NTNU
Kunnskap for en bedre verden

Department of electric energy

IELET2120

Electrical Machines and Electromagnetic Energy Conversion

# Transformer - Laboratory exercise 2

*Author:*
André Joseph Virani

April 2023

# Summary

This report goes through the assignment: *Transformer - Laboratory exercise 2*. The exercise contains two main tasks, one about single phase transformers and one about three phase transformers.

In the first task two tests were conducted. The Open-circuit test and the short-circuit test. These tests helped with calculating the transformer parameters. The single phase transformer was also tested under different load currents, to plot a characteristic for efficiency of the transformer

In the second task, the three phase transformers were configured in three different connections. The objective was to determine how the different connections(Vector groups) affected the phase angle between the primary and secondary voltages.

# Table of Contents

# List of Figures



# List of Tables

# 1 Introduction

The objective of this laboratory assignment is to investigate the behaviour and performance characteristics of transformers, specifically single-phase and three-phase transformers. The scope of this lab exercise includes parameter estimation for a single-phase transformer, determining voltage and efficiency characteristics for a single-phase transformer under varying resistive loads, and measuring the phase shift in a three-phase transformer.

Standardized test procedures, such as the Open Circuit and Short Circuit tests are used in this lab exercise to estimate the circuit parameters of a single-phase transformer. Additionally, transformer efficiency and voltage behaviour under varying resistive loads can be accurately determined through experimental measurements. This lab exercise aims to investigate the voltage and efficiency characteristics of a single-phase transformer.

Furthermore, the phase shift in a three-phase transformer is a critical factor that affects the performance of three-phase power systems. The basis for measuring the phase shift in this lab exercise is the theory of three-phase transformer connections and the corresponding phase angles. By performing the measurements on the Yy0, Dy11 and Dy1 connections, the lab exercise provides a comprehensive understanding of the phase shift behaviour in three-phase transformers.

# 2 Theory

## 2.1 Transformer testing

Transformer testing is a crucial step in determining the parameters of a transformer's equivalent circuit. The Open Circuit (OC) and Short Circuit (SC) tests are two commonly used methods for estimating these parameters.

These parameters are essential for calculating the transformer's efficiency, voltage regulation, and performance characteristics.

### 2.1.1 Open-circuit test

The purpose of the OC test is to determine the core loss and magnetizing current of the transformer. The primary side is connected to its rated voltage while the secondary side is open-circuited as shown in the figure below.

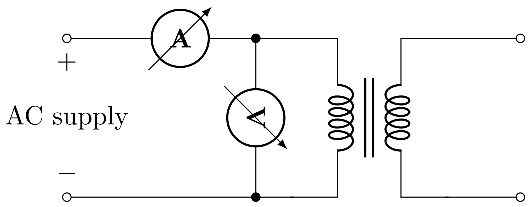


Figure 1: Connection diagram for OC-test

Since the series impedance is way smaller than the impedance in the magnetizing branch, we chose to neglect it. We then end up with a circuit as shown in figure 2

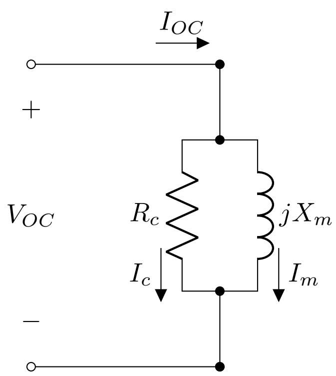


Figure 2: Transformer equivalent circuit under Open-circuit conditions

**Calculations:**
For calculating the parameters in the magnetizing branch, we use the values measured from the Open-Circuit test, and the following equations.

$$R_c = \frac{V_{OC}^2}{P_{OC}} \tag{1}$$

$$I_c = \frac{V_{OC}}{R_c} \tag{2}$$

$$I_m = \sqrt{I_{OC}^2 - I_c^2} \tag{3}$$

$$X_m = \frac{V_{OC}}{I_m} \tag{4}$$

#### 2.1.2 Short-circuit test

The purpose of conducting a short circuit test on a transformer is to determine the copper losses and the equivalent resistance and reactance of the transformer winding. During the short circuit test, the secondary winding of the transformer is short-circuited, and a low voltage is applied to the primary winding.

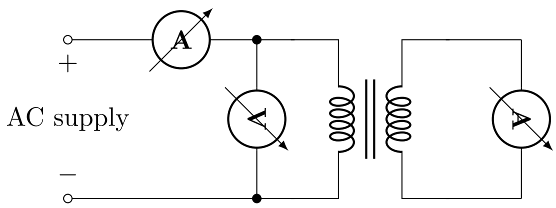


Figure 3: Connection diagram for SC-test

When the connections is configured as the diagram above, we get a new transformer equivalent circuit as shown in Figure 4. Here we can look at the magnetizing branch as open circuited since very little current will flow that way, when the secondary side is shorted. This is because there is way less resistance in the series branch.

