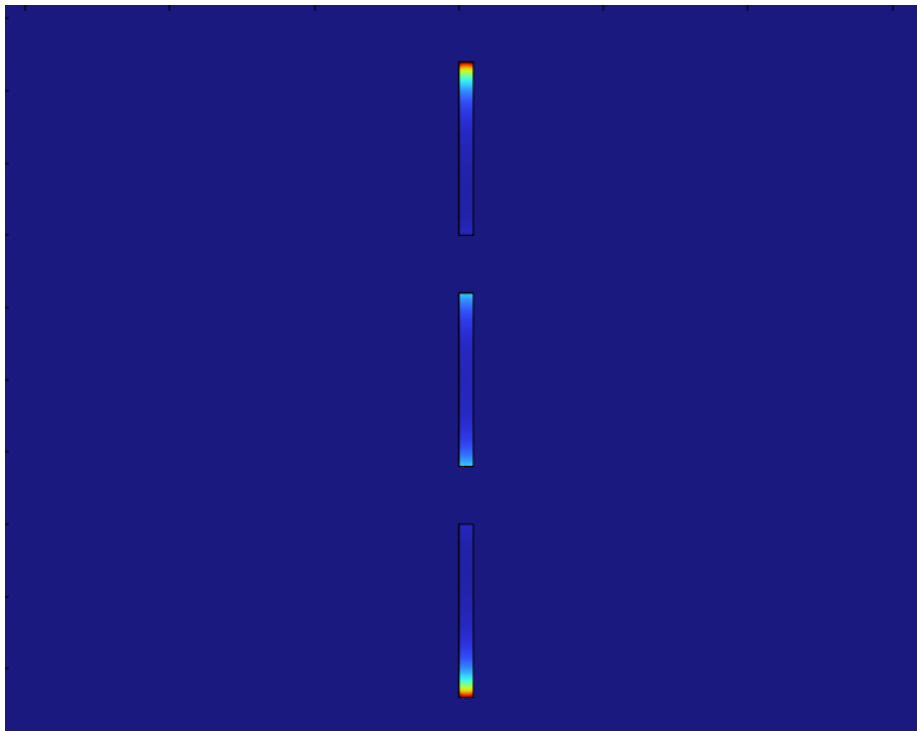


FMH606 Master's Thesis 2024
Electrical Power Engineering

Influence of skin- and proximity effects on LV fuse gear



Sandra Torsvik

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Summary:

ABB in Skien produces compact transformer stations for the distribution grid. Depending on the application, these can come with a significant number of different configurations. Manufacturers must prove that every unit satisfies the temperature limits given in the standards. Both the skin- and the proximity effect increase the resistance of AC circuits which increases power losses and can add undesirable heating.

This thesis aims to look at how the skin- and proximity effects influence LV fuse gear, and contains basic theory, COMSOL simulations focused the skin- and proximity effects, laboratory experiments and hand calculations.

The final results of the COMSOL simulations indicate that the losses increase as the distance between busbars decrease and that the losses are highest in the center busbar. The results also show that the losses do not increase linearly as the distance decreases.

Preface

This master thesis functions as a base for assessment in the course FMH606 Master Thesis at campus Porsgrunn of the University of South-Eastern Norway. This thesis is valued at 30 credits and ran over the course of the fourth and last semester of the Electrical Power Engineering (EPE) study program at USN. This thesis' focus is on the influence skin- and proximity effects have in LV fuse gear.

To understand the contents of this thesis the reader needs basic knowledge of magnetic fields, induction laws, and other electrical power engineering concepts.

The picture on the front page is taken from one of the COMSOL simulation plots made for this thesis.

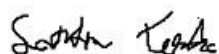
The digital tools used in this thesis were:

- COMSOL Multiphysics 6.1 (Classkit License Version)
- Microsoft Teams (work or school)
- Microsoft 365 (Word, Visio, Excel, Project)

I would like to thank my supervisors Elin Fjeld and Mohammad Khalili for their advice and input during the writing of this thesis.

I would also like to thank Yabai Li and Kenneth Mandal at ABB Skien for lending me the busbars used in the laboratory experiments.

Porsgrunn, 15.05.2024



Sandra Torsvik

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Nomenclature

A	Ampere
AC	Alternating Current
DC	Direct Current
Hz	Hertz (frequency)
LHS	Left Hand Side
LV	Low Voltage
RHS	Right Hand Side
W	Watts

1 Introduction

This introduction chapter contains information about the background, objectives, methods, scope and structure of this thesis.

1.1 Background

ABB in Skien produces compact transformer stations for the distribution grid. Depending on the application, these can come with a significant number of different configurations. Manufacturers must prove that every unit satisfies the temperature limits given in the standards. Both the skin- and the proximity effect increase the resistance of AC circuits which increases power losses and can add undesirable heating.

1.2 Objective, scope and methods

The goal of this thesis is to evaluate if the skin- and proximity effects need to be considered in LV fuse gear.

The methods used in this thesis are:

- Researching skin- and proximity effects in LV fuse gear.
- COMSOL simulations on single- and three-phase cable and busbar systems in different configurations.
- Laboratory experiments using copper busbars in single- and three-phase configurations to measure the power losses.

1.3 Limitations

The laboratory experiments are limited to rectangular copper busbars.

The AC laboratory setup was limited to 800 A due to the rating of the cables connected to the high current transformer used to supply the busbar setup with power.

The DC laboratory setup was limited to 200 A due to this being the limit of the DC power supply.

Due to the limitations in the laboratory the COMSOL simulations were also limited to 800 A to have comparable results.

The COMSOL simulation busbar geometry was set up to be the same as the geometry of the physical busbars for the results to be comparable.

The AC experiments and simulations were limited to a frequency of 50 Hz as this is the frequency of the Norwegian power grid.

This thesis does not look at the temperature aspect of added resistance in AC circuits, and it does not look into any economic aspects.

1.4 Structure

This thesis is structured to be read in its entirety as the contents of chapter 2 describe the basic principles of the skin- and proximity effect, while the creation of the COMSOL simulations is presented in chapter 3 and the details of the laboratory setup is explained in chapter 4. This information is important for understanding the results and discussion presented in chapter 5 and 6.

Chapter 2 contains theory about the basic principles of skin- and proximity effects and how these occur in AC circuits.

Chapter 3 shows how the COMSOL simulations used for this thesis were created and some information about the learning process of using COMSOL for the first time.

Chapter 4 covers the laboratory experiments, information about the different setups that were used and a discussion about the laboratory portion of the thesis.

Chapter 5 contains the key results from the COMSOL simulations and the laboratory experiments as well as some hand calculations.

Chapter 6 discusses the similarities and differences of the results presented in the previous chapter.

Chapter 7 concludes the findings of this thesis.

The appendices contain results from the COMSOL simulations, the laboratory experiments, and the hand calculations in the form of graphs and tables. The raw results are not included in this thesis.

2 Theory

This chapter contains the theory explaining the skin- and proximity effect and how these effects affect LV switchgears.

2.1 DC resistance

Resistance is what opposes electrical currents as they flow through conductors as shown in Figure 1. The resistance in conductors made of copper is very low, but still present and the resistance increases as the length of the conductor increases. The cross-sectional area of the conductor also affects the resistance as lower cross sections reduces the area which the current can flow and bigger cross sections increase it. [1]

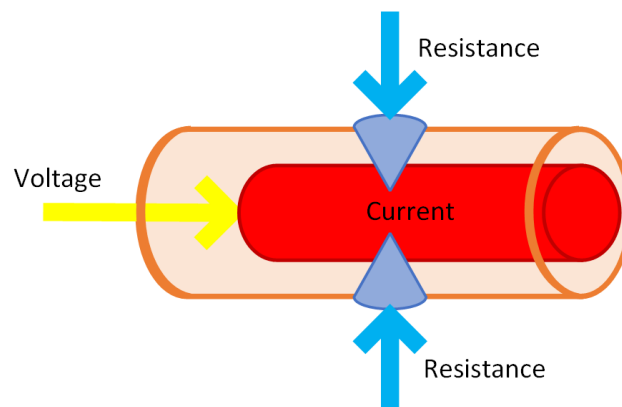


Figure 1: Visual representation of electrical resistance in a conductor based on [1]

Higher resistance means less power flow and higher losses, which in turn results in higher temperatures in the conductors. High temperatures can damage conductors and will increase the likelihood of corrosion and fires.

When DC current is applied to a conductor the current distributes equally throughout the cross-sectional area as shown in Figure 2, this is due to the absence of alternating magnetic fields.

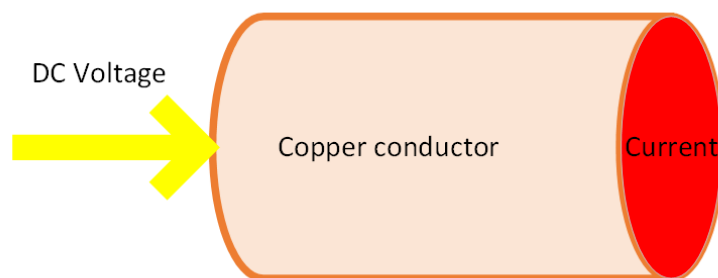


Figure 2: DC current distribution in a copper conductor

2.2 AC resistance

As AC current flows through a copper conductor the current is opposed by the same physical resistance as the DC current as this is determined by the resistivity of the material the conductor. However, AC current also experiences more resistance as the alternating current produces magnetic fields across the conductor, which is known as inductance. The size of this added resistance will depend on the applied frequency in the circuit, in Norway the frequency is 50 Hz. [2]

2.3 Eddy currents

The magnetic fields generated in conductors when AC current is applied generate currents that flow in circular patterns which are called Eddy currents. These currents flow perpendicular to the plane of the magnetic fields in closed loops. In stationary conductors like those in LV switchgears the size of the induced eddy currents is related to the size of the magnetic field surrounding it. [3]

2.4 Skin effect

Around every current carrying conductor there are magnetic fields, in AC circuits this magnetic field changes with time. These changing magnetic fields will create induced voltages according to Faradays Law shown as Equation 2.1, the size of the induced voltages depends on the frequency of the AC current, where higher frequencies equal to higher induced voltages.

$$E = N \times \left(\frac{d\Phi}{dt}\right) \quad (2.1)$$

E = induced voltage in Volts [V]

N = number of turns

$d\Phi$ = change in flux in Weber [Wb]

The induced voltage opposes the direction of the original AC current flow, and this effect is most prominent in the center of the conductor. This then causes the current to flow in the outer layers of the conductor which is also referred to as the “skin”, as shown in Figure 3. When the frequency increases it increases the area of the center of the conductor consumed by the induced voltage which pushes the current further out into the skin of the conductor. [1]

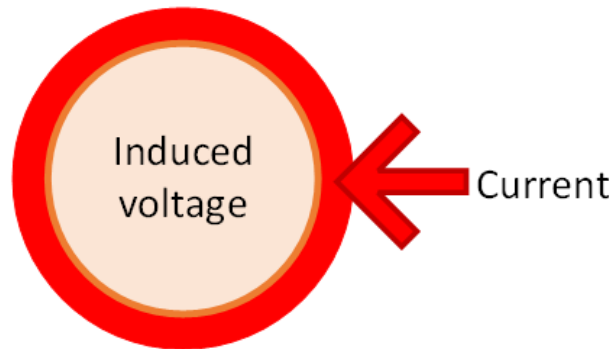


Figure 3: Visualization of skin effect on a round conductor

As the current is now flowing in the outer skin of the conductor the cross-sectional area used by the current is reduced and the resistance increases. This increases the losses experienced along the length of the conductor and leads to increased heating. [4]

