EEEE1028 Power and Energy

Coursework 2

Simulation of a Single-Phase Transformer

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1.0 Introduction

A transformer is a passive electrical device that transfers electrical energy from one circuit to another or more through the process of electromagnetic induction. A simple transformer consists of a primary winding and a secondary winding, both wounded onto an iron core with each winding connected to a separate circuit. It can be used to either step-up or step-down voltage levels between the circuits. Its working principle is based on the Faraday's law of induction which describes the induced voltage effect in a coil due to a changing magnetic flux encircled by the coil.

In this coursework, a single-phase test transformer was given. To investigate the behaviour of the transformer, PLECS software is used to run simulations to emulate an actual experiment. The objectives of the experiment are to:

- Determine the turns ratio of the transformer.
- Determine the "regulation" of the transformer.
- Determine the "efficiency' of the transformer.
- Determine the equivalent circuit parameters of the transformer.

The report contains a series of simulations and calculations which are needed to achieve the objectives stated above.

In addition to that, the report contains a discussion section where the working principle and concepts behind transformer are discussed.

2.2 Transformer Turns Ratio and Rated Load

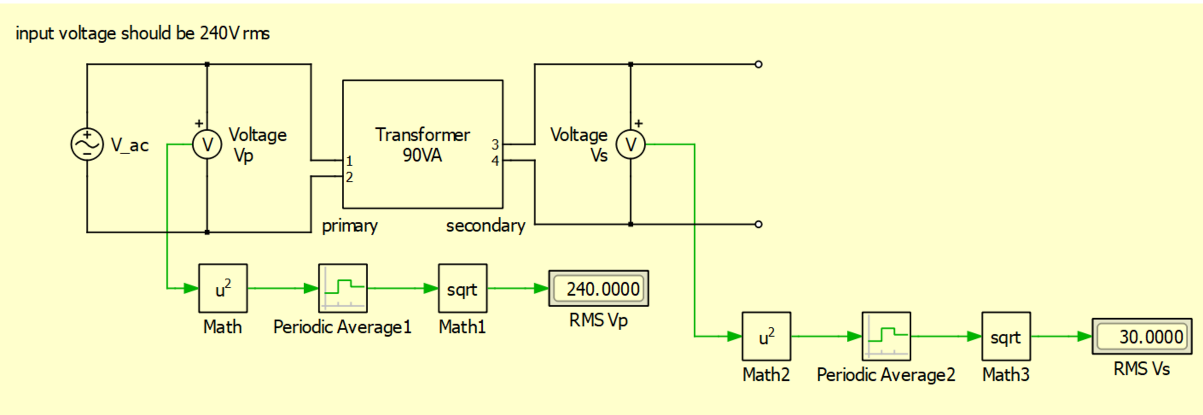

Figure 1 Simulation of Transformer

To find the value of input voltage source, V_{peak}:

$$V_{peak} = V_{rms} \times \sqrt{2}$$

$$= 240 \times \sqrt{2}$$

$$= 399.411255\ V$$

Two systems are created to measure and calculate the primary RMS voltage and secondary RMS voltage as shown in Figure 1. The values obtained are tabulated below.

Primary RMS Voltage, V_p	240V
Secondary RMS Voltage, V_s	30V

Table 1 Value of Primary and Secondary RMS voltage measured

To determine the turns ratio of the transformer, K:

$$\mathrm{K} = \frac{V_S}{V_P}$$

$$= \frac{30}{240}$$

$$= \frac{1}{8}$$

Using the VA rating, S of the transformer given and secondary RMS voltage measured, the rated current, I_s and the load resistance, R_L required to achieve the rated current can be calculated as shown below.

To find rated current, I_s:

$$I_s = \frac{S}{V_S}$$

$$= \frac{90}{30}$$

$$= 3\ A$$

To find load resistance, R_L:

$$R_L = \frac{V_S}{I_S}$$

$$= \frac{30}{3}$$

$$= 10\ \Omega$$

2.3 Transformer Behavior Under Load: Measurement of Regulation and Efficiency

Load with different resistance values were used and the results are recorded and tabulated in Table 2.

