</td>
<td>35mm2 G/Y</td>
</tr>
</tbody>
</table>

Table 4-4 2*6mm2 green/yellow wire with different distance apart
Figure 3-22 compares two 6mm² green/yellow wire in parallel of different distance between with the 35mm² green/yellow wire.
It can be seen that connecting two 6mm² green/yellow wire in parallel, only the impedance of G9 (close together) is a little higher (almost the same) than 35mm² green/yellow wire and the other two are lower than 35mm² green/yellow wire.

Comparing G7 (10cm apart from each other), G8 (5cm apart), G9 (close together), it can be seen that the longer distance the wires apart from each other, the lower impedance. So in practical, install cable need a distance to keep the impedance lower.

3.5 Summary
1. Loop area and length of wire plays a significant role in measuring impedance of test cable in high frequency, the cross section of wire is secondary. So decrease the loop area and keep the earthing cable short can keep relative lower impedance in high frequency.
2. If the loop area and the length of earthing wire kept the same, the larger the cross section, the lower the impedance.
3. Two or three 6mm² green/yellow wire in parallel is better than one 35mm² green/yellow wire, especially in high frequency. So a better earthing method could be using two or three 6mm² cable rather than one 35mm² cable.
4. Assume impedance of one 6mm² green/yellow wire is Z, two or three the same wire in parallel, the impedance is not one half of Z or one third of Z. it is quite large than one half of Z or one third of Z. however, keep the two or three cable at a long distance helps decreasing the impedance.

3.6 Reference
[1] Impedance measurement book, 2.3.2
Chapter 4 General Model for earthing on-board ships

Ten groups of wires are measured from 40Hz to 30MhHz in chapter 3 using impedance analyser and this chapter mainly research on modelling of these ten groups of wires and try to figure out a general model for on-board ships.

4.1 Parameters definition

![Figure 4-1 Test Set Up]

<table>
<thead>
<tr>
<th>Area (mm²)</th>
<th>Length (mm)</th>
<th>H₀ (mm)</th>
<th>H₁ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>250</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4-1 Parameters

The whole test set up is shown in figure 4-1: the length of test cable is 25 cm, and the other parameters are shown in the picture. Ten groups of wire tested can refer to Table 3-5.

4.2 Model building procedure and error analysis

4.2.1 Data acquisition

The measurement data is got from impedance analyser. Further, the test procedure is shown in chapter 3.3.2.

4.2.2 Measurement accuracy

Error analysis can refer to 4292 A manual [1], and measurement accuracy is defined as Eq 4-1,
\[ E = E'_{p} + \left( \frac{Z_{i}}{Z_{x}} \right) + Y'_{o} \times Z_{x} \times 100 \]  
(Eq4-1)

Where,

\[ E'_{p} = E_{pL} + E_{PBW} + E_{POSC} + E_{p}[\%] \]

\[ Y'_{o} = Y_{OL} + K_{BW} \times K_{SOSC} \times (Y_{ODC} + Y_{o})[S] \]

\[ Z'_{x} = Z_{SL} + K_{BW} \times K_{OSC} \times Z_{x}[W] \]  
(Eq4-2)

More details parameters can refer to equipment specifications. And figure4-2 shows that the measurement accuracy of impedance. It can be seen that in low frequency, the measurement error in low frequency can be up to 95% but decrease to lower than 5% above 100 kHz. Figure4-3 shows the error of angle error.

![impedance measurement accuracy--G3](image)

**Figure4-2 measurement accuracy impedance analyser (40Hz to 30MHz)**
Figure 4-3 measurement accuracy of phase angle (40Hz to 30MHz)

4.3 Model of G3

Group 3, which is green/yellow wire with a length of 25cm and cross section of 35mm², has been chosen as an example to explain the model building procedure and the other 9 groups of data will be found in the appendix. Further, the method used to build the model is curve fitting, which means first come up with a simple model then more complex one and compares the proposed model with the model of measurements by Matlab.

4.3.1 Data analysis of G3

The data got from impedance analyser are absolute value of impedance |Z| and phase angle θ.

1. In a certain high frequency, the phase angle got from impedance analyser are larger than 90 degree, which are not valid, so these data should be exclude first and the rest data are valid to build a model.
2. Determine the average value (μ) and standard deviation δ
3. There is a 99.73% possibility that the data could at [μ − 3δ, μ + 3δ], which shows in figure 4-4. In figure 4-4a, the red dots are the upper limits and the blue dots are lower limits. There is a 99.73% possibility that the data would fall in the area between upper limits and lower limits. Also it is the same to figure 4-4(b).
(a) Three time standard deviation of impedance (40Hz-30MHz)

(b) Three time standard deviation of phase angle (40Hz-30MHz)

Figure 4-4 three time deviations of impedance and phase angle
4.3.2 Modelling external inductance

As explained in chapter 2, the wire mainly consists of two parts, the external part which is represented by the loop in which current flows and also internal parts which can be present by a skin effect model.