2.5 Proximity effect

When two or more conductors carrying AC current are in close proximity to one another the magnetic fields created by each of the conductors affect the current density of each conductor. The induced eddy currents that oppose the main current are cancelled out while the eddy currents going the same direction as the main current amplify the main current as shown in Figure 4. [5]

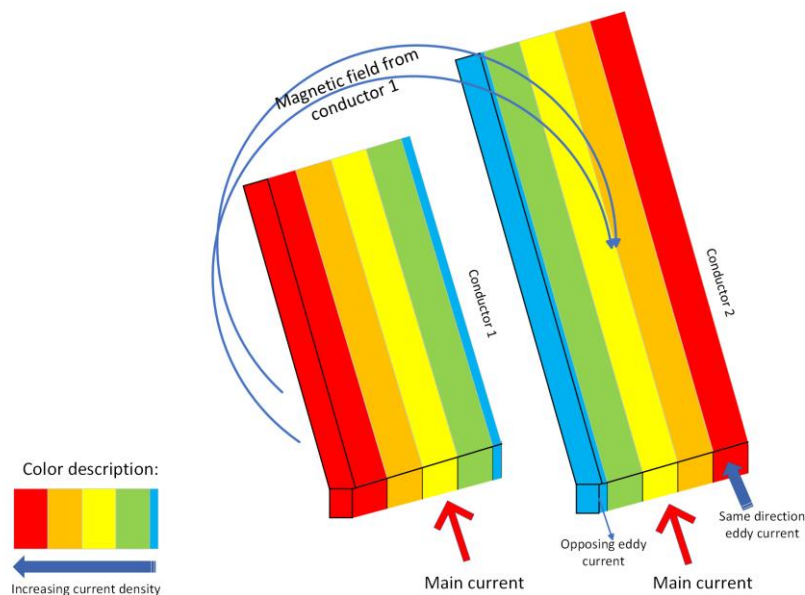


Figure 4: Magnetic fields effect on nearby conductor based on [5]

The direction the main current in the conductors flow determines which part of the conductors cross-sectional area has the highest current density. As shown in the figure above the current density is concentrated in the side of the conductor facing away from each other when the main current is flowing in the same direction in both conductors. When the main current flows in opposing directions, the current density is concentrated in the side of the conductor that faces the other conductor as shown in Figure 5. [5]

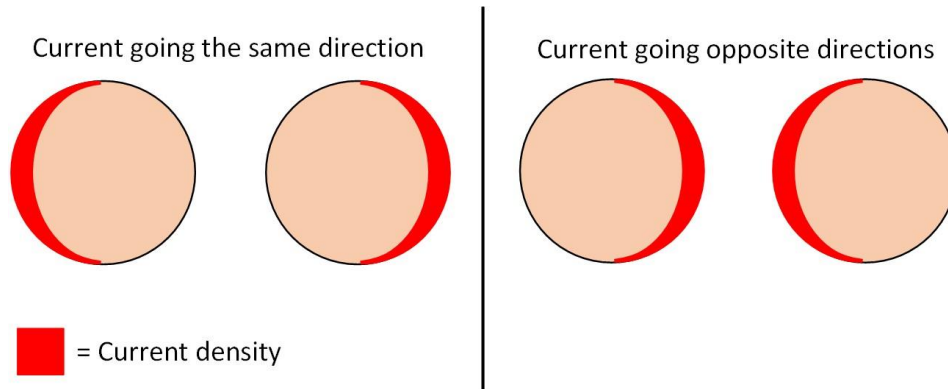


Figure 5: Current density in regard to the direction of the current flow

3 COMSOL simulations

This chapter contains information about the COMSOL simulations and how they were created.

3.1 Creating the model

First step for creating a model in COMSOL is to select the Model Wizard when opening the program, the Model Wizard is highlighted in Figure 6.

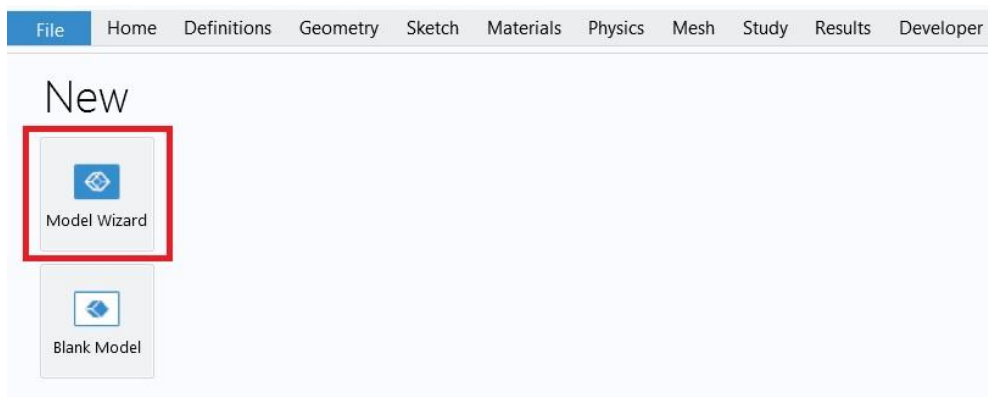


Figure 6: The Model Wizard

After selecting the Model Wizard the Space Dimension needs to be selected, this determines which dimension the model is built in. The 2D Space Dimension, which is highlighted in Figure 7, was used to create the models in this thesis.

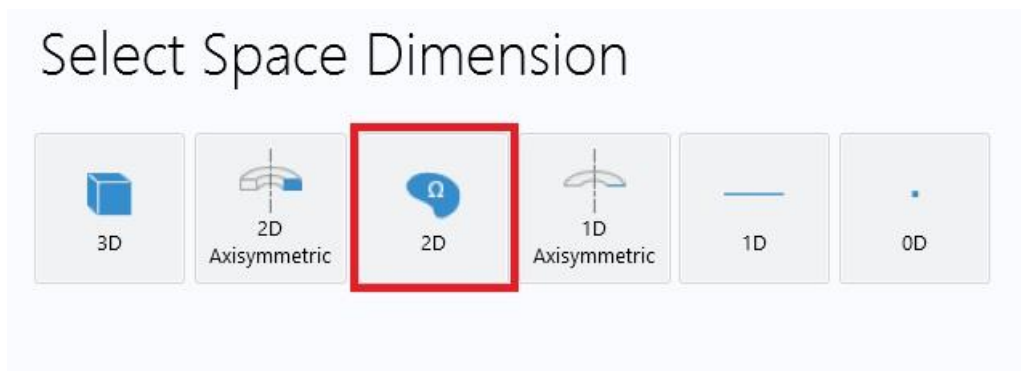


Figure 7: Selecting the Space Dimension

The next step is to choose which physics to apply to the model, the AC/DC group is the physics group that contains all the physics interfaces for low frequency electromagnetics,

which includes magnetic fields. In the AC/DC group there is a subgroup called Electromagnetic Fields which contains the Magnetic Fields (mf) interface which will be used to simulate the magnetic fields and current distribution in conductors.

The Magnetic Fields interface solves Maxwells equations and uses Amperes law to find magnetic potential, the selected physics interface is shown in Figure 8.

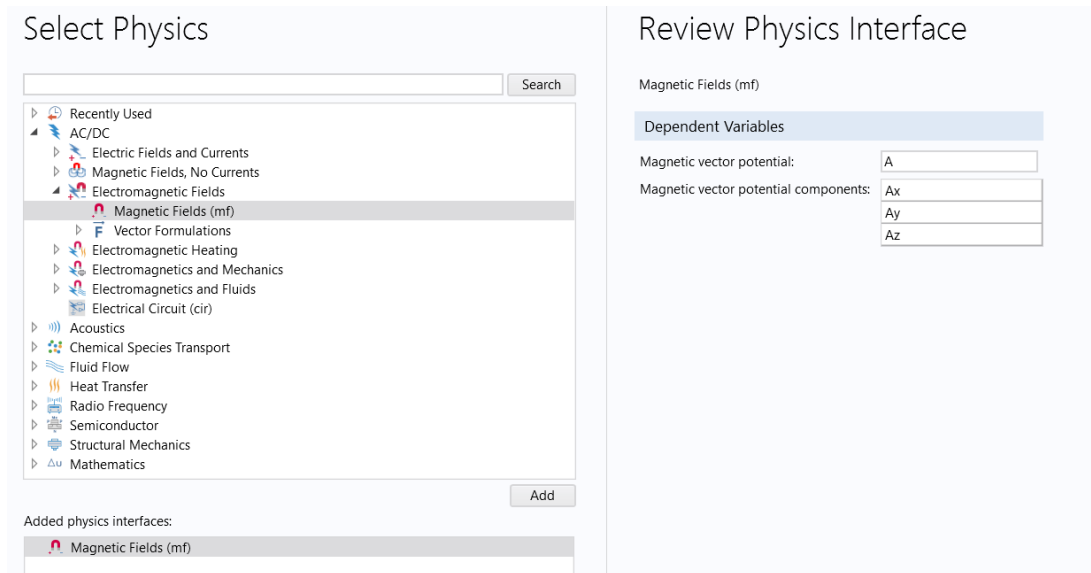


Figure 8: Physics selection

Then it's time to select the Study, for these models the Frequency Domain was used as this Study is used to compute a models responses to different frequencies. The selected Study is shown in Figure 9.

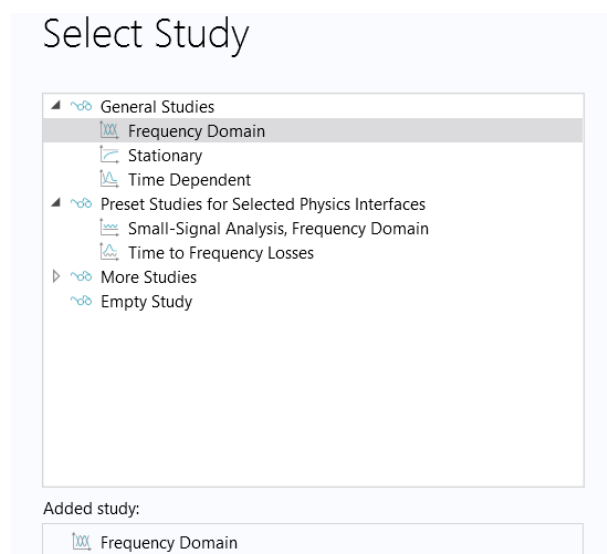


Figure 9: Selecting the Study

3.2 Model geometry and material selection

Then it's time to start making the model, first the geometry needs to be created, in this single-phase DC model the geometry consists of two rectangles. The first rectangle is the busbar with the same design as the real-life ones used in the laboratory, which is a width of 1 cm, a height of 12 cm and a length of 1,2 m as shown in Figure 10. The length is not determined here as it is a 2D model.