Load Resistance, R_L (Ω)	Active Power (W)		Input Apparent Power, S_{in} (VA)	Primary RMS Current, I_p (A)	Secondary RMS Voltage, V_s (V)	Secondary RMS current, I_s (A)
	Input, P_{in}	Output, P_{out}				
10	93.4959	83.8586	94.4236	0.3934	28.9584	2.8958
20	50.8282	43.4243	52.3993	0.2183	29.4701	1.4735
30	36.2680	29.2935	38.4091	0.1600	29.6446	0.9882
40	28.9229	22.1008	31.5535	0.1315	29.7327	0.7433

Table 2 Data recorded from the simulation with different load added

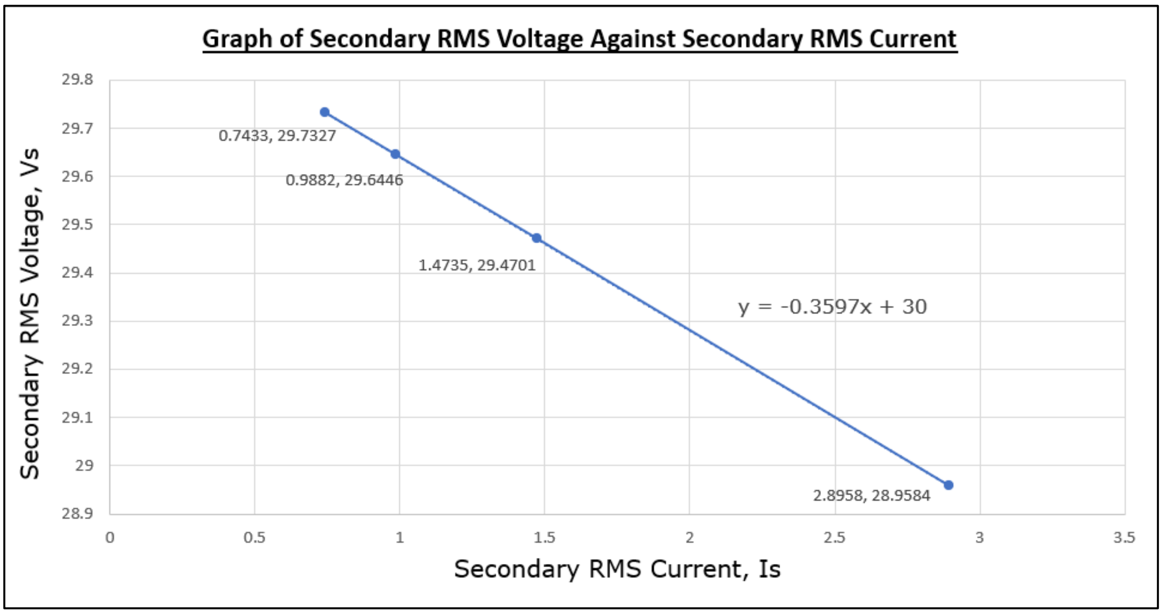

Figure 2 Graph of Secondary RMS Voltage Against Secondary RMS Current

The gradient of the graph can be related to the voltage reglation of the transformer for different load resistance as shown in the workings below.

Using the equation of graph, y=mx+c

Let V_{NL} = No load voltage, V_{FL} = Full load voltage, R = Load resistance

$$y = mx + c$$

$$V_{FL} = m(I_s) + V_{NL}$$

$$V_{FL} = m\left(\frac{V_{FL}}{R}\right) + V_{NL}$$

$$\frac{V_{FL}-V_{NL}}{V_{FL}} = \frac{m}{R}$$

$$\frac{V_{NL}-V_{FL}}{V_{FL}} = -\frac{m}{R} \quad , where \ \frac{V_{NL}-V_{FL}}{V_{FL}} = voltage\ regulation$$

The value of y-intercept represents V_{NL} because that is when secondary current equals to zero. Under no load condition, secondary current is equal to zero.

Therefore, by using the gradient of the graph divided by the resistance of the load, the voltage regulation can be determined. To calculate the resistance value of the load, The resistance of the load use the y-value (V_{FL}) divided by x-value (I_s) of any point on the graph.

To determine the efficiency and regulation of the transformer when operating at rated power:

$$Efficiency, \eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$= \frac{89.8586}{93.4959} \times 100\%$$