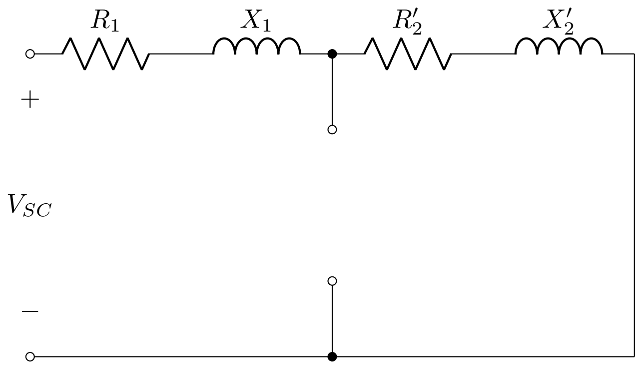


Figure 4: Transformer equivalent circuit under Short-circuit conditions

**Calculations:**
For calculating the series parameters, we use the values measuered from the Short-Circuit test, and the following equations.

$$Z = \frac{V_{SC}}{I_{SC}} \tag{5}$$

$$R = \frac{P_{SC}}{I_{SC}^2} \tag{6}$$

$$X = \sqrt{Z^2 - R^2} \tag{7}$$

Further separation of the parameters is not possible, and not needed in our situation.

## 2.2 Efficiency and voltage characteristics

The efficiency of a transformer is defined as the ratio between power output and input, and is usually between 96% - %99. Kothari and Nagrath 2020

$$\eta = \frac{P_{out}}{P_{in}} \tag{8}$$

The most accurate way of determining the transformer efficiency is to find the power losses from the open-circuit and short-circuit tests. That way the error of the measurements will only affect the losses. Kothari and Nagrath 2020

$$\eta = \frac{P_{output}}{P_{output} + P_{losses}} \tag{9}$$

The two losses calculated in this report is the iron-loss $P_i$ and copper-loss $P_c$

The iron-loss is the loss from the magnetic core of the transformer. These losses depend on the flux density, therefore a variable load will not affect the iron-losses.

However the copper-loss in the windings is affected by the load current. The copper-loss of the two windings can be calculated with this equation:

**Losses equations:**

$$P_c(copper - loss) = I_1^2 \cdot R_1 + I_2^2 \cdot R_2 \tag{10}$$

$$P_i = P_{input}\ on\ no - load/OC - test \tag{11}$$

$$P_{losses} = P_i + P_c \tag{12}$$

**Power output equation:**

$$P_{output} = V_2 \cdot I_2 \cdot cos\theta_2 \tag{13}$$

**Efficiency equation:**

$$\eta = \frac{P_{output}}{P_{output} + P_{losses}} = \frac{V_2 \cdot I_2 \cdot cos\theta_2}{(V_2 \cdot I_2 \cdot cos\theta_2) + P_i + (I_2^2 \cdot R_{eq}(2))} \tag{14}$$

This equation shows us that the efficiency of a transformer will vary with the load current and the power factor of the load.

## 2.3 Three-phase transformers

For three phase transformation, it is common to use a common core with three legs, instead of having three separate transformers. This makes the magnetic circuits of the three phases linked.

### 2.3.1 Connections

There is a variety of different connections possible for the three phase transformers. The three used in this lab is listed in the appendix. (Figure 13, 14 15) The primary and secondary sides of the transformer can be connected in either star, delta, open-delta or zigzag star. In this laboratory exercises star and delta connections is used.

**Star/star connection**

In a star-star connected transformer, both the primary and secondary side is connected as a star. This results in a phase angle of $0°$. The phasor diagram is shown in figure 13 in the appendix.

**Delta/star connection**

In a delta-star connected transformer, the primary side is connected in delta, while the secondary in star. This results in a phase angle og $\pm 30°$ depending on if the connection is Dy11 or Dy1. The difference of these two connections is showed in figures 14 and 15 in the appendix.

# 3 Measurements

## 3.1 Equipment list

| Term | Manufacturer | Cat. / NTNU No |
|---|---|---|
| Sensor-CASSY 2 | LD DIDACTIC | 524 013S |
| 30A Box | LD DIDACTIC | 524 0431 |
| Variable low voltage transformer 0-260 V /4 A | LD DIDACTIC | 726 85 |
| Single-phase transformer 1kW | LD DIDACTIC | 733 97 |
| Three-phase transformer 1kW | LD DIDACTIC | 733 91 |
| Resistive load bank | LD DIDACTIC | 732 40 |
| Three-phase voltage 400 V/2.5 A | LD DIDACTIC | 725 442 DG |
| Laboratory station laptop with CASSY Lab 2 | | |

Table 1: Equipment list

## 3.2 Task 1. Measurements

In task 1 we will be using sensor-CASSY 2 software to measure the results from the testing of a single phase transformer, and to measure efficiency and voltage characteristics.

CASSY 2 will be connected to the transformer circuit so that it can measure current, voltage and power on both primary and secondary side.

These measurements will be needed for calculating the circuit parameters, efficiency and voltage characteristics of the single phase transformer.