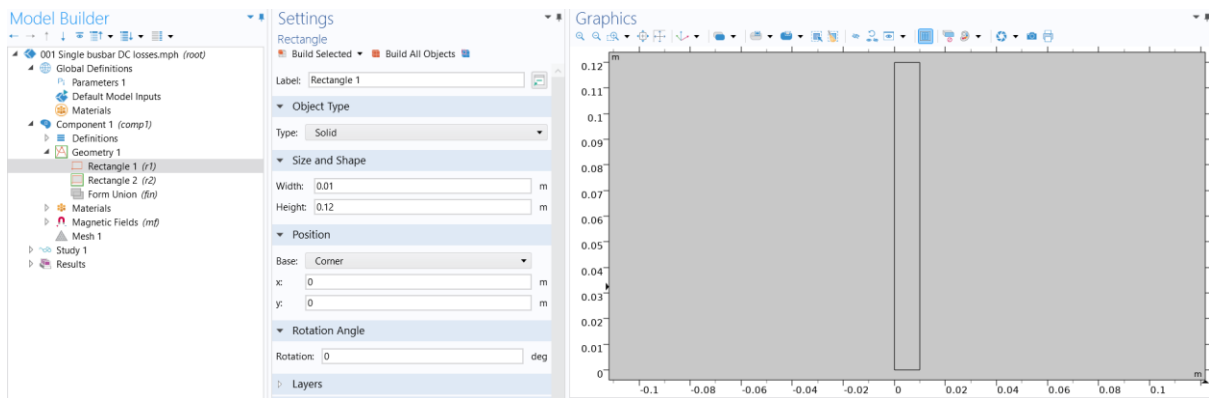


Figure 10: The geometry of the copper busbar

The second rectangle acts as the air which surrounds the busbar, it is important that this geometry is big enough to where it does not interfere with the magnetic fields which surround the busbar geometry. In this model the air geometry was set to a width of 1 m and a height of 3 m to ensure ample space around the busbar as shown in Figure 11.

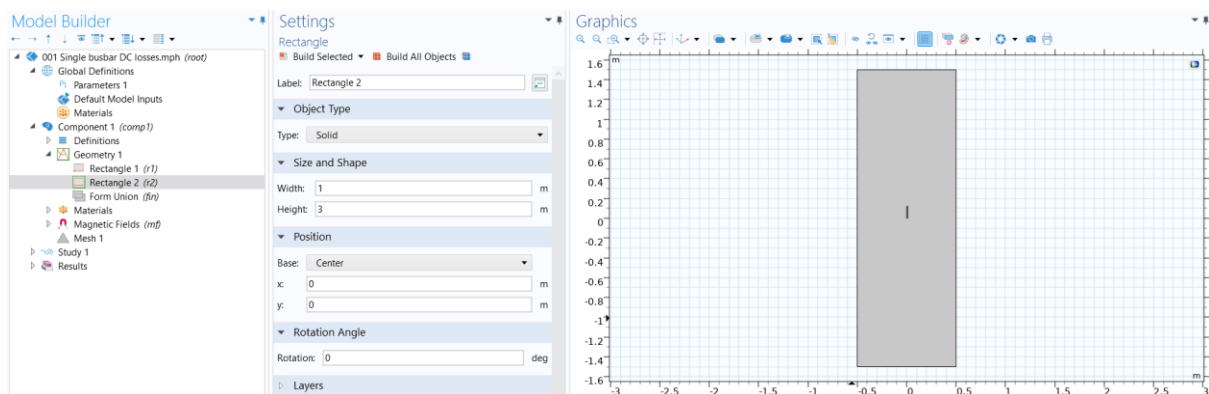


Figure 11: The geometry of the surrounding air

Next is choosing what material the different geometries should be made of in the model. In the models created for this thesis the materials were imported from COMSOL's built-in material library. The materials used were Air and Copper as shown in Figure 12.

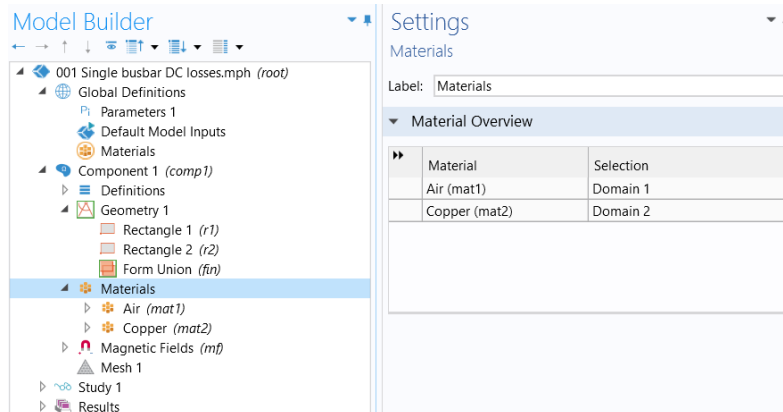


Figure 12: Material selection

Then the length of the busbar was set to 1.2 m like in real-life by setting the out-of-plane thickness to the desired value inside the settings for the Magnetic Fields interface as shown in Figure 13.

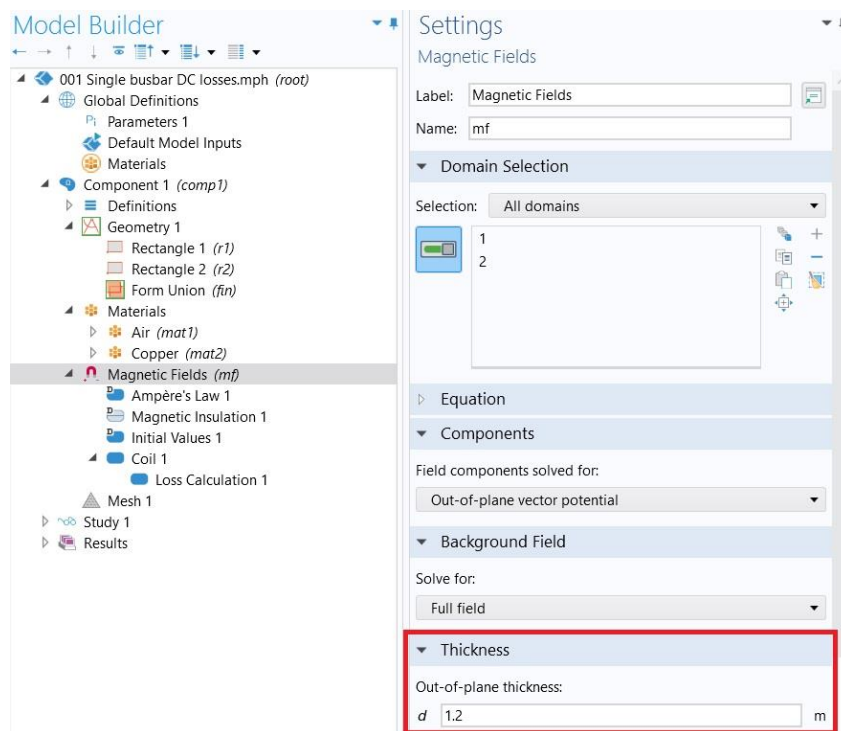


Figure 13: Determining the length of the busbar

3.3 Coil placement and mesh generation

The next step is to apply some excitation to one end of the busbar, this is done by placing a Coil node on the end of the busbar facing out of the 2D plane. Inside the Coil settings the Coil current can be selected and, in the models made for this thesis the Coil current is set to a custom parameter as shown in Figure 14. It is important to remember to apply the loss calculations for each node so that the losses are calculated while computing a Study.

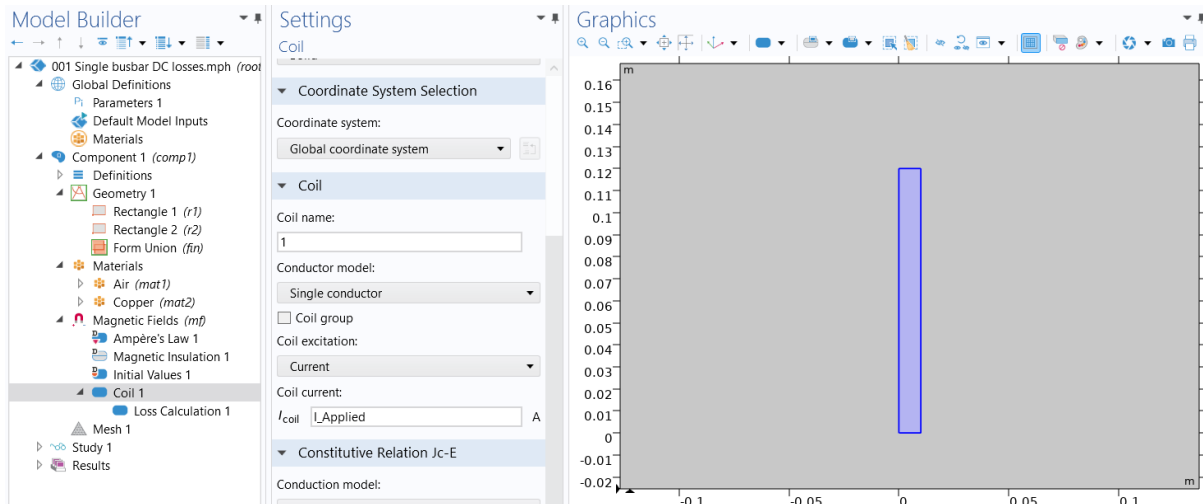


Figure 14: Coil current

Then the model needs a Mesh node, the size of the mesh determines how accurate the simulations will be. In the models used in this thesis the Mesh was set to extremely fine which increases the computation time of each model. The mesh of the single-phase busbar is shown in Figure 15.

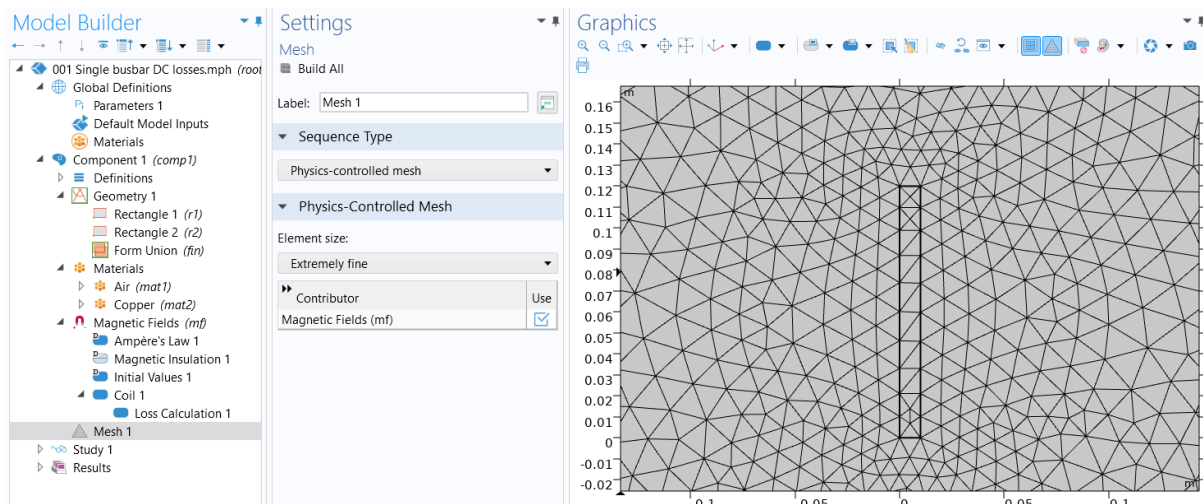


Figure 15: The model Mesh

3.4 Setting up the Study

The Study that was selected during the creation of the model was the Frequency Domain, inside the settings of this study the frequency that is applied to the model when computing a study is chosen, for the DC models it is set to 0 Hz.