First a model with R in series with L is tested. The impedance of 40Hz can be chosen as R for low frequency, L can be ignored. Z in 40Hz is 0.016145Ω.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Impedance(Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.016145</td>
</tr>
<tr>
<td>1.3323*10^7</td>
<td>24.4432</td>
</tr>
</tbody>
</table>

Table 4-2

In high frequency, R can be ignored. L can be calculated by the highest value of impedance divided by 2πf. So L equals 2.9214*10^-7H.

\[ Z = R + j \cdot 2\pi f \cdot L \]  

(Eq4-3)

4.3.2.1 Impedance and phase angle comparison between model and measurement

Put Z into Matlab and compare the curve between the model and the measurement data, which is shown in figure 4-5 below. The upper part of the figure is a comparison of absolute value of impedance and it shows that they are quite fitted with each other. The lower half gives the phase angle comparison and it shows in around 2000Hz, the phase angle of model is a little lower than the measurement data and in frequencies higher than 20000Hz, the phase angle of model is a little larger than the measurement data. Overall, this model is quite satisfactory.

Figure 4-5 impedance and phase angle comparisons (40Hz-13MHz)
4.3.2.2 Real and imaginary part comparison between model and measurement

Figure 4-6 compares real part and imaginary part between model and measurement separately. The real part of the model and measurement are fit quite well with each other. Further, the real part of model in high frequency is a little larger than the measurement. Overall speaking, the real and imaginary part also quite fit with each other.

4.3.2.3 Impedance deviation

The difference between the model and the measurement is called deviation. Two deviations (impedance and phase deviation) are defined and compared in the following part.

Assume that the impedance of the measurements is \( Z_i \) (absolute value) and the phase angle is \( \Theta_i \), the impedance of the model is \( Z_m \) (absolute value) and the phase angle of the model is \( \Theta_m \).

Deviations of the impedance Dev1, the percentage of impedance deviation, deviation of phase angle, the percentage deviation of phase angle are defined as the equations below:

\[
\text{Dev1} = Z_i - Z_m; \quad \text{Eq4-4}
\]

\[
\text{Dev2} = \Theta_i - \Theta_m; \quad \text{Eq4-5}
\]

\[
\text{DEV1,p} = \frac{Z_i - Z_m}{Z_i} \times 100\% \quad \text{Eq4-6}
\]
\[
\text{Dev2,} p = \frac{\theta \cdot m \cdot \theta}{\theta m} \cdot 100\%
\]
(Eq4-7).

**Figure 4-7** impedance deviation and impedance deviation in percentage (40Hz-13MHz)
Figure 4-8 phase deviation and impedance deviation in percentage (40Hz-13MHz)

Figure 4-7 shows impedance differences in Ω and differences in percentage between the model and the measurement data. From the upper part of the figure, highest differences in Ω can be found in the highest frequency point, it is around 0.4Ω and the highest deviation in percentage happens at around 2000Hz and the value is 17%.

Figure 4-8 gives the deviation of phase angle in degree and in percentage. The highest deviation in degree happens at 4000Hz and around 5 degrees and the largest deviation in percentage happens at the beginning 40Hz and can reach as high as 600%, but it calm down at 50Hz.

4.3.2.4 Summary
From above analysis, the deviation of impedance and phase angle between the model and the measurement data is quite small and a simple model of R in series in L could be enough for modelling the earthing wire.

Further, modelling are done with the rest 9 groups of wires and shows the model R in series L is fitted with the measurement data obtained from impedance analyzer. More information will be found in the appendix.

<table>
<thead>
<tr>
<th>Group</th>
<th>R(Ω)</th>
<th>L(uH)</th>
<th>Impedance deviation in Ω</th>
<th>Impedance deviation in %</th>
<th>Phase angle deviation in degree</th>
<th>Phase angle deviation in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>0.0175</td>
<td>0.2843</td>
<td>0.14</td>
<td>18%</td>
<td>5</td>
<td>4500(only below 50Hz)</td>
</tr>
<tr>
<td>G2</td>
<td>0.01837</td>
<td>0.2580</td>
<td>0.41</td>
<td>17%</td>
<td>5</td>
<td>600(below 50Hz)</td>
</tr>
<tr>
<td>G3</td>
<td>0.01615</td>
<td>0.2921</td>
<td>0.17</td>
<td>20%</td>
<td>5.5</td>
<td>160</td>
</tr>
<tr>
<td>G4</td>
<td>0.01821</td>
<td>0.3338</td>
<td>-0.3</td>
<td>18.5%</td>
<td>5</td>
<td>82</td>
</tr>
<tr>
<td>G5</td>
<td>0.01895</td>
<td>0.2307</td>
<td>0.15</td>
<td>19%</td>
<td>4.5</td>
<td>320%</td>
</tr>
<tr>
<td>G6</td>
<td>0.01711</td>
<td>0.2469</td>
<td>0.22</td>
<td>19%</td>
<td>4.5</td>
<td>130%</td>
</tr>
<tr>
<td>G7</td>
<td>0.01793</td>
<td>0.2631</td>
<td>0.26</td>
<td>18%</td>
<td>4.2</td>
<td>80%</td>
</tr>
<tr>
<td>G8</td>
<td>0.01811</td>
<td>0.2772</td>
<td>0.32</td>
<td>17%</td>
<td>4</td>
<td>430%</td>
</tr>
<tr>
<td>G9</td>
<td>0.01735</td>
<td>0.3020</td>
<td>0.28</td>
<td>17.5%</td>
<td>5</td>
<td>88%</td>
</tr>
<tr>
<td>G10</td>
<td>0.01706</td>
<td>0.2622</td>
<td>0.17</td>
<td>18.5%</td>
<td>5.5%</td>
<td>84%</td>
</tr>
</tbody>
</table>