**Settings in Cassy software:**

**Measurement for OC-test:**

1. Connect the CASSY-sensor as shown in figure 1
2. In the CASSY software chose Voltage, Current and make a formula for Power by using the power factor. (Do not use the 30A boks, as this cannot measure power factor.)
3. Connect the primary terminals to the variable voltage transformer and increase the voltage to the transformers nominal voltage. In this case 230V.
4. Write down the measurements. (Voltage, Current, Power and powerfactor)

**Measurement for SC-test:**

1. Connect the CASSY-sensor as shown in figure 3
2. The current on the secondary side shal we measured with the 30A box on $I_{A2}$
3. In the CASSY software chose to measure Voltage, Current and make a formula for power by using the power factor.
4. Connect the primary terminals to the variable voltage transformer and increase the voltage slowly until reaching the rated current at the secondary side. Check the rating plate of the transformer.
5. Write down the measurements. (Voltage, Current, Power and powerfactor)

**Measurement for transformer with resistive load:**

1. Connect the three resistors on the resistance bank in parallel, and connect these to the terminals on the secondary side of the transformer.
2. Set the resistive load to 100 percent and turn up the voltage gradually to 230 V.
3. Set sampling rate (Interval in Measurement Settings) to 100 ms, resulting in 10 measurements per second. Leave the field Measuring Time blank. This enables
4. Make sure you activate the power factor measurement, and use this in the definition of formulas for primary and secondary power, losses and efficiency. (Ploss=Pin-Pout).
5. In Displays (all the way down in Settings), create a new display. Select secondary side current (IA2) along the x-axis and efficiency along the y-axis.
6. Create another display. Create three new curves, one for primary power, one for secondary power and one losses. Select secondary side current along the x-axis.
7. Create a display showing power factor on the primary side and voltage on the secondary side as a function of secondary side current.

## 3.3 Task 2. Measurements

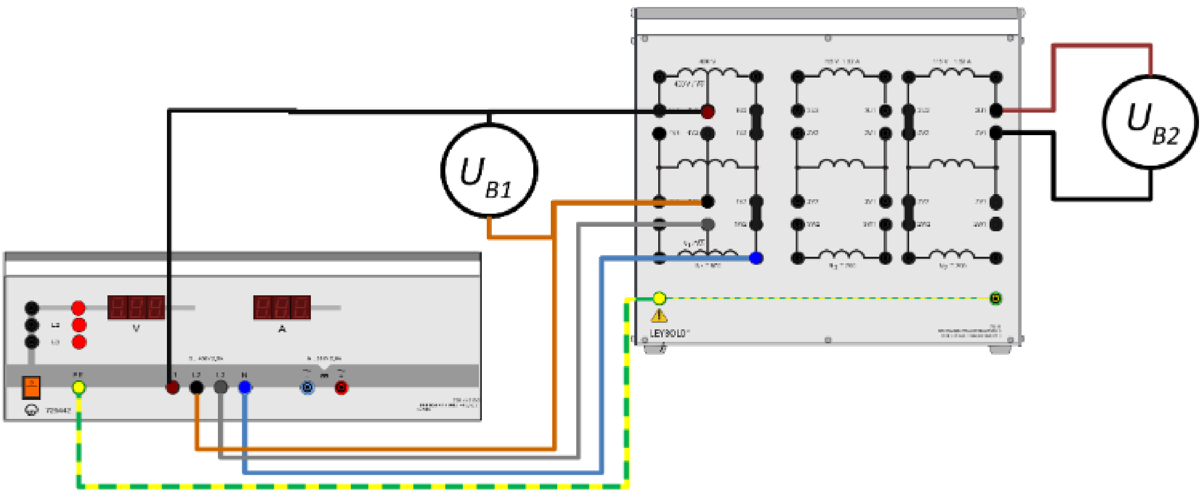


Figure 5: Yy0 transformer configuration

**Transformer in star-star circuit Yy0**

1. Wire the set up as shown in figure 5
2. Measure input voltage and output voltage in CASSY
3. Plot the waveforms for primary and secondary in the same measurement.
4. Make shure the plot has a measurement time that makes it easy to read out the phase shift.

### Transformer in delta-star circuit Dy11

1. Rewire the previous connection on the primary side, so that it matches the vector group in figure 14.
2. Plot the waveforms for primary and secondary in the same measurement.
3. Make shure the plot has a measurement time that makes it easy to read out the phase shift.

### Transformer in delta-star Dy1

1. Swap the supply leads L2 - L3 feeding the primary side of the 3-phase transformer on the 3-phase power supply unit
2. Plot the waveforms for primary and secondary in the same measurement.
3. Make shure the plot has a measurement time that makes it easy to read out the phase shift.

# 4 Results

## 4.1 Task 1:

### 4.1.1 Transformer equivalent circuit:

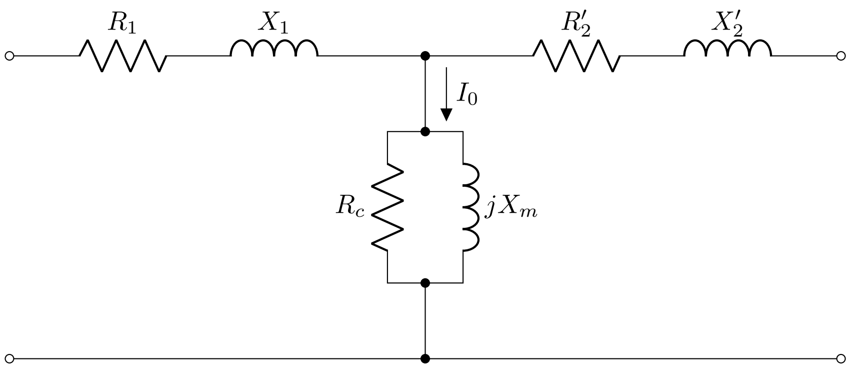


Figure 6: Transformer equivalent circuit referred to primary side

$R_1$ : Primary side resistive copper losses.
$X_1$ : Primary side leakage inductance.
$R_2'$ : Secondary side resistive copper losses, referred to the primary side.
$X_2'$ : Secondary side leakage inductance, referred to the primary side.
$R_c$ : Core losses
$X_m$ : Magnetizing component