When using coils, it is important to add the Coil Geometry Analysis to the Study, this study is used to compute how the current flows in the Coil geometry. Last the Parametric Sweep is added to the Study so that multiple currents different currents can be applied to the Coil during one computation. In the models used in this thesis the current was increased in increments of 50 A from 50-800 A. The Study is shown in Figure 16.

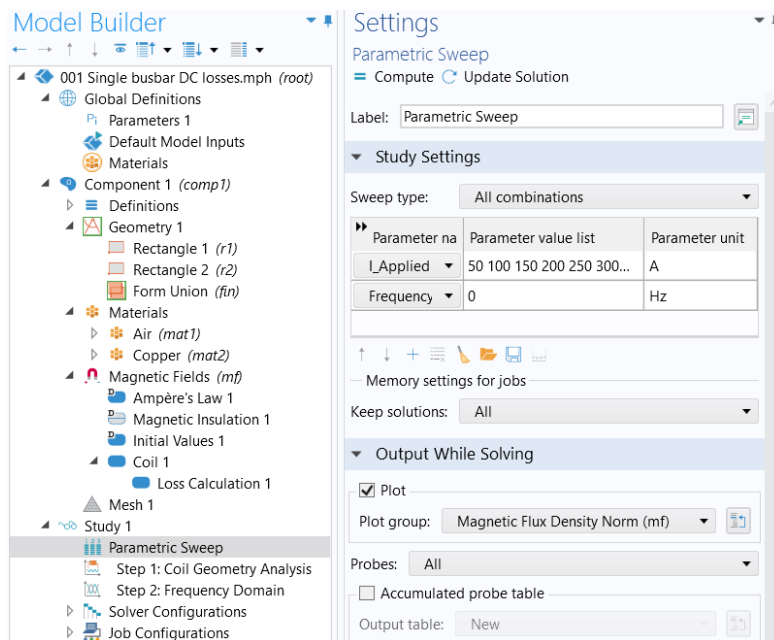


Figure 16: The Study selections

To evaluate the results of the computed model Study, a Global Evaluation of the Coil Power was conducted. This results in a table of values for the losses in each busbar for each applied current step. Figure 17 shows the computed losses in the single-phase DC busbar in watts, the same procedure was conducted for all the different models.

I_Applied (A)	Frequency_applied (Hz)	freq (Hz)	Coil power (W)
50.000	0.0000	0.0000	0.020840
100.00	0.0000	0.0000	0.083361
150.00	0.0000	0.0000	0.18756
200.00	0.0000	0.0000	0.33344
250.00	0.0000	0.0000	0.52101
300.00	0.0000	0.0000	0.75025
350.00	0.0000	0.0000	1.0212
400.00	0.0000	0.0000	1.3338
450.00	0.0000	0.0000	1.6881
500.00	0.0000	0.0000	2.0840
550.00	0.0000	0.0000	2.5217
600.00	0.0000	0.0000	3.0010
650.00	0.0000	0.0000	3.5220
700.00	0.0000	0.0000	4.0847
750.00	0.0000	0.0000	4.6891
800.00	0.0000	0.0000	5.3351

Figure 17: Table with busbar losses

3.5 Discussion

Before this thesis I had no experience with simulating in COMSOL and it was a steep learning curve to jump directly from zero experience to simulating current distribution in busbars. At first, I had trouble with choosing the right interface as I started with the electric fields interface which did not provide me with any current distribution plots or any loss values. I also started simulating with the Stationary Study which didn't allow me to set the frequency to 50 Hz in my simulations.

Originally, I hoped to make one simulation which would allow me to move the busbars closer to each other in steps with preset coordinates in the Parameter Study. However, I ran into a problem where the coil applied to phase L2 would also be applied to phase L3, and the coil applied to phase L3 would disappear entirely. After trying to fix this and not succeeding to do so I decided to rebuild the simulation from scratch, but still ran into the same issues, which I suspect is tied to the coils being locked to the coordinates of the geometry you apply them to while building the simulation. And when moving the geometry in the Parameter Study the coils stop behaving as expected. So, I decided to make one simulation for each busbar distance with a Parameter Study that only changes the applied current, which worked without problems.

There were some unforeseen complications with the COMSOL program license among other things during this project as the license server address expired halfway through the project which left me unable to use the program for several weeks while waiting for help from IT.

4 Laboratory

The laboratory experiments were conducted in both single- and three-phase configurations, where the main goal was to measure the power loss across busbars to see how the skin- and proximity-effects affect different setups. For all the setups the current was ramped up in 50 A increments from 50 A to 800 A. The experiments were limited to 800 A due to restrictions with the laboratory equipment.

4.1 Test object

The test object consists of three copper busbars with the dimensions of 0.01x0.12x1.2 m from ABB. These busbars are the same as the ones used in LV switchgear and are shown in Figure 18.



Figure 18: Copper busbars.

4.2 Experimental setup and procedure

The experiment was conducted on a setup built in the high current lab at the University of South-Eastern Norway. Figure 19 contains the experimental setup and shows the copper busbars mounted on a wooden frame. The first experiment was single-phase and, in this setup, both the left hand side (LHS) and right hand side (RHS) were cable connections. During the three-phase setups the LHS was short circuited and the RHS was used for cable connections. When measuring the power losses across the busbars.

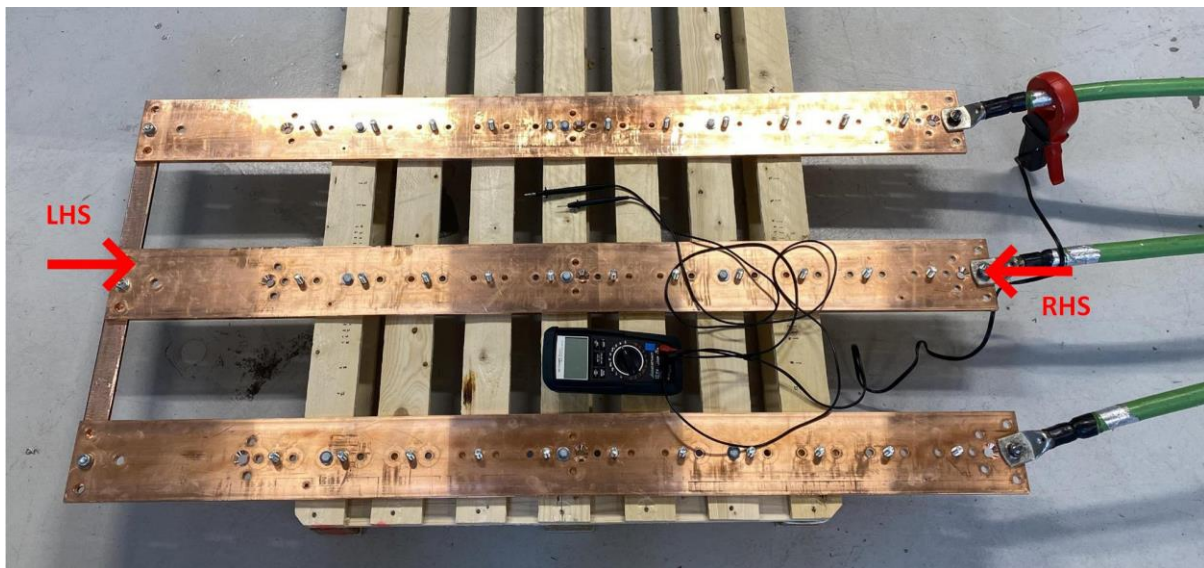


Figure 19: The experimental setup.

During the experiments the handheld multimeter shown in Figure 19 is used to measure the power losses, this is done by placing the ampere clamp around the cables connected to the RHS and then using the measuring probes to measure the voltage drop between the LHS and the RHS. The voltage drop was measured on all phases every time the current was increased to get accurate readings of the power losses.



Figure 20: The AC current injector.

Figure 20 shows the AC current injector which is used for both the single- and three-phase setups. The current was ramped up in 50 A increments up to 800 A, then the AC current

injector was turned off and the setup was modified for the next round of measurements with a shorter distance between the busbars.

The experiment was conducted on a single-phase setup first, this was to have measurements of the power loss across the busbars when there is no skin- and proximity-effects present.

4.2.1 Single-phase setup

The single-phase experiment was done using phase L1 and L2, with L1 connected to the LHS and L2 connected to the RHS. The diagram for the setup is illustrated in Figure 21 and the physical lab setup is shown in Figure 22.

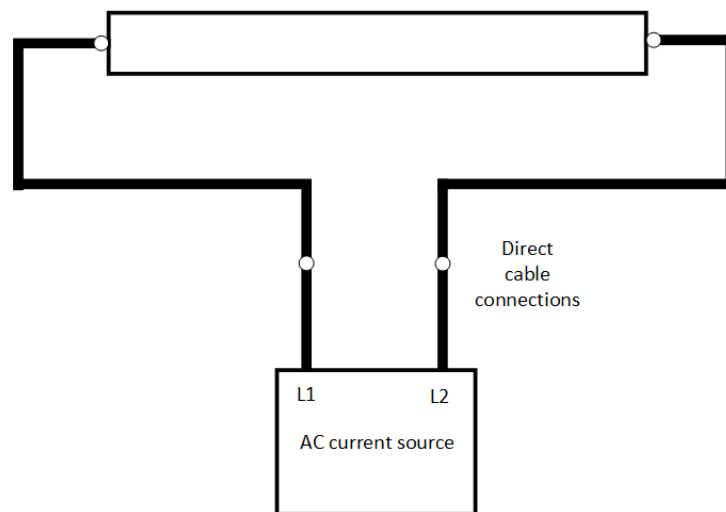


Figure 21: Single-phase connection diagram.