Table 4-3 general information for ten groups of wires

4.3.2.5 Improvement
From the last section, model is built using the data got from impedance analyzer. The impedance measured includes two parts: first part is the coaxial cable part and the test cable loop part. However, the interested part is the test cable loop part while the coaxial cable part is an unnecessary part which needs to be excluded from the measurement. One idea is to short circuit the coaxial cable in the end and measure the impedance and phase angle of this part, then build a simple R-L model of it and finally a new model of test cable loop will be obtained which will be explained in the following part.
Figure 4-9 measurement test set up

So some extra measurements are done on the coaxial cable in the figure 4-9. Five coppers in parallel are added in order to play a role as short circuit in figure 4-9.

The size of the copper is 13cm (length) * 4.5cm (width) * 0.15mm (thickness) and the DC resistance measured is around 0.22 Ohm. Five in parallel the DC resistance is 0.044 Ohm. And the impedance of test cable is around 0.4 Ohm, the DC resistance of the wire is almost ten times higher than the copper added.
The same procedure of building a model as before: choose low frequency impedance as R and L is calculated by high frequency Z divided by (2*pi*frequency).

That is R=0.015721Ohm and L=0.0493uH and the figure below is a comparison between measurement and model.

Figure4-11 impedance and phase angle comparisons (40Hz-30MHz)

Figure4-12 Real and imaginary part comparison between model and measurement(40Hz-30MHz)
Figure 4-13 impedance deviation and impedance deviation in percentage ((40Hz-30MHz))

Figure 4-14 phase angle deviation and impedance deviation in percentage ((40Hz-30MHz))

<table>
<thead>
<tr>
<th>Group</th>
<th>R(Ω)</th>
<th>L(uH)</th>
<th>Max Impedance deviation in percentage</th>
<th>Max Impedance deviation</th>
<th>Max Phase angle deviation in degree</th>
<th>Max Phase angle deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparing table 4-6 and table 4-7, the model of test wire with earth plate is list in the table 4-8 below:

<table>
<thead>
<tr>
<th>Group</th>
<th>R(mΩ)</th>
<th>L(uH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.779</td>
<td>0.235</td>
</tr>
<tr>
<td>2</td>
<td>2.649</td>
<td>0.2087</td>
</tr>
<tr>
<td>3</td>
<td>0.424</td>
<td>0.2428</td>
</tr>
<tr>
<td>4</td>
<td>2.489</td>
<td>0.2845</td>
</tr>
<tr>
<td>5</td>
<td>3.229</td>
<td>0.1814</td>
</tr>
<tr>
<td>6</td>
<td>1.389</td>
<td>0.1976</td>
</tr>
<tr>
<td>7</td>
<td>2.209</td>
<td>0.2138</td>
</tr>
<tr>
<td>8</td>
<td>2.389</td>
<td>0.2279</td>
</tr>
<tr>
<td>9</td>
<td>1.629</td>
<td>0.2527</td>
</tr>
<tr>
<td>10</td>
<td>1.339</td>
<td>0.2129</td>
</tr>
</tbody>
</table>

Table 4-8 models of test cable + metal plate

So generally speaking, the model is a low frequency R with a high frequency L.

### 4.3.3 Model of G3----internal model

In the chapter 4.3.2, the resistance is kept constant in order to model the external inductance. However, in high frequency, the internal resistance becomes significant due to skin effect, it could not be ignored.

However, the challenge is that this high frequency resistance is quite small compare with the impedance caused by external inductance. Some calculation using Equation 4-4 can get the high frequency resistance in 30MHz is around 16.775mΩ, this is quite small compared with the external impedance (20Ω or above). But in order to get a complete model about the model to do further analysis, it is necessary to analysis the resistance and get an impression of the high frequency resistance. In the previous chapter, the absolute value of impedance |Z| and phase angle θ are gained from the impedance analyser. R can be easily obtained from equation \( R = |Z| \cdot \cos(\theta) \). Zoom in figure 4-6, it can be seen that the resistance obtained from calculation.
From figure 4-16, it can be seen that the resistance is quite small (less than 0.2 Ω) and in high frequency, it drop down and rise again, this may be caused by the accuracy of the impedance analyser. Since the results may not be trustful, it is necessary to have some theoretical analysis together with possible fitting process.

According to the analysis in chapter 2, there are mainly two approaches can be used to get a model of resistance.