### 4.1.2 Open circuit test

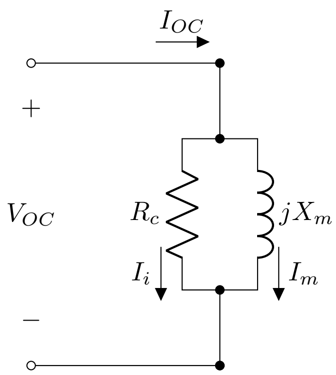


Figure 7: Transformer equivalent circuit under Open-circuit conditions

| Term | Measured Value |
|---|---|
| $V_{OC}$ | 230V |
| $I_{OC}$ | 0,418A |
| $P_{OC}$ | 21.5W |
| $cos\varphi$ | 0,23 |

Table 2: Measured values from Open-Circuit test

**Calculations:**

$$R_c = \frac{V_{OC}^2}{P_{OC}} = \frac{230^2}{21,5} = 2460,47\Omega \tag{15}$$

$$I_c = \frac{V_{OC}}{R_c} = \frac{230}{2460,47} = 0,093478A \tag{16}$$

$$I_m = \sqrt{I_{OC}^2 - I_c^2} = \sqrt{0,418^2 - 0,093478^2} = 0,40741A \tag{17}$$

$$X_m = \frac{V_{OC}}{I_m} = \frac{230}{0,40741} = 564,5\Omega \tag{18}$$

We can separate the magnetizing branch parameters, $R_c$ and $X_m$ , from the rest of the equivalent circuit when conducting the open circuit test, because the secondary side is open circuited. This causes all the current to flow through the magnetizing branch. Since the impedance in the magnetizing branch is way higher than the impedance elsewhere in the circuit, the power is also much greater, thus we can neglect the series impedance.

### 4.1.3 Short circuit test

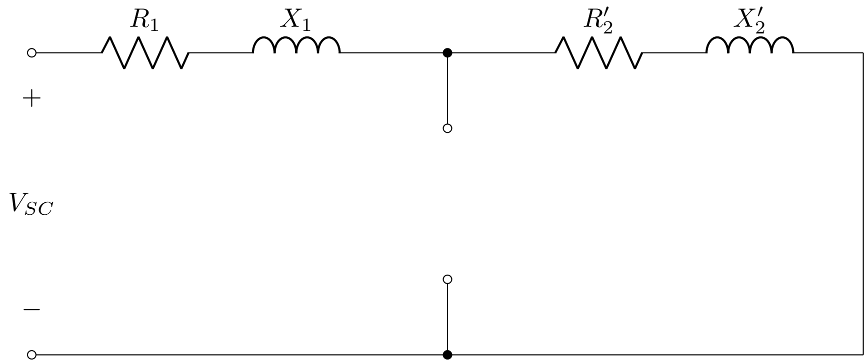


Figure 8: Transformer equivalent circuit under Short-circuit conditions

| Term | Measured Value |
|---|---|
| $V_{SC}$ | 4,15V |
| $I_{SC}$ | 0,950A |
| $P_{SC}$ | 16,6W |
| $cos\varphi$ | 0,94 |

Table 3: Measured values from Short-Circuit test

**Calculations:**

$$Z_{eq} = \frac{V_{SC}}{I_{SC}} \angle\varphi = \frac{4,15}{0,95} \angle cos^{-1}(0,94) = 4,1 + j1,487\ \Omega \tag{19}$$

We can neglect the magnetizing branch when conducting a SC-test because the secondary side is shorted, thus very little current will go through the magnetizing branch. This is explained in more detail in the theory chapter.

### 4.1.4 Transformer with resistive load: Efficiency and voltage characteristics

This section will examine the performance of the transformer under different operating conditions. The variable will be the load current.