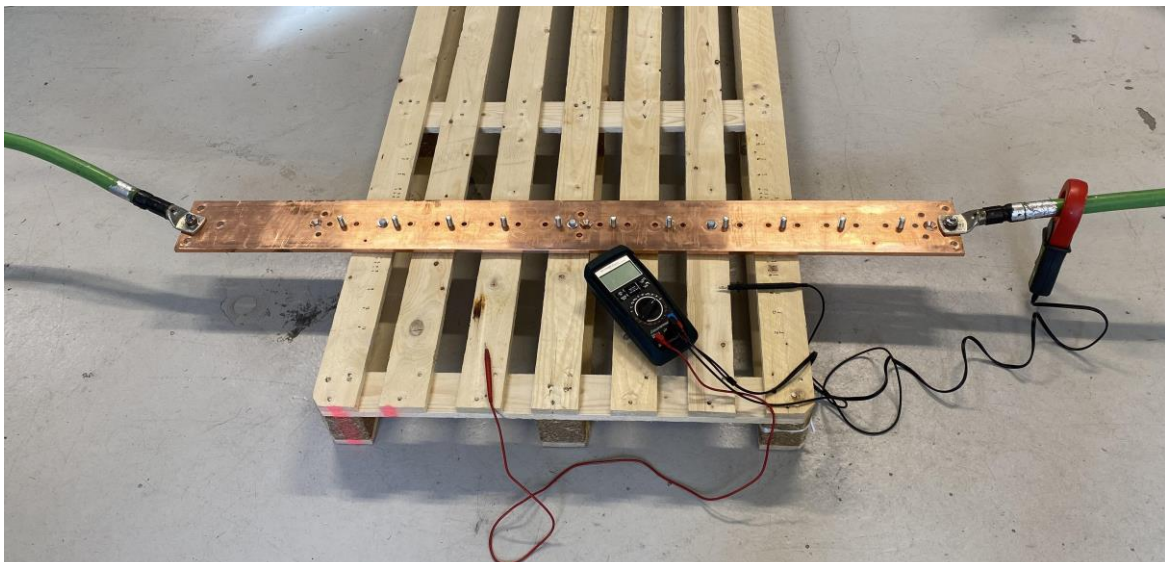


Figure 22: Single-phase laboratory setup.

4.2.2 Three-phase setup

The three-phase setups were done by connecting all three phases to the busbars on the RHS and creating a short circuit with a fourth busbar on the LHS as shown in Figure 23.

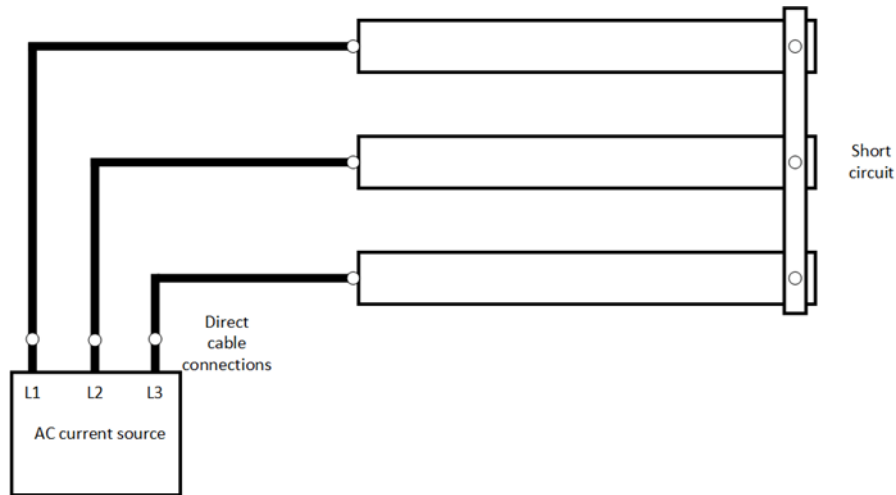


Figure 23: Three-phase connection diagram.

4.3 Discussion

In hindsight it would have been better to measure the voltage drop across the busbars and used the results to calculate the resistance and then calculated the power losses. However, I had already decided to use the power measurement setting on the multimeter in the laboratory before starting the experiments. Then during the experiment all the three-phase AC experiments showed similar trends in the measured losses after taking the lab setup apart to modify it multiple times between measurements, so I did not consider the possibility of the measurements being incorrect before the laboratory experiments were concluded and I had made all the graphs and tables and as such there was not enough time to redo the experiments.

5 Results

This chapter contains the most important results from the COMSOL simulations, the laboratory experiments, and some hand calculations.

5.1 Single-phase DC

The calculated losses in the single-phase DC busbar using values from the measurements taken in the laboratory were higher than the losses found in the COMSOL simulation as shown in Figure 25 and Figure 24. The calculated laboratory losses were 8 W at 800 A while the losses in the COMSOL simulation were 5.33 W at 800 A. This slight difference is likely caused by the difference in resistivity for copper used in the hand calculations shown in Appendix C and the resistivity found in the copper material in the COMSOL library. Both the calculations and the COMSOL simulation show the same trend with the losses increasing as the applied current increases.

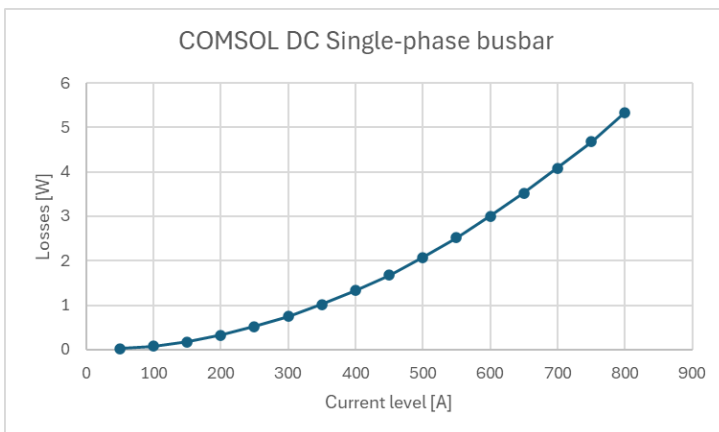


Figure 24: Single-phase COMSOL DC losses

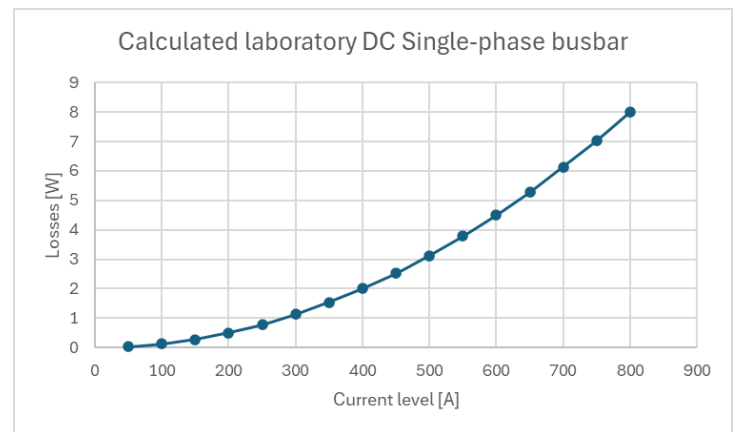


Figure 25: Single-phase calculated DC losses

For comparison the losses for a single-phase copper busbar was calculated using standard values found in [6], the values used are also shown in Appendix C. As shown in Figure 26 the losses when using standard values for the resistivity in copper are higher than both the simulated losses in COMSOL and the losses calculated with values from the laboratory.

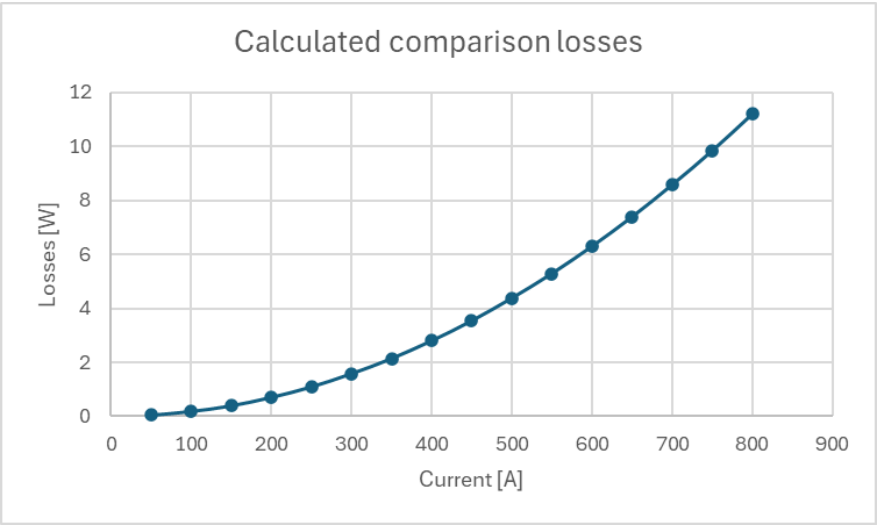


Figure 26: Losses calculated using standard values

The volumetric loss density was plotted in COMSOL to show that the current density is equal across the entire cross-sectional area as it should be in a DC circuit. The loss density was plotted with an applied current of 100 A and is shown in Figure 27.

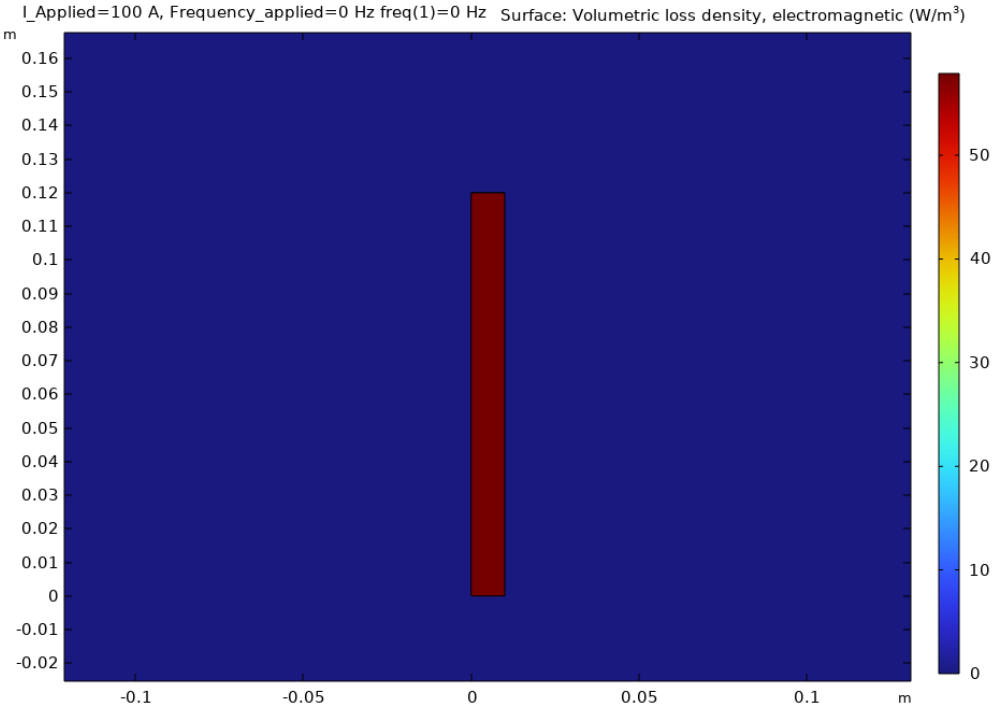


Figure 27: Volumetric loss density at 100 A DC

5.2 Single-phase AC

The single-phase AC losses simulated in COMSOL are higher than the simulated DC losses which shows that the added resistance from the skin effect is present, the simulated losses of the single-phase busbar is shown in Figure 28.

The same cannot be said for the single-phase losses measured in the laboratory which is shown in Figure 29. The losses increase until the applied current reaches 400 A and then starts dropping slightly until the current reaches 600 A and the watt meter was no longer able to measure any losses.