According to [3] and also some analysis in chapter 2,

For \( r_w << \delta \), \( r_f = r_{dc} = \frac{1}{\sigma \pi r_w^2} \) (Ω/m) \hspace{1cm} (Eq2-3)

For \( r_w >> \delta \), \( r_f = \frac{1}{\sigma [\pi r_w^2 - \pi (r_w - \delta)^2]} \approx \frac{1}{\sigma 2 \pi r_w \delta} = \frac{r_w}{2 \delta} r_{dc} = \frac{1}{2r_w} \sqrt{\frac{\mu_0}{\pi \sigma}} \sqrt{f} \) (Ω/m) \hspace{1cm} (Eq2-4)

So it can be modelled use a critical frequency point, below that frequency, Eq2-3 is used and above the frequency, Eq2-4 is used. Since \( r_w >> \delta \) means \( r_w \) should be at least 10 times larger than \( \delta \). So the critical point can be chosen to \( r_w = 10\delta \) and \( \delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}} = \frac{6.6 \times 10^{-3}}{\sqrt{f}} m \), so the critical frequency pint can be calculated, that is
\( f_{cri} = 39048 \text{Hz} \)

The model can be if

\[
\text{if } f \leq 39048 \text{Hz} \quad R = R_{DC}
\]

\[
\text{if } f > 39048 \quad R = \frac{r_w}{2 \times 6.6 \times 10^{-2}} \sqrt{f} \cdot R_{DC} = 0.025 \times \sqrt{f} \cdot R_{DC}
\]

And put these two equation into the model

In low frequency it fit well, while in high frequency, it not good. This may be due to the coaxial cable added. After some trial and error, the coefficient is adjusted from 0.025 to 0.0056.

Figure4-17 comparisons between measurement and model ((40Hz-13MHz))

Figure4-18(a) shows the new corrected model, and it shows that this model is quite fit with the measurement from 40Hz to around 5MHz

Figure4-18(b) and figure4-19 shows that the model of phase angle in high frequency is almost the same as measurement, it can be presented in figure4-20 that the deviation between the measurement and model is almost zero!
(a) Comparisons between model and measurement of resistance (40Hz-13MHz)

(b) Impedance and phase angle (40Hz-13MHz)

Figure 4-18 comparisons between model and measurement
Figure 4-19 phase angle deviation in degree and in percentage ((40Hz-13MHz))

So, by theoretical analysis and some verification using measurement data, the conclusion can be drawn is that in a frequency which below critical frequency point, which is \( r_w = 10\delta = 10 \frac{6.6 \times 10^{-2}}{\sqrt{f}} \), the internal resistance is DC resistance, and at frequencies high than the critical frequency point, in principle,

\[
R_{hf} = \frac{r_w}{2 \times 6.6 \times 10^{-2}} \sqrt{f} \cdot R_{DC},
\]

sometimes it need a coefficient \( A \) to adjust to fit the measurement.

\[
R_{hf} = A \times \frac{r_w}{2 \times 6.6 \times 10^{-2}} \sqrt{f} \cdot R_{DC}.
\]

In summary, the internal resistance in low frequency can use DC resistance, and in high frequency, it goes up proportional to \( \sqrt{f} \).

Another approach is use equivalent circuit figure2-5 and it needs some calculation. Further, a four ladder compact circuit is proposed by [5], but the principle behind it is quite complex, it needs more research on this aspect.

In summary, the general model is shown in figure4-20
4.4 Theoretical analysis external inductance of group 3

First, the test set up as shown in figure 4-1 consist three parts: the test wire part, the metal plate part and the rod part. For each part, it has an internal inductance and resistance. In addition, these three parts form a loop which test current flow, and thus form an external inductance. So theoretical analysis of these three parts using partial inductance is quite necessary:

4.4.1 Internal inductance and resistance

4.4.1.1 Test cable
In low frequency, the current are uniformly distributed in the cable and the internal resistance and inductance in low frequency and high frequency can refer to Eq 2-3, 2-4, 2-5, 2-6, so

In DC:

\[ R_{DC,wire} = 0.1231 \text{m} \Omega \]
\[ L_{DC,wire} = 12.5 \text{nH} \]

In high frequency (30MHz)

\[ R_{30MHz,wire} = 16.775 \text{m} \Omega \]
\[ L_{30MHz,wire} = 9.1 \times 10^{-3} \text{nH} \]

4.4.1.2 Metal plate
It not easy to predict the current flow in the metal plate, an ideal situation is that the current flow uniformly in the metal plate, so some calculation could be done.
As shown in figure 4-1, the test wire connect to one bolt and then flow through the metal plate and finally back to the source through another bolt. The distance between these two bolts is 25 cm. So assume the current uniformly go through the metal plate (figure 4-21), so the resistance and inductance in DC and 30 MHz can be calculated.

The metal plate is made by steel, but could not figure out which type steel it is. Take steel (SAE 1045) as an example, the conductivity relative to copper, permeability relative to free space are shown in the table below.

<table>
<thead>
<tr>
<th>Conductor</th>
<th>Conductivity (( \sigma_r ))</th>
<th>Permeability (( \mu_r ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Steel</td>
<td>0.1</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 4-9 conductivity and permeability of copper and steel

Where \( \mu_{copper} = \mu_0 = 4\pi \times 10^{-7} \text{H/m} \), \( \sigma_{cu} = 5.8 \times 10^7 \text{S/m} \)

In low frequency,

\[ R_{DC, \text{metal}} = 0.048 \text{m}\Omega \]

The calculation of DC inductance can be refer to [2] and because \( \frac{t}{w} = \frac{8\text{mm}}{9\text{cm}} \ll 0.01 \)

\[ L_{DC, \text{metal}} = \frac{400\pi}{6} \cdot \frac{t}{w} \cdot l = 4.652 \text{nH} \]

In high frequency,
\[ \delta = \sqrt{\frac{1}{\pi \cdot f \cdot \mu \cdot \sigma}} = 0.00121\text{mm} \]