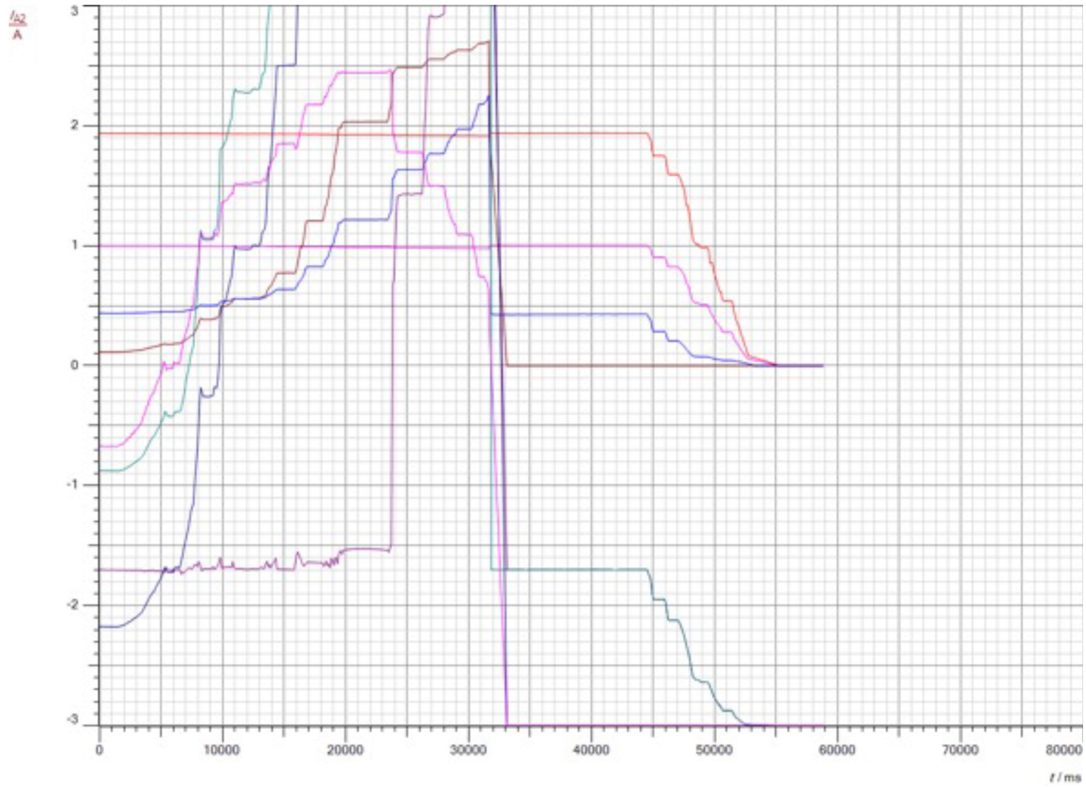


Figure 9: Efficiency and voltage characteristics

## 4.2 Task 2:

### 4.2.1 Transformer in star-star circuit Yy0

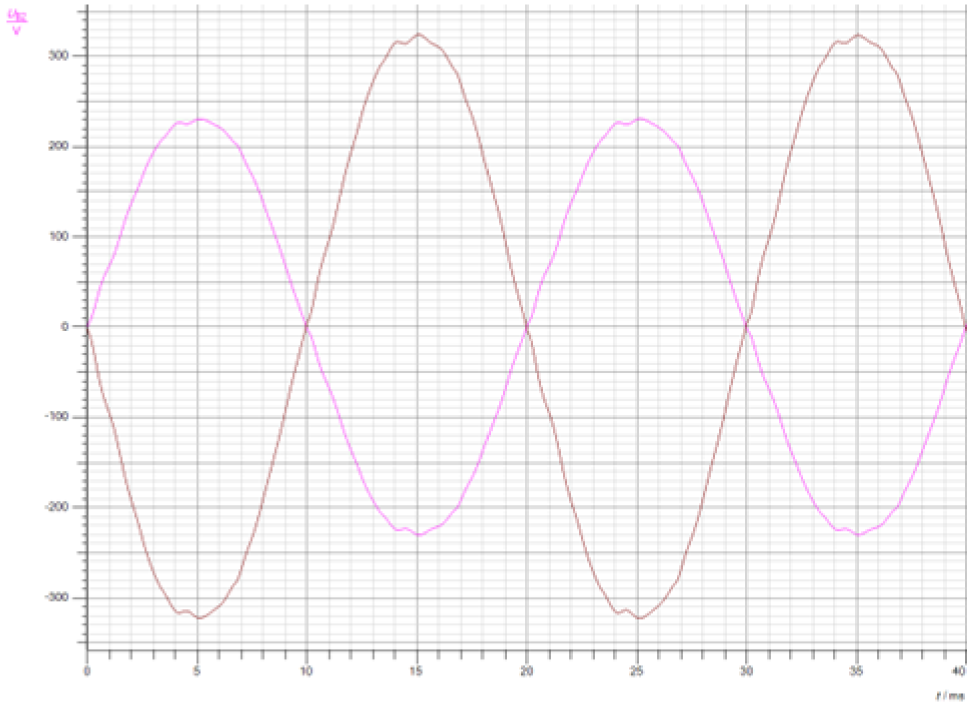


Figure 10: Plot of primary and secondary voltage waveforms

As seen on figure 10 the phase-shift between the primary and secondary side of the transformer is about 180°

In theory there is possible to have a star-star connection that gives a phase shift of 0°or 180°. This depends son whether the winding terminals on the secondary side is reversed or not.