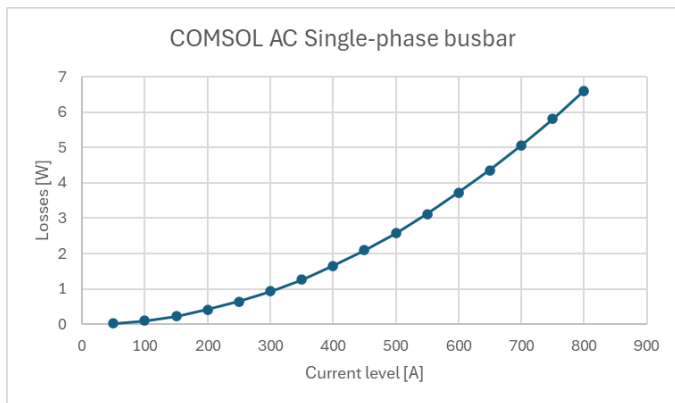


Figure 28: Single-phase COMSOL AC losses

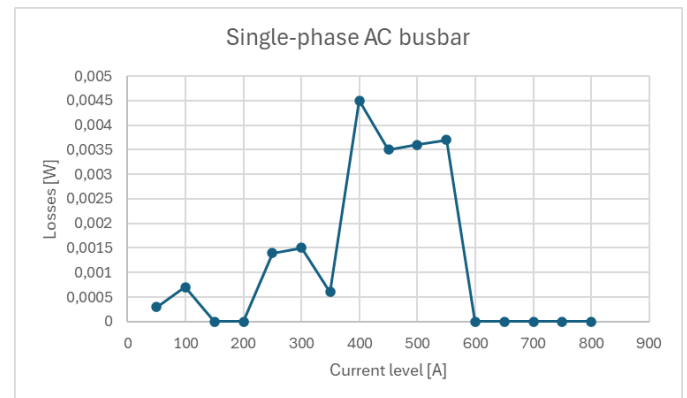


Figure 29: Single-phase laboratory AC losses

The volumetric loss density was plotted for every applied current in the COMSOL simulation and Figure 30 shows the loss density for 50 A and Figure 31 for 800 A. This shows that the current density is concentrated in the same areas of the busbar for all the applied currents when the busbars are not affected by nearby current carrying conductors.

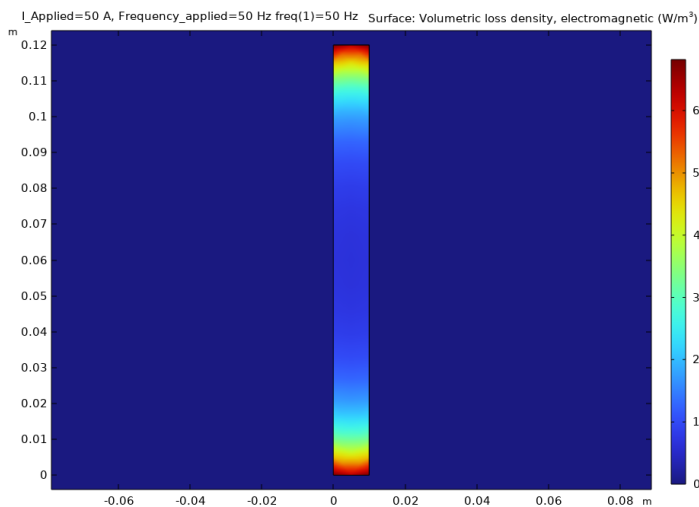


Figure 30: Single-phase volumetric loss density at 50 A AC

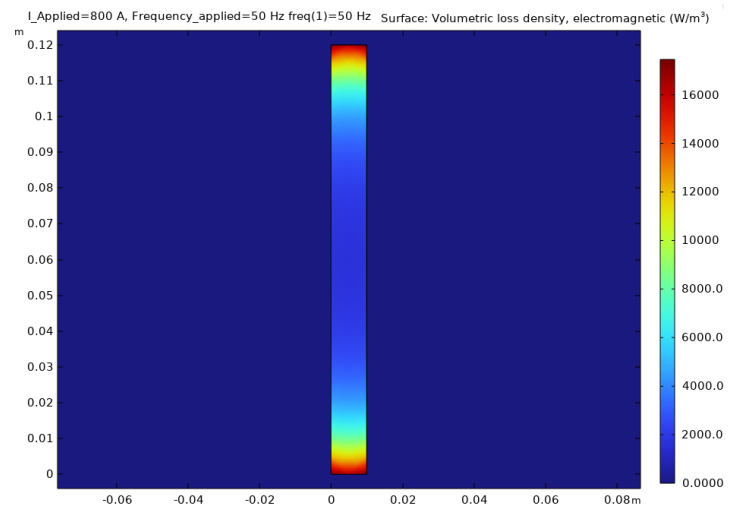


Figure 31: Single-phase volumetric loss density at 800 A AC

5.3 Three-phase AC

This subchapter contains the most important results from the three-phase COMSOL simulations and the laboratory experiments. More graphical results can be found in Appendix B and D.

5.3.1 COMSOL

The power losses from three-phase COMSOL simulations show the same trend as the single-phase simulation with the losses increasing as the current increases and that the losses increase as the distance between the busbars decreases. The biggest increase in losses depending on the distance was found in phase L2 which was as expected as it is affected by both phase L1 and L2. This is shown in Figure 32 and Figure 33 where L2 has the highest losses and phase L1 and L2 mostly overlap due to the differences between them being small.

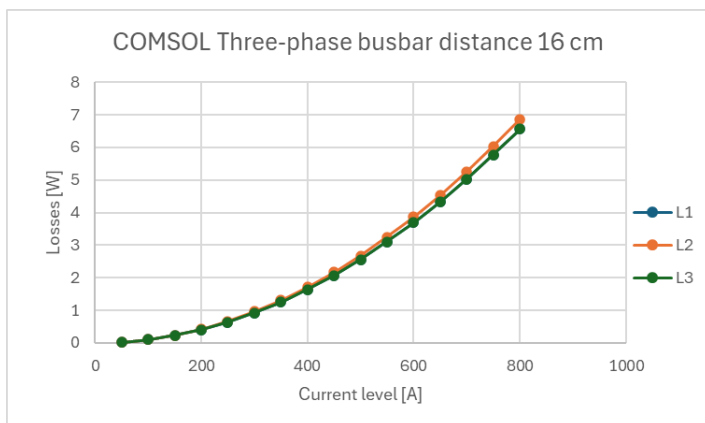


Figure 32: Three-phase COMSOL AC losses with a distance of 16 cm between busbars

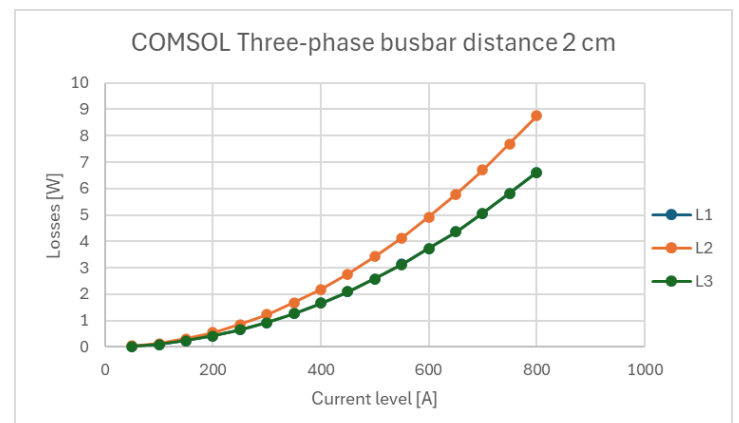


Figure 33: Three-phase COMSOL AC losses with a distance of 2 cm between busbars

When taking a closer look at the power losses in phase L2 it is clear that the distance between the busbars is affecting the losses. Figure 34 shows that the increase in losses is not linear when compared to the distance between the busbars, as the losses increase more when moved from 4 cm to 2 cm than it does when moved twice this distance from 8 cm to 4 cm.

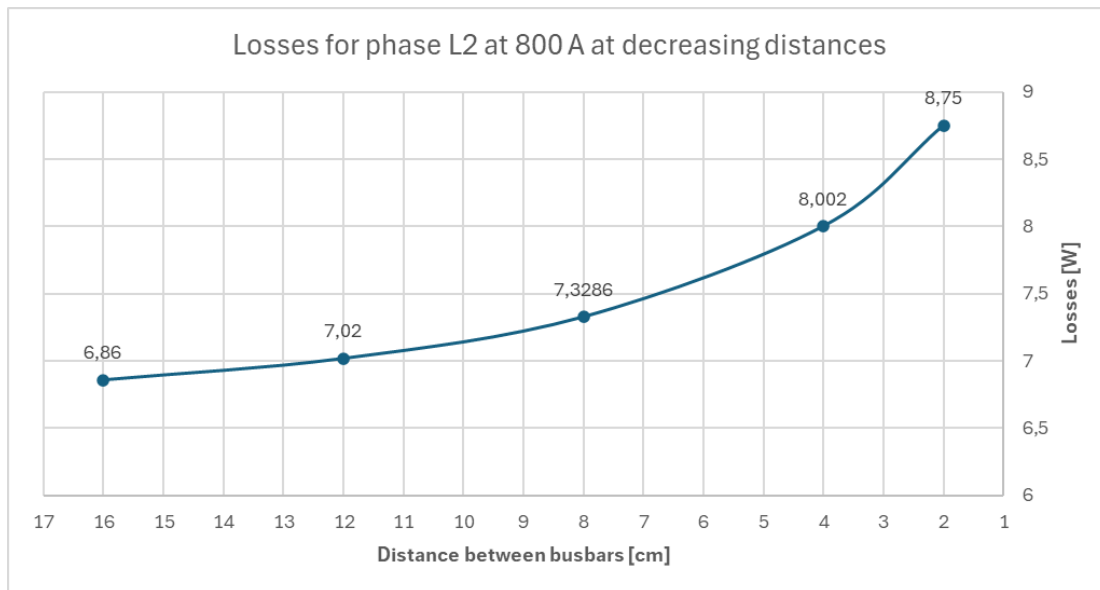


Figure 34: Losses in phase L2 compared with distance between busbars

To further illustrate this increase in losses the volumetric loss density was plotted using COMSOL, here it is plotted for 50 A and 800 A as these were the values furthest apart from each other. Figure 35 and Figure 37 show the loss density with a distance of 16 cm and from these plots it is evident that the amount of current does not affect where in the cross-sectional area the current flows. Then Figure 36 and Figure 38 show the loss density with a distance of 2 cm and here it is also shown that the distance matters more than the current in terms of current density.

Figure 35 and Figure 36 also show that the area of the cross-section used by the current is decreased the most for phase L2 which matches the increased losses in the plots above.