Figure 4-22 high frequency metal plate current distribution

The calculation of resistance can refer to [3] and the current is concentrate on the surface of the metal plate (figure 4-22)

\[
R_{30\text{MHz, metal}} = \frac{l}{2\sigma \delta (w + t)} = 1.97m\Omega
\]

However, there is no formula to calculate the inductance at high frequency, but it could see that the inductance in high frequency is much lower than DC inductance

\[
L_{50\text{MHz, metal}} = L_{\text{DC, metal}} << 4.652nH
\]

4.4.2 External inductance

The external inductance mainly includes two parts: the inductance of test wire and the inductance of metal plate as shown in figure 4-23.
4.4.2.1 Self-partial inductance of test wire

The self-partial inductance of wire can refer to equation 2-15, which is

\[
L_p = \frac{\mu_0}{2\pi} l \left[ \ln\left(\frac{l}{r_w}\right) + \sqrt{\ln\left(\frac{l}{r_w}\right)^2 + 1} - \sqrt{1 + \left(\frac{r_w}{l}\right)^2 + \frac{r_w}{l}} \right]
\]

(Eq2-15)

\( l \) is the length of the test wire, \( r_w \) is the radii of the test wire, \( L_p \) is the partial inductance of test wire.

For \( l \gg r_w \), equation 2-16 is used

\[
L_{p,wire} \approx 2 \times 10^{-7} l \left[ \ln \left( \frac{2l}{r_w} \right) - 1 \right] = 0.201 \mu H
\]

The self-inductance of metal plate can also be referred to [5],

And because the \( W = 90 cm \geq 10l(8 cm) \), the self-inductance can be presented as:

\[
L_p \approx L_{p(t=0)} = 2 \times 10^{-7} \frac{t}{w} l
\]

(Eq4-8)

\( W \) is the width of the metal plate, \( t \) is the thickness of the metal plate, \( l \) is the length of metal plate. \( L_{p,t=0} \) is the partial inductance of thickness is 0.

Because \( u = \frac{l}{w} = 0.28 \leq 1 \), so

\[
\frac{L_{p,t=0}}{l} \approx \frac{\mu_0}{2\pi} u \left( \ln \frac{2}{u} + \frac{1}{2} + \frac{u}{3} \right)
\]

(Eq4-9)
Where \( u = \frac{l}{w} \)

The self-inductance of metal plate is calculate base on Eq4-9 and Eq4-8

\[ L_{p,metal} = 0.0355\mu H \]

**4.4.2.2 Mutual inductance of the wire and metal plate:**
There is no reference on how to calculate the mutual partial inductance between the metal and the test wire.

So the partial inductance of test cable and metal plate is approximates to

\[ L_{cal} = L_{p,metal} + L_{p,wire} = 0.0355\mu H + 0.201\mu H = 0.236\mu H \]

**4.4.2 Total resistance and inductance**

**4.4.2.1 Total resistance**

**DC**

In DC the resistance consist two parts: the resistance of metal plate and the resistance of test wire

\[ R_{DC, total} = R_{DC,wire} + R_{DC,metal} = 0.1711\text{m}\Omega \]

**30MHz**

\[ R_{30MHz, total} = R_{30MHz,wire} + R_{30MHz,metal} = 18.745\text{m}\Omega \]

**4.4.2.2 Total inductance**

The total inductance is the external inductance plus internal inductance

**DC**

\[ L_{DC, total} \approx L_{cal} + L_{DC,metal} + L_{DC,wire} = 0.2528\mu H \]

**30MHz**

\[ L_{30MHz, total} \approx L_{cal} + L_{30MHz,metal} + L_{30MHz,wire} \approx 0.2356\mu H \]

<table>
<thead>
<tr>
<th>Group 3</th>
<th>R(mΩ)</th>
<th>L(μH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.424</td>
<td>0.2428</td>
</tr>
<tr>
<td>Theoretical calculation</td>
<td>0.1711</td>
<td>0.2528(DC inductance)</td>
</tr>
<tr>
<td></td>
<td>18.75</td>
<td>0.2356(30MHz inductance)</td>
</tr>
</tbody>
</table>

Table 4-10 comparisons between model and theoretical calculations-G3

The same to group 4
<table>
<thead>
<tr>
<th>Group 4</th>
<th>R (mΩ)</th>
<th>L (μH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2.489</td>
<td>0.2845</td>
</tr>
<tr>
<td>Theoretical calculation</td>
<td>0.769</td>
<td>0.26175 (DC inductance)</td>
</tr>
<tr>
<td></td>
<td>84.2</td>
<td>0.2446 (30 MHz inductance)</td>
</tr>
</tbody>
</table>

Table 4-11: Comparisons between model and theoretical calculations - G4

G8

<table>
<thead>
<tr>
<th>Group 4</th>
<th>R (mΩ)</th>
<th>L (μH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>2.389</td>
<td>0.2279</td>
</tr>
<tr>
<td>Theoretical calculation</td>
<td>0.4085</td>
<td>0.1720 (DC inductance)</td>
</tr>
<tr>
<td></td>
<td>43.045</td>
<td>0.154865 (30 MHz inductance)</td>
</tr>
</tbody>
</table>

4.5 Reference


[2] DC internal inductance for a conductor of rectangular cross section, Christopher L. Holloway and Edward F. Kuester


Chapte5 Conclusion and Recommendation

In this thesis, measurement and modelling of on-board earthing were studied. Impedance of earthing wire is measured by test equipment and a model is proposed for further analysis of the signal integrity and fault caused by inappropriate earthing method.