$$= 89.6923\%$$

$$Voltage\ regutalion = \frac{V_{NL}-V_{FL}}{V_{FL}} \times 100\%$$

$$= \frac{30-28.9584}{28.9584} \times 100\%$$

$$= 3.5969\%$$

2.4 Determine the Transformer Equivalent Circuit

2.4.1 Open Circuit Test

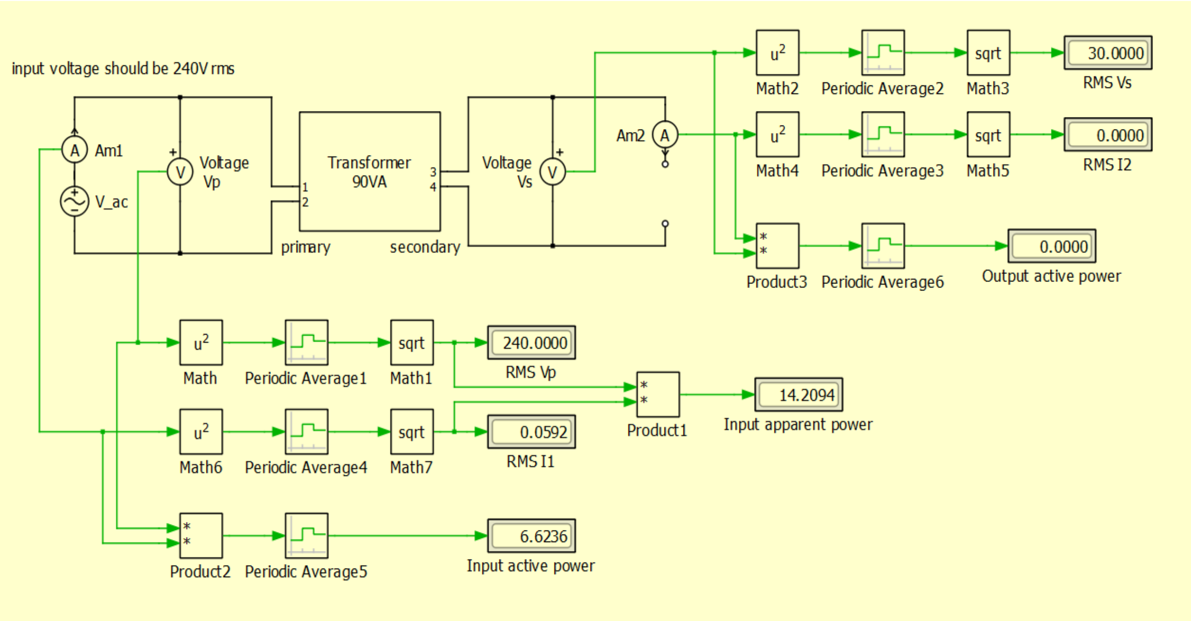

Figure 3 Circuit for Open Circuit Test

The data from the open circuit test was recorded and tabulated in the table below.

Primary RMS Voltage, V_P	240V
Primary RMS Current, I_p	0.0592A
Primary Active Power, P_{in}	6.6236W

Table 3 Data Obtained From The Open Circuit Test

To construct a phasor diagram, first find the power factor of the transformer as shown:

$$P_{in} = |V_p||I_p| \cos\theta$$

$$6.6236 = (240) \times (0.0592) \times (\cos\theta)$$

$$\theta = 62.21°$$

Then, find the magnitude of I_m and I_c:

$$|I_c| = |I_p| \cos\theta$$

$$= 0.0592 \cos(62.621)$$

$$= 0.0276\ A$$

$|I_m| = |I_p| \sin\theta$

$= 0.0592 \sin(62.621)$

$= 0.05237\ A$

With the above information a phasor diagram can be constructed as shown below.

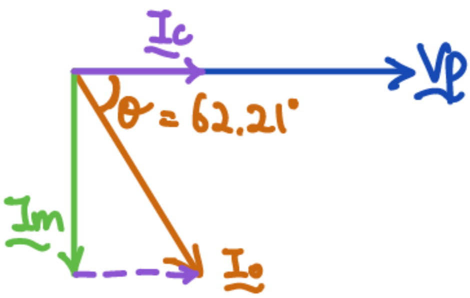

Figure 4 Phasor Diagram for Open Circuit Test

Use I_m and I_c calculated above to determine the value of R_c and X_m:

$|V| = |I_c| \times R_c$

$240 = 0.0276 \times R_c$

$R_c = 86.9565\ \Omega$

$|V| = |I_m| \times X_m$

$240 = 0.0276 \times X_m$

$X_m = 4582.78\ \Omega$

2.4.2 Short Circuit Test

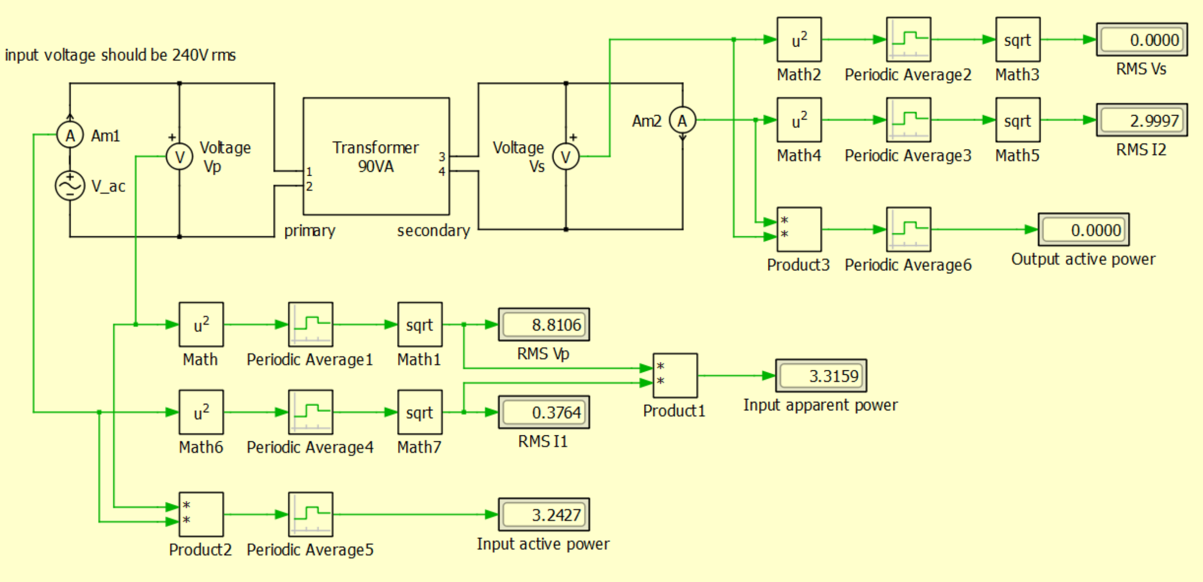

Figure 5 Circuit for Short Circuit Test

The input peak voltage value of AC source and its RMS value used in the simulation are recorded in the table below. The input RMS voltage value used is 8.8106V and the output RMS current is found to be 2.9997A which is well within 10% of its rated value.

Primary Peak Voltage	12.46V
Primary RMS Voltage	8.8106V
Secondary RMS Current	2.9997A

Table 6 Input Peak Voltage Used and Output RMS Current Produced

The data from the short circuit test was recorded and tabulated in the table below.

Primary RMS Voltage, V_P	8.8106V
Primary RMS Current, I_P	0.3764A
Primary Active Power, P_{in}	3.2427W

Table 7 Data Obtained From Short Circuit Test

To construct a phasor diagram, first find the power factor and the power factor of the transformer as shown:

$$P_{in} = |V_p||I_p| \cos\theta$$

$$3.2427 = (8.8106) \times (0.3764) \times (\cos\theta)$$

$$\theta = 12.0944°$$

Then, find the magnitude of V_R and V_X:

$$|V_R| = |V_p| \cos\theta$$

$$= 8.8106 \cos(12.0944)$$

$$= 8.6150\ V$$

$$|V_X| = |V_p| \sin\theta$$

$$= 8.8106 \sin(12.0944)$$

$$= 1.8460\ V$$

With the values calculated, a phasor diagram can be constructed as shown below.

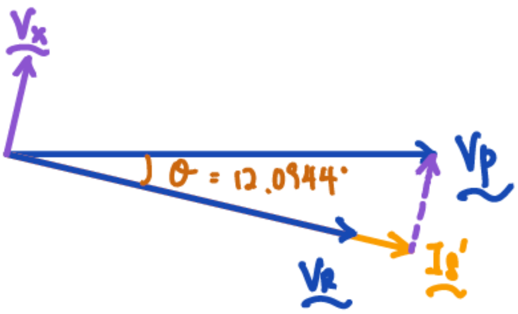

Figure 8 Phasor Diagram for Short Circuit Test

Use V_R and V_X calculated above to determine the value of R and X:

$$|V_R| = |I_p| \times R$$

$$8.6150 = 0.3764 \times R$$

$$R = 22.8879\ \Omega$$

$$|V_X| = |I_p| \times (X)$$

$$1.8460 = 0.0276 \times (X)$$

$$X = 4.9044\ \Omega$$

2.5 Phasor Diagram for the Full Load Condition

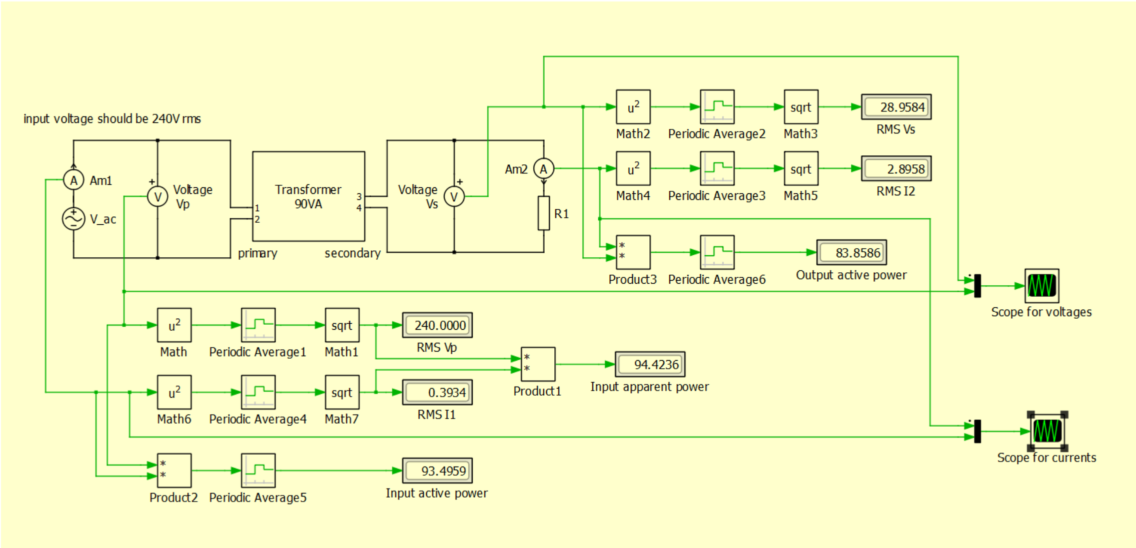

Figure 9 Circuit to Determine Phase Angle

2.5.1 Phase Angle Between Primary and Secondary Voltages

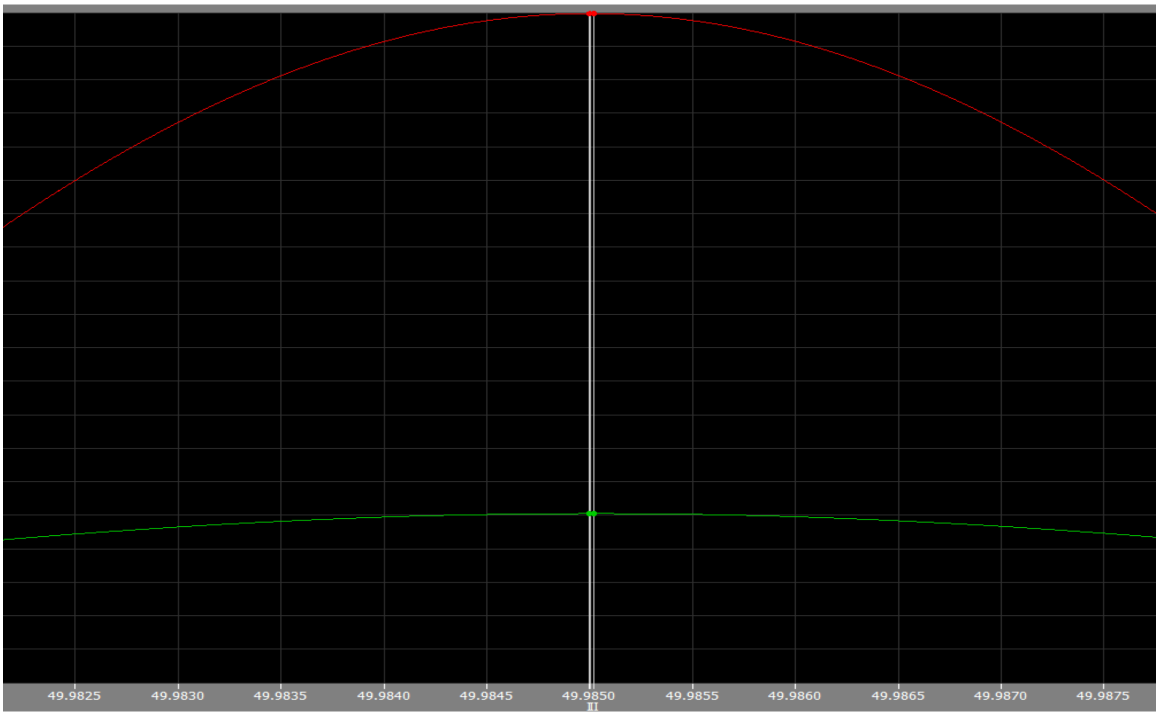

Figure 10 Graph Showing Peaks of Primary and Secondary Voltages

Data				
Name		Cursor 1	Cursor 2	Delta
Time		49.985	49.985	2e-05
Plot 1				
Voltage	Vs:Measured voltage	40.9524	40.9535	-0.00105709
Voltage	Vp:Measured voltage	339.411	339.405	0.00669969