5 Results

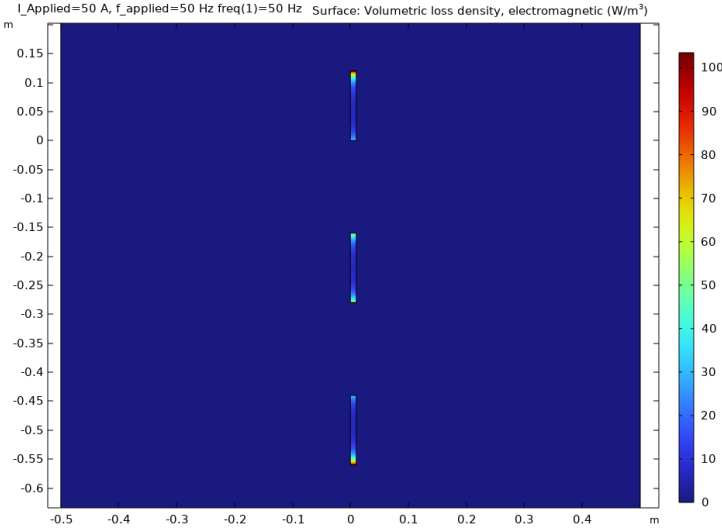


Figure 35: Three-phase volumetric loss density at 50 A AC with a distance of 16 cm between the busbars

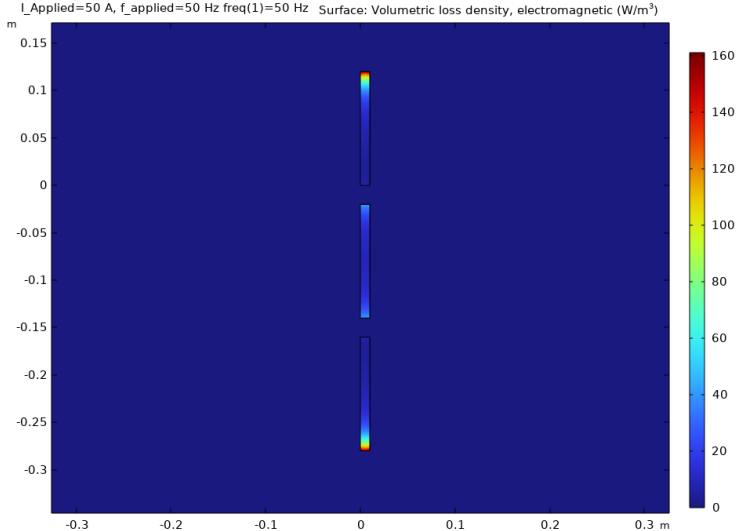


Figure 36: Three-phase volumetric loss density at 50 A AC with a distance of 2 cm between the busbars

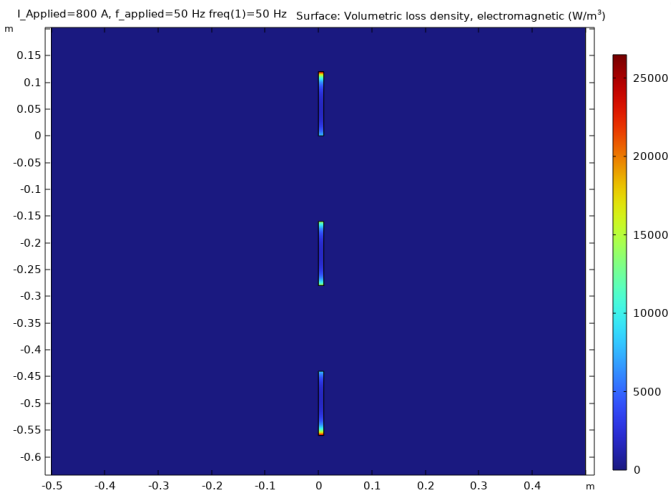


Figure 37: Three-phase volumetric loss density at 800 A AC with a distance of 16 cm between the busbars

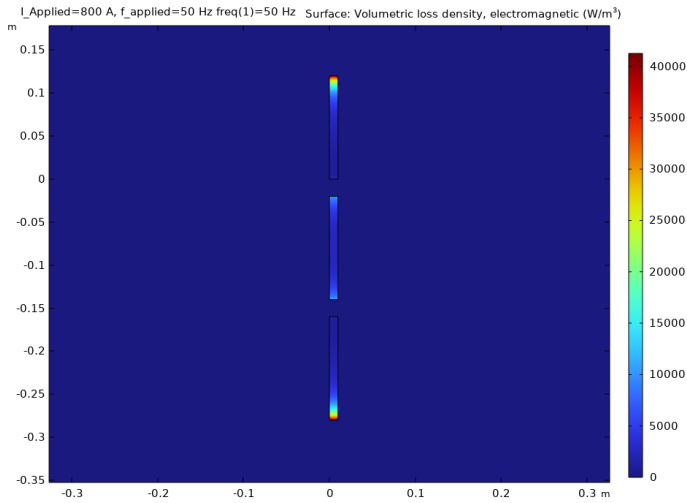


Figure 38: Three-phase volumetric loss density at 800 A AC with a distance of 2 cm between the busbars

5.3.2 Laboratory

The results from the laboratory all have a similar trend of only showing losses in phase L1 and L2 while either not showing any losses or just showing losses for a few applied currents in phase L3 as shown in Figure 39 and Figure 40. The three-phase experiments also had the same phenomenon that the single-phase experiment had where the watt meter was unable to measure any losses in the phases when the applied current reached 500-650 A.

5 Results

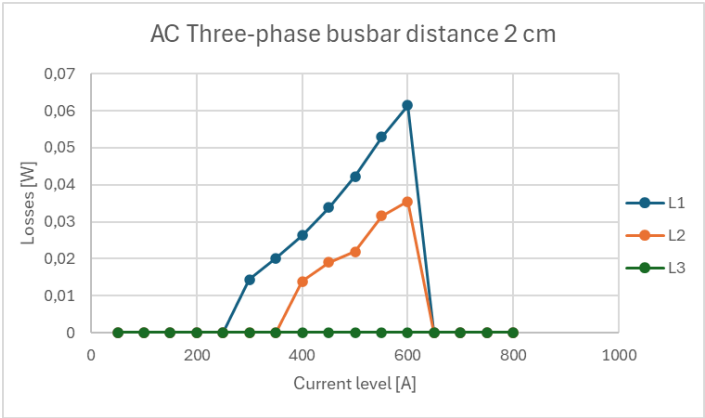
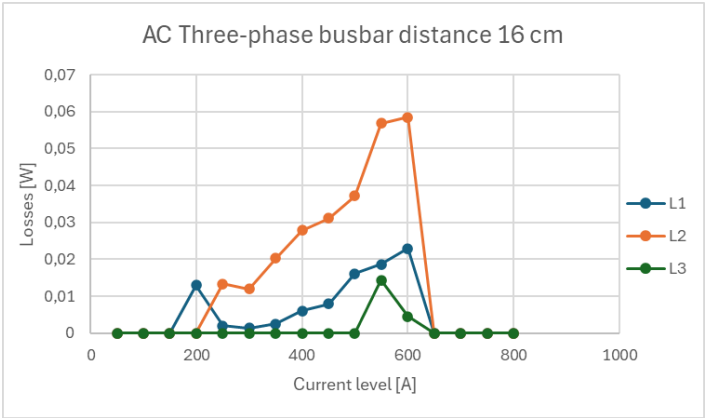


Figure 39: Three-phase laboratory AC losses with a distance of 16 cm between busbars

Figure 40: Three-phase laboratory AC losses with a distance of 2 cm between busbars

6 Discussion

In this discussion the main findings of the previous chapters will be discussed.

The single-phase DC losses from the COMSOL simulation and the simulated AC losses match the theory in the sense that the DC losses are lower than the AC losses. However, the single-phase DC losses calculated with values from the laboratory and the comparison results calculated using standard values for the resistivity are both higher than the simulated single-phase AC losses.

The three-phase COMSOL simulations match the theory as the losses in phase L2 are higher than the losses in the outside phases, while the losses in phase L1 and L2 are similar to one another with some minor differences that are too small to be visible on the graphical representations in Chapter 5.3.

The laboratory results all have a similar trend to one another, but since the values are so different from the simulation results it is difficult to draw any conclusions from them other than what was presented in Chapter 5.2 and Chapter 5.3.2.

7 Conclusion

The results of the three-phase COMSOL simulations show that the power losses gradually increase as the distance between the busbars decreases and that this increase is not linear. While the power losses from the skin- and proximity effect are low with currents below 800 A they could be more influential at higher current levels and should be considered in installations with small distances between busbars and poor cooling capabilities such as LV fuse gear.

References

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Appendix A: COMSOL Single-phase results

The losses were computed in COMSOL and then exported to Excel, Figure 41 shows the losses in the single-phase DC busbar and Figure 42 shows the losses in the single-phase AC busbar.

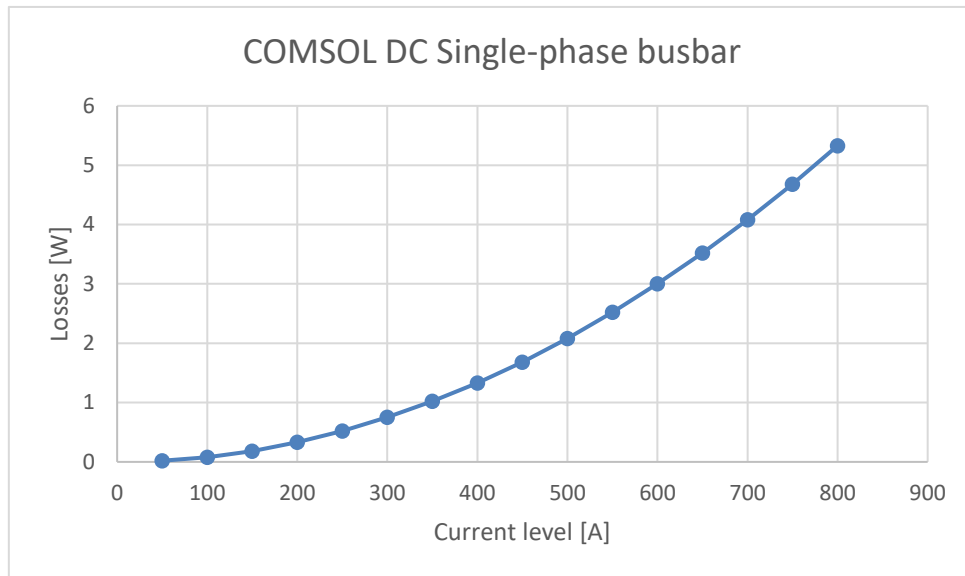


Figure 41: Single-phase DC busbar results

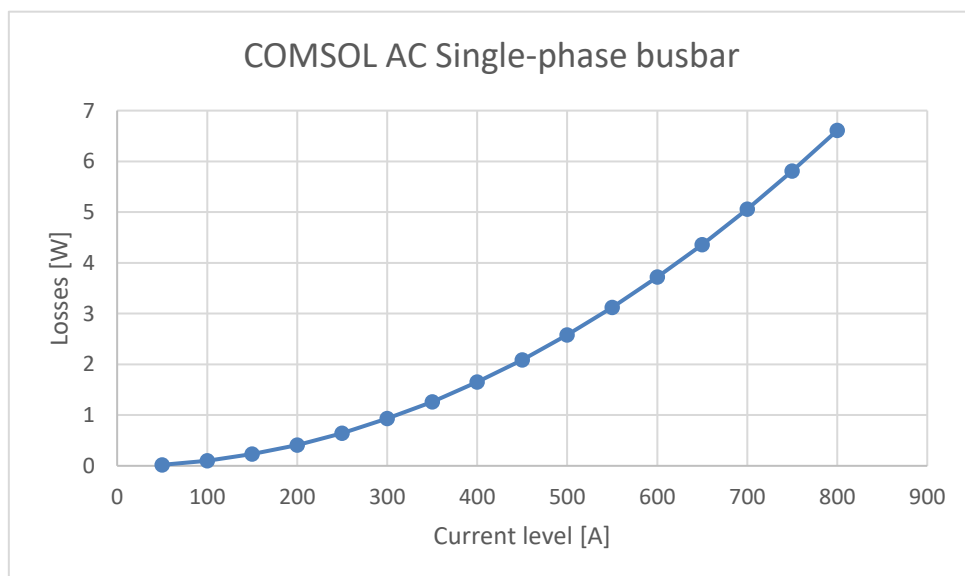


Figure 42: Single-phase AC busbar results

Appendix B: COMSOL Three-phase results

The losses were computed in COMSOL and then exported to Excel, Figure 43 shows the losses in the three-phase AC busbar at 50 Hz with a distance of 16 cm between the busbars. Figure 44 shows the losses in the three/phase busbars with a distance of 12 cm, Figure 45 with a distance of 8 cm, Figure 46 with a distance of 4 cm and Figure 47 with a distance of 2 cm.