### 4.2.2 Transformer in delta-star circuit Dy11

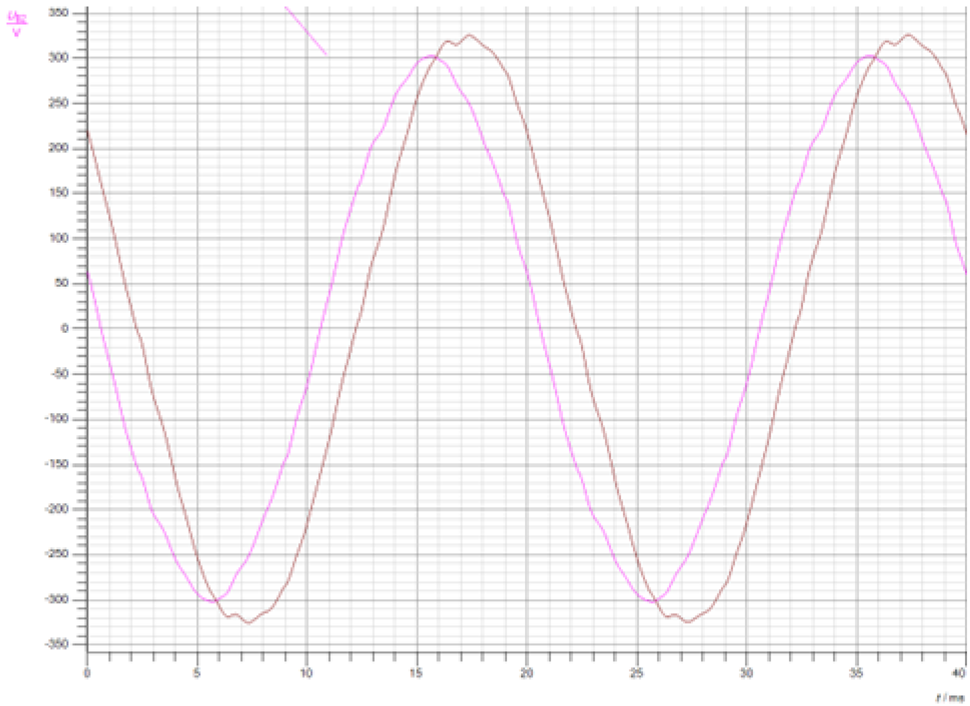


Figure 11: Plot of primary and secondary voltage waveforms

As seen in figure 11 the phase shift between the primary and secondary voltage appears to be around 30°.

In theory we should get a phase shift of ±30° on a delata-star connection. By relabling the terminals it is also possible to get ±90°

**Swaping the supply leads L1 and L2:**

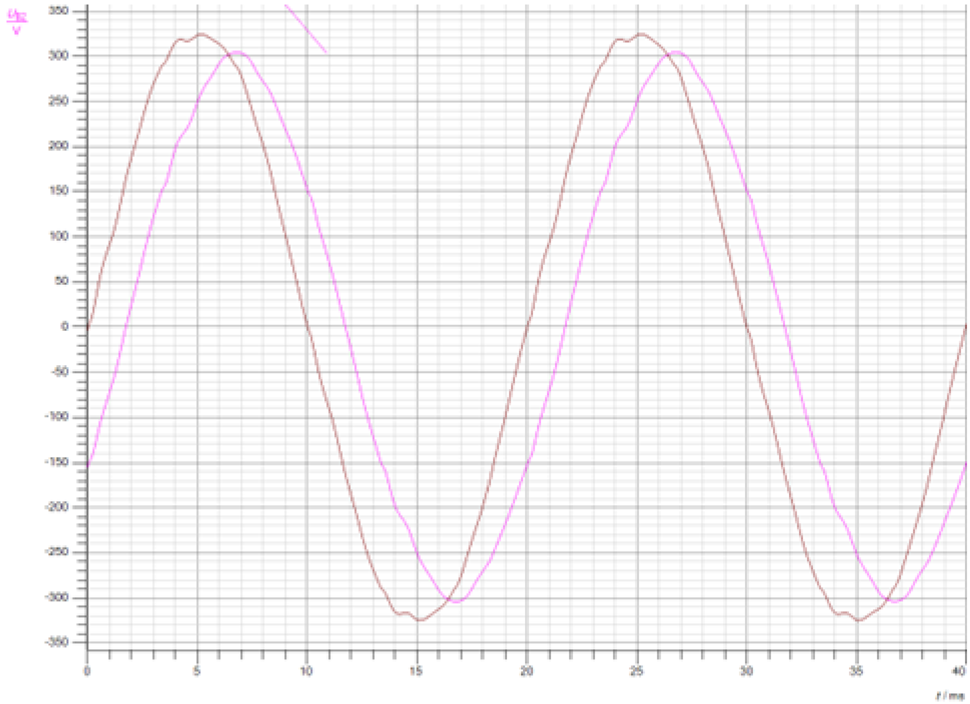


Figure 12: Plot of primary and secondary voltage waveform

As seen in figure 12 the phase shift between primary and secondary voltage appears to be around -30°.

# 5 Analisys and Discussion

This chapter examines the results obtained from the experiments conducted on single-phase and three-phase transformers. The collected data from the short circuit and open circuit testing, as well as the efficiency and voltage characteristics, will be analyzed. By thoroughly examining and interpreting the data, conclusions can be drawn regarding the performance of these transformers under different operating conditions. Additionally, any significant observations and potential areas for improvement will be discussed. The overall aim of this chapter is to provide a comprehensive analysis of the data and facilitate a deeper understanding of the behavior of transformers in practical settings.