First measurement methods related to measuring impedance are studied in order to measure the impedance of earthing wire. Then, two approaches of conducting the measurements are proposed with a well-defined test set up to make the measurement data more reproducible. One approach is based on the equipment in the company (Damen shipyard and Imtech marine), as explained in chapter3, which power supply, voltage meter, LCR meter and Spectrum analyser are used separately for measuring impedance from DC to high frequency. This part mainly investigates how the loop, length and cross section influence on the impedance of test wire. The other approach is based on the test equipment in EPP lab, which impedance analyser, power supply, voltage meter are chosen to finish the test. Ten groups of wires were tested in order to get the best earthing method based on the measurements. Finally, models are built using curve fitting to these ten groups of wire and a general model is proposed. Some further steps need to be done in order to get the high frequency resistance.

There are some conclusions and guidelines on how to install earthing wire based on my measurement

(1) The measured inductance of test wire consists two parts, one parts is internal inductance, which decrease with the frequency. The external inductance is exist in the current flow from the wire and then back to the test equipment, it may change with frequency, so in order to defined the loop which current flow, a well-defined environment and test set up are needed in order to get a trustful and reproducible value of the impedance.

(2) Keep the cross section and wire length constant, the larger loop the current flow, the higher the impedance. Keep the loop and wire cross section constant, the longer the wire, the larger the impedance. Similarly, keep the loop and wire length constant, the larger the wire cross section, the smaller the impedance.

(3) Decrease the loop area and length of test cable can reduce the impedance of wire significantly. The cross section also has some influence on the impedance, but not as much as the first two.

(4) (Keep the wire length constant) comparing litze wire, 6mm2 green/yellow wire and the 35mm2 green/yellow wire, the impedance of litze wire is the smallest.

(5) The impedance of two or three 6mm2 green/yellow wires in parallel with a distance between them is smaller than one 35mm2 green/yellow wire or litze wire, for it has a cross section of 40mm2.

(6) Keep the wire length constant, the impedance of two or three 6mm2 green/yellow wire with a distance between (among) the wire is lower than one 35mm2 green/yellow wire. In the practical situation, it better to use two or more small cross section wire in parallel rather than one wire with large cross section.

(7) The general model of ten tested wire can be represented by an external inductance and an internal resistance, however, this internal resistance is quite small compare with the impedance
caused by the external inductance. So more research need to be done on how to measure high frequency resistance which caused by skin effect.

Recommendations:

1. The general model is proposed and still some researches need to be done on how to measure the high frequency resistance and then build a more accuracy model.
2. Since a model is built, the next steps would be put this model into figure 1-4 and figure 1-5 to analysis on how the earthing part’s influence on the signal integrity
3. It is still a mystery why the military standards choose ‘ earthing wire/bond strap should provide less than 25 ohms impedance at 30 MHz’ or ‘8ohms at 10MHz’, so some test still need to be done on this parts
4. When doing research work, more reading and thinking are both important in finish a high level work.
Appendix A: Measurement methods

Five commonly used measurement methods are studied when measuring impedance, each has advantages and disadvantages.

A.1 Bridge method

![Bridge Method Diagram]

The principle of the bridge is: when no current flows through the detector (D), the impedance of $Z_x$ can be obtained by $Z_x = \frac{Z_1}{Z_2}Z_3$. $Z$ can be a combination of L, C, and R for different applications.

Advantage and disadvantage: the advantage of bridge method is first high accuracy (0.1%), then wide frequency range by using different types of bridge, in addition, it is low cost. While its disadvantages are: first, the bridge needs to be manually balance, and if we use only a single instrument, applicable frequency range is from DC to 300MHZ.

A.2 Resonant method

![Resonant Method Diagram]

Figure A-2 equivalent circuit of resonant method
The principle of resonant method is, when a circuit is adjusted to resonance by adjusting a tuning capacitor(C), the unknown impedance LX and Rx values are obtained from the test frequency, C value and Q value. Q is measured directly using a voltage meter placed across the tuning capacitor. There are other series and parallel connection other than this direct connection which can be used for a wide range of impedance measurement.

The advantage of resonant method is good Q accuracy up to high Q (300) but the disadvantage is obviously, first, the tuning capacitor needs to be adjusted to get resonance. Second is the accuracy is quite low in measuring the impedance. The applicable frequency range is from 10 kHz to 70MHz.

A.3 I-V method

![Figure A-3 equivalent circuit of I-V method](image)

I-V method is usually used for grounded device measurement. The Principle behind it is: the unknown impedance \( Z_x \) can be calculated from measured voltage and current value. Current is calculated using the voltage \( V_2 \) across an accurately known low value resistor(R), which is \( I = \frac{V_2}{R} \). So, the impedance \( Z_x = \frac{V_1}{I} = \frac{V_1}{V_2} R \). In practice, a low loss transformer is used in place of R to prevent the voltage drop caused by the low value resistance. The transformer, however, lower the range of applicable frequency.