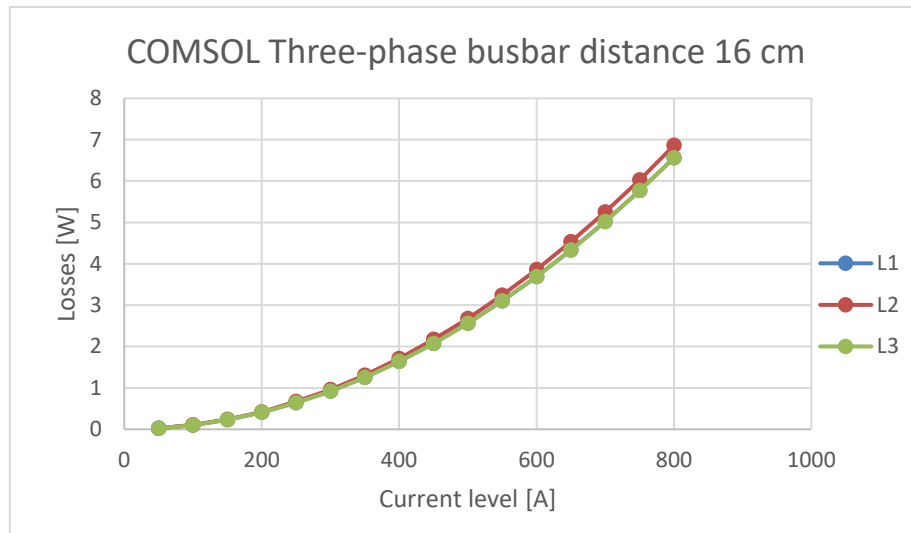


Figure 43: Three-phase busbar with 16 cm distance

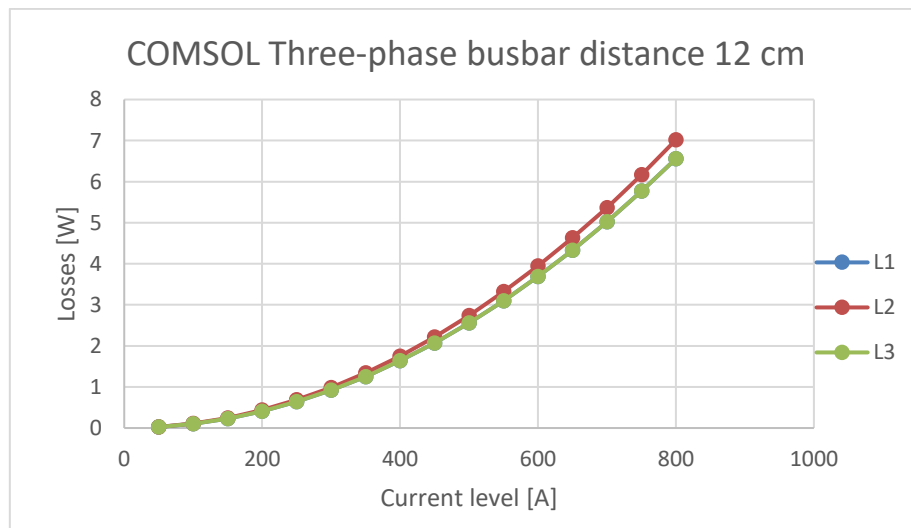


Figure 44: Three-phase busbar with 12 cm distance

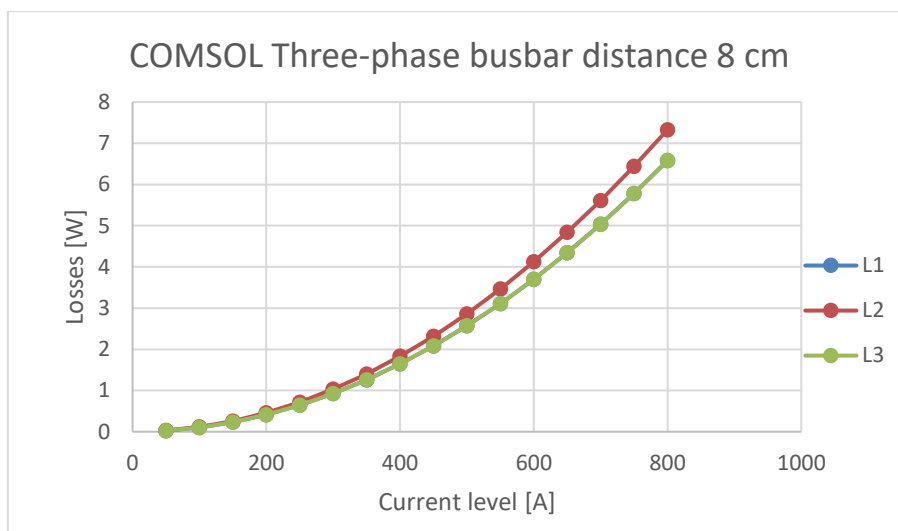


Figure 45: Three-phase busbar with 8 cm distance

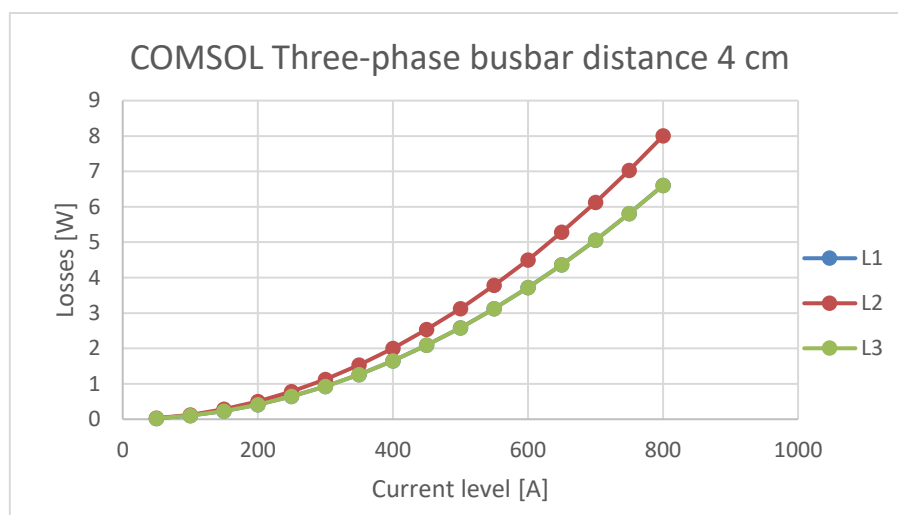


Figure 46: Three-phase busbar with 4 cm distance

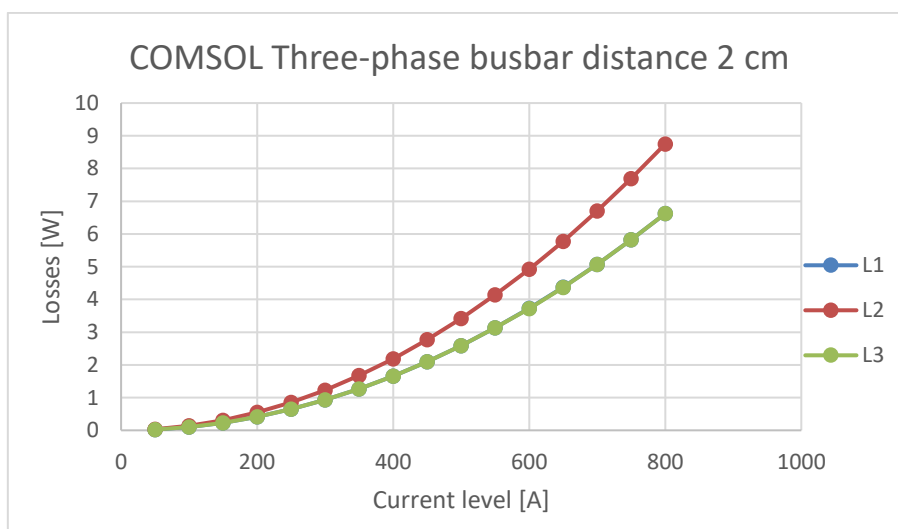


Figure 47: Three-phase busbar with 2 cm distance

Appendix C: Calculated DC Resistance

The voltage drop measured across the busbars was 0.00125 V with an applied DC current of 100 A. The calculated resistance is then 0.0000125 Ω using Equation C.1, then Equation C.2 was used to calculate the power loss. Table 1 shows the calculated power loss.

$$R = \frac{U}{I} \quad (\text{C.1})$$

$$P = I^2 \cdot R \quad (\text{C.2})$$

Table 1: Calculated power loss

Applied current [A]	Power loss [W]
50	0.03
100	0.13
150	0.28
200	0.5
250	0.78
300	1.13
350	1.53
400	2
450	2.53
500	3.13
550	3.78
600	4.5
650	5.28
700	6.13
750	7.03
800	8

Then the power loss was calculated using the values for resistance in copper which was calculated using Equation C.3. The resistivity of copper used in this calculation is $0.0175 \Omega \cdot \text{mm}^2/\text{m}$ and the length of the busbar is 1.2 m and the area of the conductor is 1200 mm^2 .

This gives a resistance of 0.0000175Ω which was then used to calculate the power loss across the busbar, the values are shown in Table 2.

$$R = \frac{\rho \cdot l}{A} \quad (\text{C.3})$$

Table 2: Calculated comparison losses

Applied current [A]	Power loss [W]
50	0.04
100	0.18
150	0.39
200	0.7
250	1.09
300	1.58
350	2.14
400	2.8
450	3.54
500	4.38
550	5.29
600	6.3
650	7.39
700	8.58
750	9.84
800	11.2

Appendix D: Lab results

This appendix contains all the laboratory results represented as graphs. All the graphs show the power losses in watts compared to the applied current in amps and the number of phases and distances between busbars is noted in the title of each graph.

