BIRZEIT UNIVERSITY

Faculty of Engineering & Technology
Electrical & Computer Engineering Department

Electrical Machines Laboratory (ENEE3101)

$\frac{9}{10}$

Report 1

"Single-Phase Transformers"

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1. Abstract

The experiment's primary goal is to thoroughly investigate single-phase transformers, assessing their performance under varying loads (including resistive, inductive, capacitive, and no-load conditions), analyzing the resultant effects on real power, and determining critical parameters such as efficiency and internal impedance through the execution of open-circuit and short-circuit tests.

2. Method used

Single-phase transformer	733 97
Single-phase toroidal core transformer (didn't use)	733 98
Single-phase autotransformer	733 99
Variable Transformer 0 ... 260 V / 4 A	726 85
Resistive load	73240
Inductive load	732 42
Capacitive load	732 41
2 AC Power Meter (GW Instek)	GPM 8212

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3. Theory

➢ Transformer

A transformer is a device that converts electric energy from one voltage level to another by utilizing a magnetic field. It can either step up (increase) or step down (decrease) the voltage. Transformers play a crucial role in power stations, where they are used to raise the voltage generated by electric generators. This increase in voltage is necessary for the efficient transmission of electric power over long distances. [1]

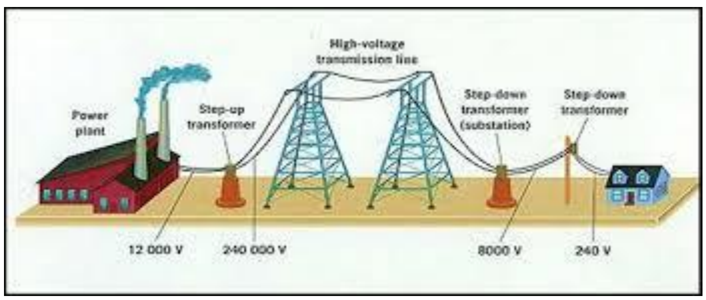

Figure 1: Electric Stations [2]

➢ How Does a Transformer Work?

A transformer is a machine that operates based on the principle of electromagnetic induction. Its primary function is to convert voltage while maintaining a constant power level. Notably, the frequency remains unchanged in a transformer. According to Faraday's Law of Electromagnetic Induction, the induced electromagnetic field in a coil or conductor is directly proportional to the rate of change of flux linkage with respect to time. In practice, the primary winding or input is connected to an AC electric power source, and the secondary winding is linked to a load. In cases where there is a third winding, it is referred to as the Tertiary winding. [3]

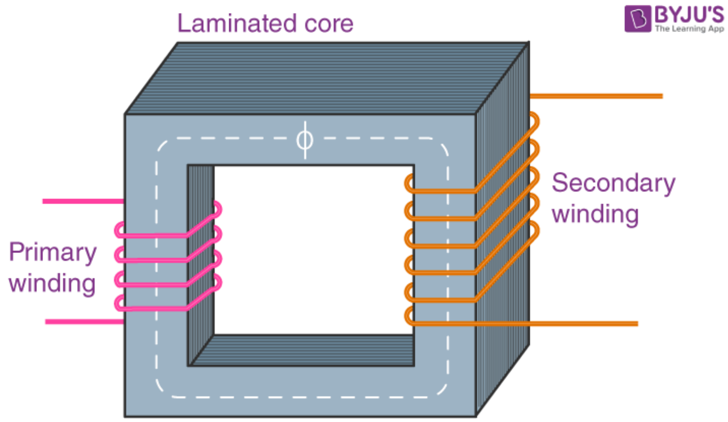

Figure 2: Transformer working [4]

When an alternating current flows through the primary coil, it generates a changing magnetic field that induces a voltage in the secondary coil. The ratio of turns in the coils determines whether the transformer steps up or steps down the voltage, with a corresponding change in current. Transformers provide electrical isolation between circuits, conserve power, and are essential for electrical power distribution, voltage conversion, and adapting voltage levels for various applications, playing a pivotal role in the efficient transmission of electrical energy. [5]

"The main winding is the one connected to the power supply where the initial flux is generated. Both coils are insulated from each other. The initial magnetic flux is induced in the main winding through which the magnetic core runs and is connected to the secondary winding with low resistance. This helps maximize connections or links. What the core really does is create a magnetic circuit that bridges the flow of electricity to the secondary winding to complete the current flow. Also note that for certain types of Transformers, the secondary winding can reach a pulse when both windings are wound on the same core. This allows the generated magnetic field to create movement". [6] .There are two types of construction of transformer: core form and shell form

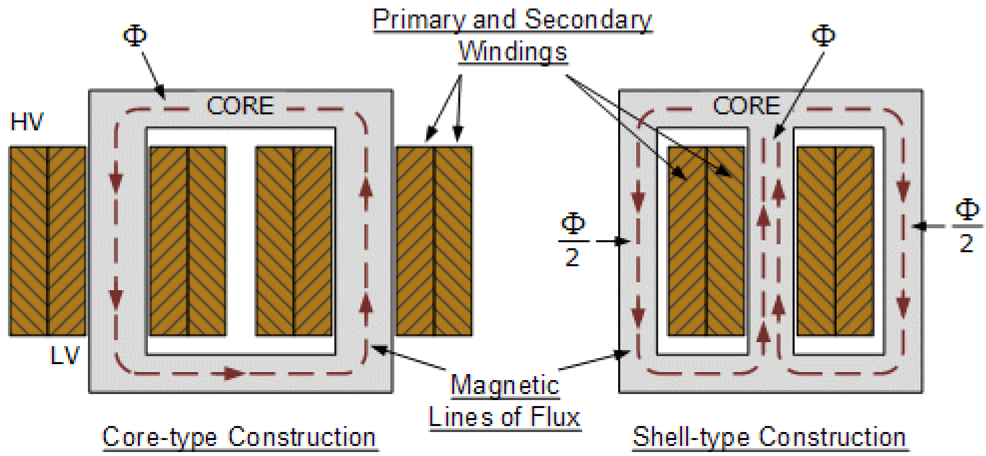

Figure 3: Transformer Construction [7]