## 5.1 Task 1

### 5.1.1 Open circuit test

In the OC-test we got the values $R_c = 2460,47\Omega$ and $X_m = 564,5\Omega$. These values is 600 and 300 times larger than the impedance measured in the SC-test. The copper resistance $R_c$ was higher than expected when compared to other groups. This might be unique for this exact transformer, or some error in the measurements.

In the notes that was taken while conducting the lab there were noted two $P_{OC}$ values. The noted values was $P_{OC} = 96W$ and $P_{OC} = 21,5W$. This will give two different values for $R_c$.

We can either have a copper resistanse value of $R_{c1} = 551,042\Omega$ or $R_{c2} = 2460,47\Omega$.

In the *Results* chapter, $R_{c2}$ was chosen because that was the latest value noted.

### 5.1.2 Short circuit test

In the SC-test we got the values $R = 4,1\Omega$ and $X = 1,487\Omega$.

The Voltage required to obtain rated current where lower than expected. In *Electric Machines* Kothari and Nagrath 2020 it says that the voltage needed for a SC-test is typically 5% of the rated value. In this case that would be $\frac{230V\cdot 5}{100} = 11,5V$. When conducting the test it only required $4,15V$ to reach the rated secondary current $I_{A2} = 0,950A$.

There is a uncertainty

### 5.1.3 Transformer with resistive load: Efficiency and volatge characteristics

In this experiment there were made some mistakes in the measurement, and the plot lacks a lot of information. When saving the plots, the labels where unfortunately not included.

When measuring the efficiency of the transformer, we used the simpler formula $\eta = \frac{P_{out}}{P_{in}}$ instead of the more accurate formula in equation (14).

## 5.2 Task 2

### 5.2.1 Transformers in star-star circuit Yy0

During the setup of the transformer connection, an error was made in which the polarity of one winding were inadvertently switched, resulting in a 180 degree phase angle between the primary and secondary voltages instead of the intended 0 degree angle in the Yy0 transformer connection.

The connection was supposed to be as shown in figure 13, but one of the windings were inverted.

### 5.2.2 Transformers in delta-star circuit Dy11 and Dy1

In the Dy11 connection there is a phase shift of $+30^\circ$, this is as expected compared to the theory. Figure 14 in the Appendix explains how the connection is set up, and why we get a $30^\circ$ phase shift.

In the Dy1 connection there is a phase shift of $-30^\circ$. This is as expected compared to the theory in figure 15.

# 6 Conclusion

In conclusion, the experiments conducted in this lab provided valuable insights into the performance of single-phase transformers, including their efficiency and voltage characteristics, as well as the different three-phase connections, such as wye-wye and delta-wye.

**Single phase transformer**

The tests conducted on the single phase transformers gave us the parameters shown in table 5 for the equivalent transformer circuit.

| Parameter | Value |
|---|---|
| $R_c$ | $2460,47\Omega$ |
| $X_m$ | $564,5\Omega$ |
| $R_{eq}$ | $4,1\Omega$ |
| $X_{eq}$ | $1,487\Omega$ |

Table 4: Parameters from single phase transformer testing.

The experiment involving a resistive load yielded results that demonstrated the impact of varying load current on efficiency and voltage. Figure 9 shows the efficiency and voltage characteristics when varying the load current. As expected we see that the efficiency increases as the load current increases.

**Three phase transformers**

In this part of the lab, we can conclude that we get really close to the theoretical phase shifts. We had one error in our setup, resulting in a 180° phase shift instead of 0° on the Yy0 connection. Our results as shown in figures 10, 11 and 12, shows the accuracy.

| Connection | Theoretical angle | Measured angle |
|---|---|---|
| Yy0 | 0° | 180° |
| Dy11 | +30° | +30° |
| Dy1 | −30° | −30° |

Table 5: Three phase connections and their angle.

**Overall** there was some failures in the experiments, none of them had a considerable impact on the results and learning.

# Bibliography

Kothari, D P and I J Nagrath (2020). *Electric Machines Fifth Edition*. McGraw Hill Education.
NTNU, Electric Power Systems group (2018). *Vector groups for three-phase transformers*.