Figure 11 Data Obtained from the Voltage Graph

The time difference between peak values of both voltages, Δt obtained from the simulation is $2{\times}10^{-5}$s. Knowing the frequency of the AC source, which is 50Hz, the phase angle, θ_V can be calculated as shown below.

$$\theta_V = \frac{\Delta t}{0.02} \times 360°$$

$$= \frac{2{\times}10^{-5}}{0.02} \times 360°$$

$$= 0.36°$$

By using the information obtained from the graph, the phasor diagram for the voltages can be drawn.

Figure 12 Phasor Diagram for Primary and Secondary Voltages

2.5.2 Phase Angle Between Primary and Secondary Currents

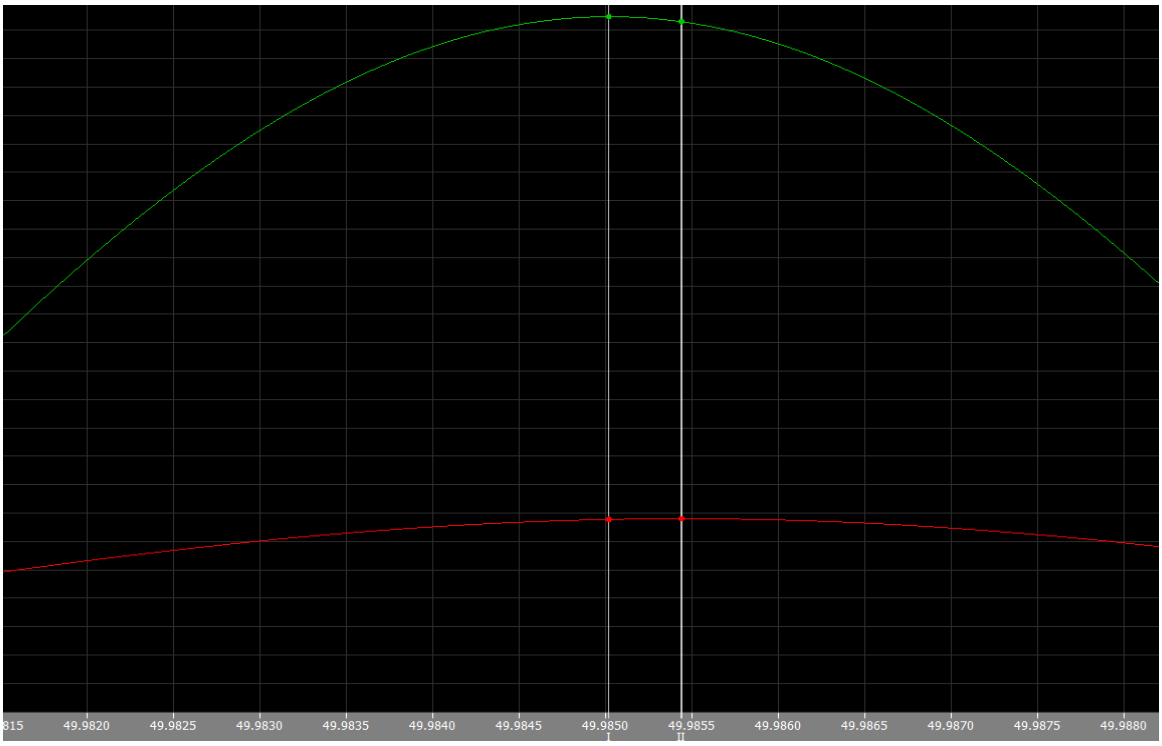

Figure 13 Graph Showing Peaks of Primary and Secondary Currents

Data

Name	Cursor 1	Cursor 2	Delta
Time	49.985	49.9854	0.00042
Plot 1			
Am2:Measured current	4.09535	4.06027	0.0350775
Am1:Measured current	0.553824	0.558799	-0.00497507

Figure 14 Data Obtained from the Current Graph

The time difference between peak values of both currents, Δt obtained from the simulation is 0.00042s. To calculate the phase angle, θ_I:

$$\theta_I = \frac{\Delta t}{0.02} \times 360°$$

$$= \frac{0.00042}{0.02} \times 360°$$

$$= 7.56°$$

By using the information obtained from the graph, the phasor diagram for voltages can be drawn.