The advantage of I-V method is that it is suitable for probe-type test, while its disadvantage, as mentioned before, the operating frequency is limited by transformer used in test head.

Frequency range: 10 kHz to 100MHz
A.4 RF I-V method

The principle of RF I-V method is based on I-V method. It is configured in a different way by using impedance-matched measurement circuit (50Ω) and a precision coaxial test port for operation at high frequency. There are two separate method which suitable for measure high frequency and low frequency impedance.

As we can see from figure A-4(a), the unknown impedance can be calculated using the equation

\[ Z_x = \frac{V}{I} \]

The voltage: \( V = \frac{V_1}{2} \) and the current \( I = \frac{V_2}{R} - \frac{V_1}{R} \).
According to Kirchhoff’s law, impedance can be presented as $Z_x = \frac{V_1}{I} = \frac{2R}{V_2 - V_1}$. It is the same applied to high frequency calculation which impedance can be obtained by

$$Z_x = \frac{V_1}{I} = \frac{R}{2} \left( \frac{V_1}{V_2} - 1 \right)$$

In practice, a low loss transformer is used in place of $R$. The transformer limits the low end of applicable frequency range.

**A.5 Auto-balancing method**

![Equivalent circuit of auto-balancing method](image)

The current $I_x$ balances with the current $I_r$ which flows through the range resistor ($R_r$), by operation of the I-V converter. The potential at the low point is maintained at zero volts. The impedance of the DUT is calculated using the voltage measured at high terminal ($V_x$) and the across $R_r$ ($V_r$).

$$\frac{V_x}{Z_x} = I_x = I_r = \frac{V_r}{R_r} \quad \text{(EqA-1)}$$

$$Z_x = \frac{V_x}{I_x} = R_r \frac{V_x}{V_r} \quad \text{(EqA-2)}$$

The advantages of the auto-balance bridge method are as followed. First, it is widely frequency coverage, from LF to HF. Second, a high accuracy over wide impedance can be gained by using this method. Third, it can be used for ground device measurement.

Frequency range: 20Hz to 110MHz.
Appendix B Experiential test set up

Test set up is quite important in measuring the impedance of the earthing wire. Because the impedance of the earthing impedance is quite small (less than 1mΩ) and a little interference from the outside will have significant influence on measuring the impedance in low frequency. In high frequency, coupling and also stray capacitance will also have more or less influence on measuring results. So it is quite important to have a well-defined measuring environment to make the measurement data reproducible in a large frequency range (from DC to 30MHz). Three different test set ups are proposed and compared. The best measurement test set up is found considering reproducibility, minimum error and easy to operate in low frequency and high frequency.

B.1 Test set up-1

The first test set up is quite simple. This test set up is valid for both LCR meter and DC measurement. As shown in figure B-1, the red fixture connects to one side of the earthing wire and the black one connects to the other side. The earthing wire is put on the table.

B.1.1 Test procedure

1. 30 minutes warm up
2. Open/short calibration from 20Hz to 100kHz
3. Connect the test fixtures to the test cable as shown in figure B-1, choose ‘auto’ option.
4. Record the measurement data, the absolute value of impedance, phase angle, inductance and resistance.
5. Data analysis and plot it in Matlab
The advantage of this test set up is quite easy to connect the wire to the measurement equipment. The disadvantages are quite apparently. First, the test environment is quite poor, for instance, the metal bar under the wooden table will produce a parasitic capacitance which will influence accuracy of impedance in high frequency. Second, the loop (figure B-2) which created by the test fixture (the length of the cable is about 35cm) will has some influence on the reproducibility of the measurement. As said in chapter2, the external inductance of wire is much relying on the loop area, the large the loop, the high the inductance. Further, when measuring the same earth strap (figureB-1), the loop which created by test fixture cable is quite different, so it is quite difficult to keep the measurement loop constant, which cause the poor repeatability.

**B.1.2 Loop area influences on test impedance (litze wire)**

Below are two examples of loop influence the impedance of the test wire, one is measuring earth strap (figureB-2) and the other is measuring green/yellow wire (figureB-4).
Figure B-2 small, middle and large loop on measuring the same earth strap

Figure B-2 shows that using LCR meter measuring the same earth strap with different size of loop areas: small loop (a), middle loop (b) and large loop(c). Measurement results of impedance, phase angle, resistance and inductance can be found in figure B-3.

Figure B-3(a) compares the impedance and phase angle of different loop area with the change of frequencies. The unit of x axis is Hz and it is plotted in log scale. The units of y axes are mΩ (a) and degree (b) separately. From figure B-3(a) we can see, in highest frequency (around 200kHz), the impedance of large loop is around 400mΩ while small loop is less than 50mΩ. The impedance of large loop is eight times larger than small loop! This can be explained by figure B-3(b), which shows that the difference is caused by different value of inductance of big loop (around 0.35uH) and small loop (around 0.05uH).
(a) Impedance (upper) and phase angle (bottom) comparison of small, middle, large loop

(b) Inductance (upper) and resistance (bottom) comparison of small, middle, large loop

Figure B-3 measurement plots

**B.1.3 Loop area influences on test impedance (green/yellow wire)**

The other measurement was also done with 35mm2 green/yellow wire, as shown in figure B-4.
Figure B-4: Measurement of Green/Yellow wire

(a) Large loop

(b) Small loop

Graphs showing frequency response of large and small loops.
As can be seen from figure B-5, the loop area also plays quite significant in measuring impedance of green/yellow wire. In highest frequency, the impedance of large loop is about 180mΩ while the small loop impedance is below 70mΩ. The large loop is 2.5 times larger than small loop.