# Appendix

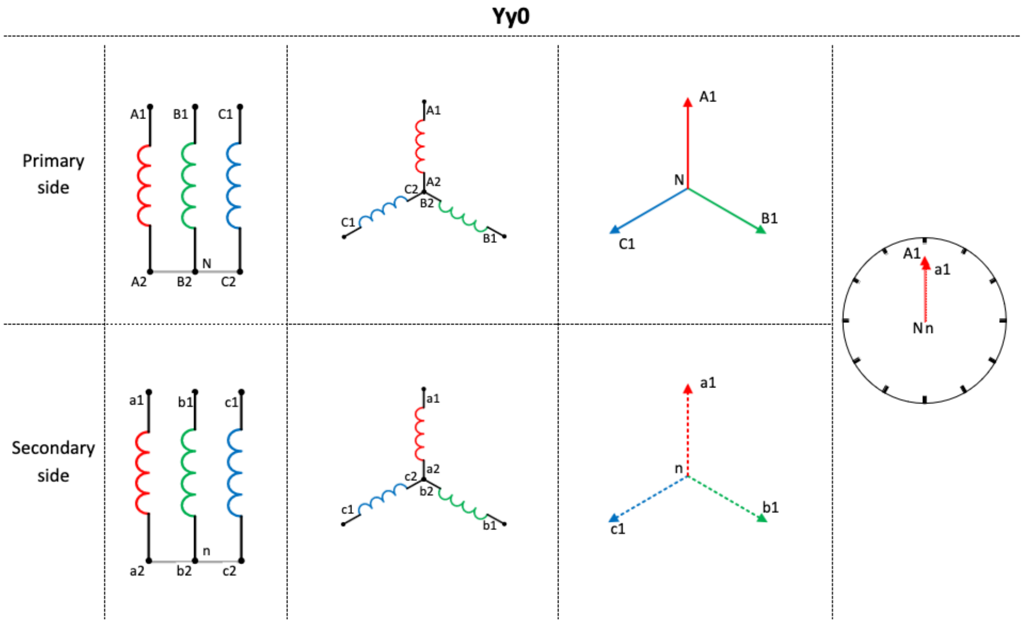


Figure 13: Yy0 connection NTNU 2018

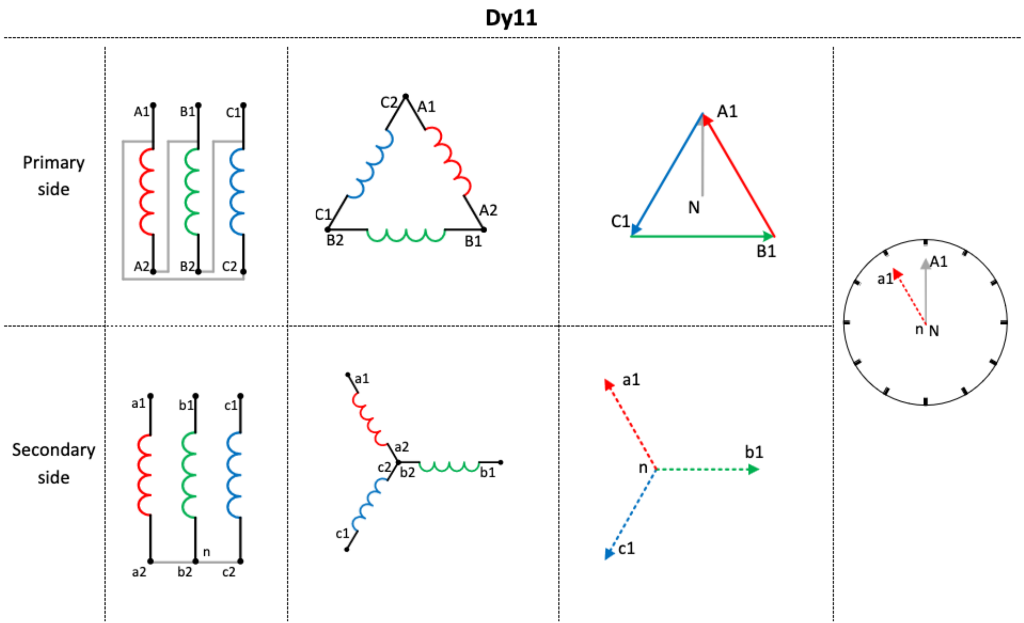


Figure 14: Dy11 connection NTNU 2018

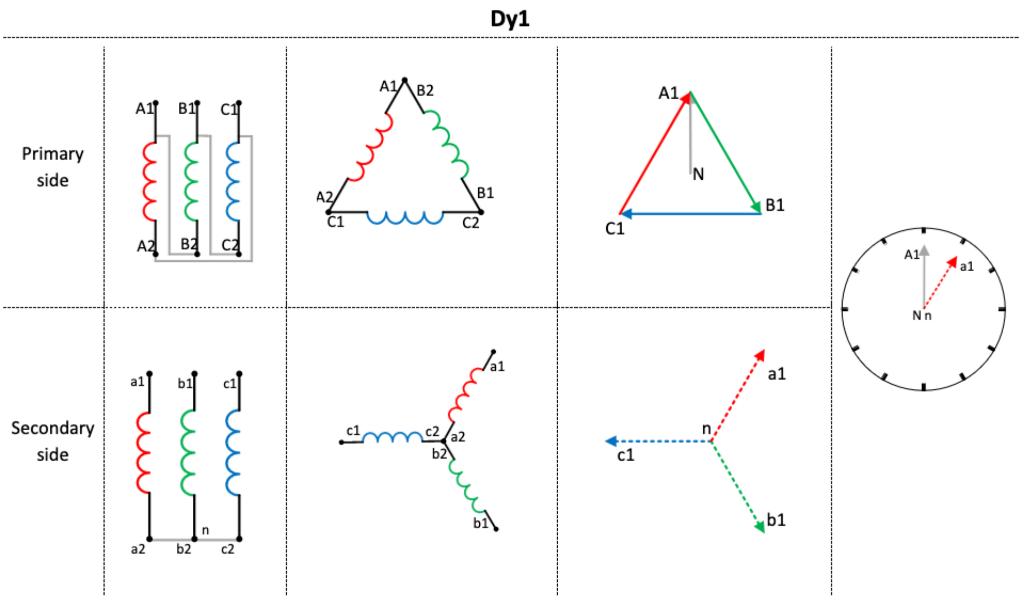


Figure 15: Dy1 connection NTNU 2018