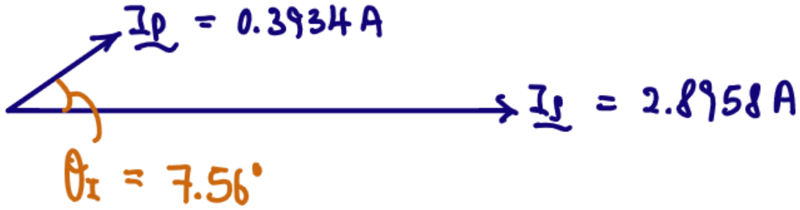

Figure 15 Phasor Diagram for Primary and Secondary Currents

3.0 Discussion

(a) What is the purpose of the core in a transformer?

The function of the core in a transformer is o channel the magnetic flux generated at the primary coil to the secondary coil. It concentrates the magnetic flux from the primary coil to pass majority of the flux created to the secondary coil, reducing flux leakage.

(b) In a transformer that has no magnetic leakage, explain what (if anything) happens to the flux waveform in the core when the secondary current is changed assuming the primary voltage and frequency remain the same.

No change. Because the magnetic flux in the core is directly proportional to the primary voltage. The primary voltage remains unchanged so the magnetic flux in the flux will also remain unchanged.

The change in secondary current may be caused by load added to or removed from the transformer. The change in secondary current will only result in the change in reflected load current, that is the extra primary current flow that generates flux to cancel off the flux produce by the secondary current. Thus, flux in the core will always be constant unless the voltage supply changed.

(c) Explain what is meant by leakage flux and mutual flux in a transformer.

Leakage flux is the flux that links only one of the windings but not both. In other words, leakage flux is the flux that generated by either the primary or secondary winding that does not flow in the core. The leakage flux may pass through winding insulation, transformer insulation oil or the air.

Mutual flux is the flux that links both the primary and secondary winding channelled by the core. This mutual flux is the useful flux that generates current in the secondary winding.

Mutual flux is the resultant flux between the flux produce in the primary coil and the flux induced in the secondary coil that flows in the core. The secondary coil will produce a small amount of flux that can be add up or to or reduce the flux produced by the primary coil [based on the direction of the current flow and the polarity of voltage] due to Lenz’s Law.

(d) What is the main effect of leakage flux on the performance of a transformer? How can the leakage flux be minimised by suitable design of the transformer?

Flux leakage will reduce the output current induced in the secondary coil. To achieve a desired output current, the total magnetizing current must increase, hence more energy will be used and more power will be consumed. Increasing the magnetizing current will also result in the increase of copper loss (V=IR), which leads to low efficiency and poor regulation of the transformer.

To minimise flux leakage, the core can be constructed by thin iron laminations to reduce the formation of eddy current that will cause magnetic loss. Soft iron is normally used to make the core because it has high permeability and low hysteresis curve, hence less energy loss.

For the design, instead of using a core-type transformer design, a shell-type transformer design can be utilised where both the primary and secondary winding are wounded on the same limb of the core as shown in the diagram below. This design reduces magnetic flux leakage as it allows two closed magnetic flux to flow around the two external limbs at both sides of the core to the centre limb.

A transformer with secondary winding winds on top of primary winding in a toroidal geometry can also be used to reduce leakage flux.

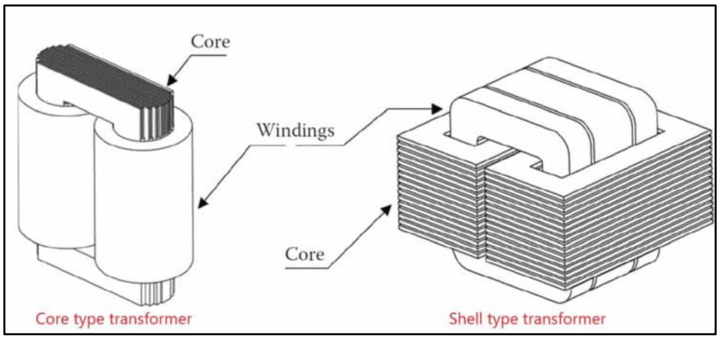

Figure 16 Core Type Transformer and Shell Type Transformer

(e) Draw an equivalent circuit for a transformer including the effects of winding resistance, magnetic leakage and core loss. Explain the relationship between each component in the model and the physical effect that it models.