B.2 Test set up -2
Test set up-1 shows that the loop area of test fixture cable has significant influence on measuring inductance thus influence the impedance of earthing cable. Some improvement has been done by test set up-2. First, put the test cable on the surface of a metal plate, which can help reducing the parasitic capacitance which produces by the metal under the table. Second, by keeping the two test fixture table close to each other to reduce the loop area and the test wire is bended as a circle to do the measurement.

However, if want to guarantee the data got from measurement is repeatable, the bending shape should be the same as before, which quite hard to achieve by hand. So the data got from LCR meter is unstable.
In addition, the wire can be bended to different shapes and the impedance is different with each other, thus it is difficult to determine which impedance value is the one wanted. As shown in figure B-7.

![Image](a)

![Image](b)

Figure B-7 other types of measurement

Furthermore, the position of wire also influences the impedance. For instance, the measurement performed above are the wire in parallel with the surface of table, while it can also be vertical or any other angle to the table, the impedance got from LCR meter is different from each other. The most important thing in measuring impedance of a wire should give a well-defined position as well as environment, which can make the data more reproducible. So researches only deal with one situation of earth impedance, a well-defined one and further use these data to build a model which only suitable for this specific situation.

Finally, test set up-1 and test set up-2 only suitable for low frequency measurement, in the other words, only suitable for LCR meter. Not suitable for high frequency measurement, the Spectrum analyser use BNC connector (figure B-8) to do the measurement. The BNC connector could not directly connect to the earthing wire, because they are not fitted with each other. So test set up-3 is introduced in the following part.
Figure B-8 top view of FSH3 spectrum analyser
Appendix C Verifications

Figure C-1 is the measurements using 4292A impedance analyser. In order to check the possibility of using this improvement, some verification tests are performed first.

(a) 25Ω load

(b) 30Ω load
(c) 50 Ω load

Figure C-1 verifications use different known load

(d) 75Ω load
Appendix D  Nine groups of model---external

D.1 G1 Litze wire Length 30cm width 2 cm thick 2mm

figureD-1 test set up for litze wire

figureD-2 impedance and phase angle comparison between model and measurement data
Figure D-3 Real and imaginary part comparison between model and measurement

Figure D-4 Impedance deviation and impedance deviation in percentage

Figure D-5 Phase deviation and impedance deviation in percentage
D.2 G2: Litze wire length 24.5cm width 2cm thick 2mm

Figure D-6 impedance and phase angle comparison between model and measurement data

Figure D-7 Real and imaginary part comparison between model and measurement

Figure D-8 impedance deviation and impedance deviation in percentage
D.3 G4 length 25cm, 6mm² green/yellow wire

figureD-9 phase deviation and impedance deviation in percentage

figureD-10 impedance and phase angle comparison between model and measurement data

figureD-11 Real and imaginary part comparison between model and measurement data
Figure D-12 impedance deviation and impedance deviation in percentage

Figure D-13 phase deviation and impedance deviation in percentage

D.4 G5 G/Y wire 3*6mm², 10cm apart

Figure D-14 1 test set up for G5
Figure D-15 impedance and phase angle comparison between model and measurement data

Figure D-16 Real and imaginary part comparison between model and measurement

Figure D-17 impedance deviation and impedance deviation in percentage
Figure D-18 phase deviation and impedance deviation in percentage

D.5 G6 3*6mm2 5 cm apart

Figure D-19 test set up

Figure D-20 impedance and phase angle comparison between model and measurement data
Figure D-21 Real and imaginary part comparison between model and measurement

Figure D-22 Impedance deviation and impedance deviation in percentage

Figure D-23 Phase deviation and impedance deviation in percentage
D.6 G7 2*6mm2 10 cm apart

Figure D-24 test set up for G7

Figure D-25 impedance and phase angle comparison between model and measurement data

Figure D-26 Real and imaginary part comparison between model and measurement data
Figure D.274 impedance deviation and impedance deviation in percentage

Figure D.28 phase deviation and impedance deviation in percentage

D.7 G8 2*6mm2 5 cm apart

Figure D.29 test set up for G8
Figure D-30 impedance and phase angle comparison between model and measurement data.

Figure D-31 Real and imaginary part comparison between model and measurement.

Figure D-324 impedance deviation and impedance deviation in percentage.
D.8 G9 2*6mm2 close together

FigureD-33 phase deviation and impedance deviation in percentage

FigureD-34

FigureD-35 impedance and phase angle comparison between model and measurement data
Figure D-36 Real and imaginary part comparison between model and measurement

Figure D-37 Impedance deviation and impedance deviation in percentage

Figure D-38 Phase deviation and impedance deviation in percentage

D.9 G10 3*6mm2 close together
Figure D-39

Figure D-40 impedance and phase angle comparison between model and measurement data

Figure D-41 Real and imaginary part comparison between model and measurement
Figure D-424 impedance deviation and impedance deviation in percentage

Figure D-43 phase deviation and impedance deviation in percentage