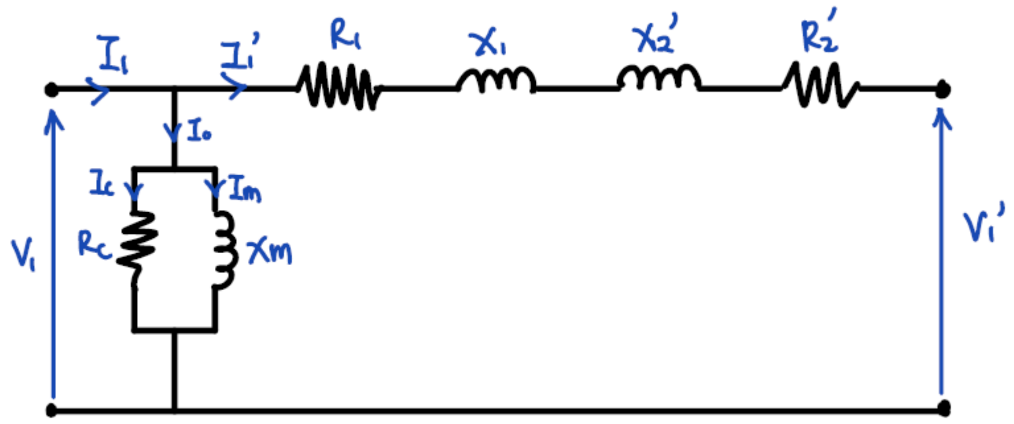

Figure 17 Transformer Equivalent Circuit

R_1 and R_2 are the resistance in the primary and secondary windings, which account for energy dissipation. X_1 and X_2 are the (induction in the windings) which account for the magnetic energy loss due to flux leakage. R_c represents core loss, which accounts for the real power dissipation due to eddy current and hysteresis effect in the core. X_m is the inductance added to show the magnetizing current (I_m), which set up the magnet flux in the core. Magnetizing current is also observed to lag the supply current by 90degree, so inductor is best used to represent or show the magnetizing current flows in the transformer.

(f) Explain the difference between the regulation and efficiency of a transformer.

Regulation of a transformer is defined as the percentage change in the magnitude of secondary voltage under load and no-load condition under various load condition. The voltage regulation of a transformer determines the ability of the transformer to provide a constant voltage under variable loads. When the transformer is loaded with continuous supply voltage, the terminal voltage of the transformer varies where the variation of the voltage depends on the load and its power factor.

Voltage regulation of a transformer can be calculated using the formula:

$$\frac{V_{NL} - V_{FL}}{V_{FL}}$$

Where, V_{NL} = No load voltage, V_{FL} = Full load voltage, R = Load resistance.

Efficiency is defined as the ratio of the secondary output power to the primary input power of the transformer.

(g) If a transformer is designed to work at 240V, 50Hz why will it not work satisfactorily at 240V, 25Hz?

V_1 is maintained at 240V. At a constant voltage, I_m will be inversely proportional to frequency. Therefore, when the frequency of a transformer is reduced to its half, I_m will be doubled compared to its original value. A real transformer is made of non-linear magnetic material, which means that the permeability is not constant but varies with the magnetising current. Based on the curve of magnetising flux against I_m, the magnetising current does not increase linearly with I_m infinitely. After the linear region, the flux will then reach a saturation region and stop increasing even though I_m increases. Therefore, doubling the I_m will cause saturation of the core.

Saturation of the core will cause multiple problems. A transformer with saturated core will distort the waveform from its primary to secondary windings. This will create harmonics in the secondary winding's output. The presence of harmonics causes overheating, power loss, reduced efficiency, and shortened lifespan of the devices. Thus, core saturation must be avoided.

(h) Explain why a transformer of a particular VA rating can be made smaller if it operates at a higher frequency.

The statement can be explained by using the formula:

$$A_c N_1 = \frac{V_1}{2\pi f B}$$

From the formula, it can be clearly seen that the size of a transformer is inversely proportional to the frequency of the AC voltage supply. This is because A_c and N_1 determines the size of a transformer where A_c represent the area of the core and N_1 represents the number of turns of the primary winding. However, we need to keep in mind that B has to be kept under 1.6T to prevent saturation of the core when designing a transformer.

Conclusion

In conclusion, all the objectives have been achieved. To summarize,

- The turns ratio of the transformer determined is 1:8.
- The “regulation” of the transformer determined is 3.5969%.
- The “efficiency” of the transformer determined is 89.6923%.
- The equivalent circuit parameters of the transformer were determined. Where, R_c = 86.9565Ω, X_m = 4582.78Ω, R = 22.8879Ω and X = 4.9044Ω.