➢ Ideal Transformer

The ratio of voltages is equal to the ratio of the number of turns, as shown in the equation below:

$$V2/V1 = N2/N1$$

Where V2 is the voltage secondary voltage, V1 is the primary voltage, and N1 is the number of turns in the primary coil, N2 is the number of turns in the secondary coil. An ideal transformer is a theoretical concept where there are no losses, perfect energy transfer, and precise voltage and current transformations based on the turns ratio. In reality, practical transformers exhibit losses and imperfections, but the ideal transformer serves as a fundamental model for understanding transformer principles and behavior. "In an ideal transformer, the primary voltage and current are in phase with the secondary, so the transformer's turns' ratio affects the magnitude only, but not their angles." [1]

The current ratio

$$I1/I2 = N2/N1$$

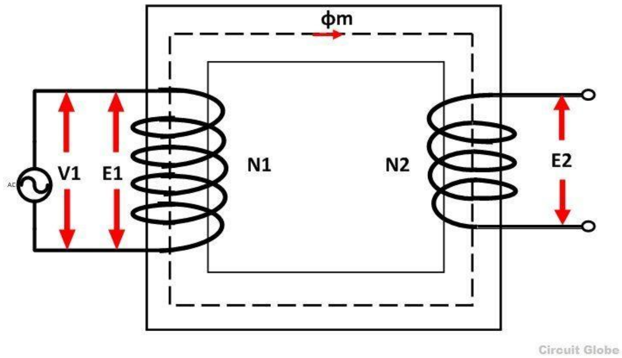

Figure 4: Ideal transformer [8]

➢ The Equivalent Circuit of a Transformer

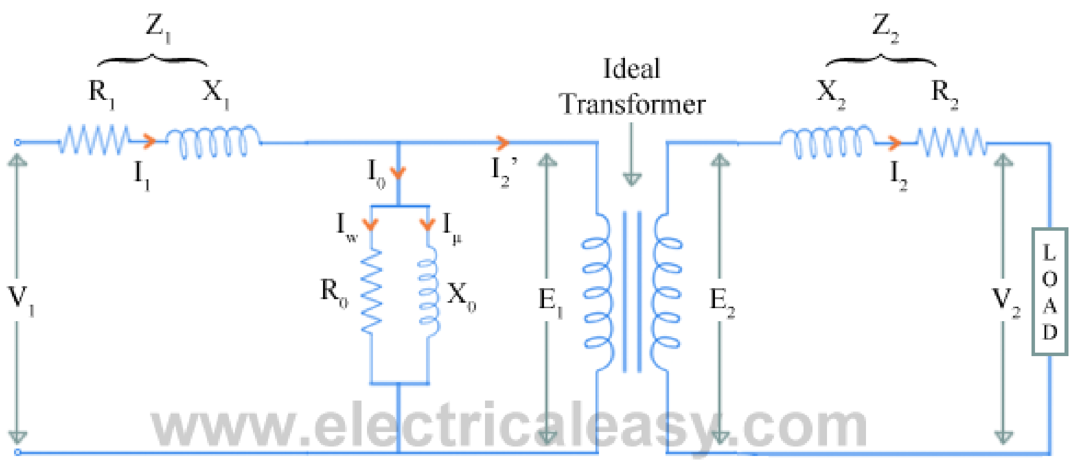

Figure 5: The Equivalent Circuit of a Transformer [9]

Transformers encounter several efficiency-impacting losses:

1. Copper Losses (I^2R): These stem from the resistance in the windings, causing resistive heating as current flows. The loss is proportional to the square of current and winding resistance.

2. Eddy Current Losses: Induced circulating currents in the core generate resistance and heat, directly proportional to the square of the applied voltage.

3. Hysteresis Losses: These result from the magnetic domains rearranging during each AC cycle. Their effect is a complex, nonlinear function of the applied voltage.

4. Leakage Flux: When magnetic flux escapes the core and passes through only one winding, it causes self-inductance in both primary and secondary coils.

The exact equivalent circuit of a real transformer simplifies as follows: Copper losses are represented by resistors RP in the primary circuit and RS in the secondary circuit. The core loss current ($ih + e$) is approximated by a resistor RC connected across the primary voltage source, despite its nonlinearity. The magnetization current (im) is represented by a reactance XM, connected across the primary voltage source and lagging the applied voltage by 90 degrees in the unsaturated region. Leakage flux gives rise to voltages, eLP in the primary and eLS in the secondary, both incorporated into the primary resistance and inductance to consider the internal voltage drop from primary winding resistance and the establishment of primary leakage flux. It's crucial to understand that core loss and magnetization currents are linked to mutual flux and eP, not to vP or eLP. For ease of circuit analysis, the transformer's equivalent circuit can be converted into a single circuit, either on the primary or secondary side.

Approximate Equivalent Circuits of a Transformer

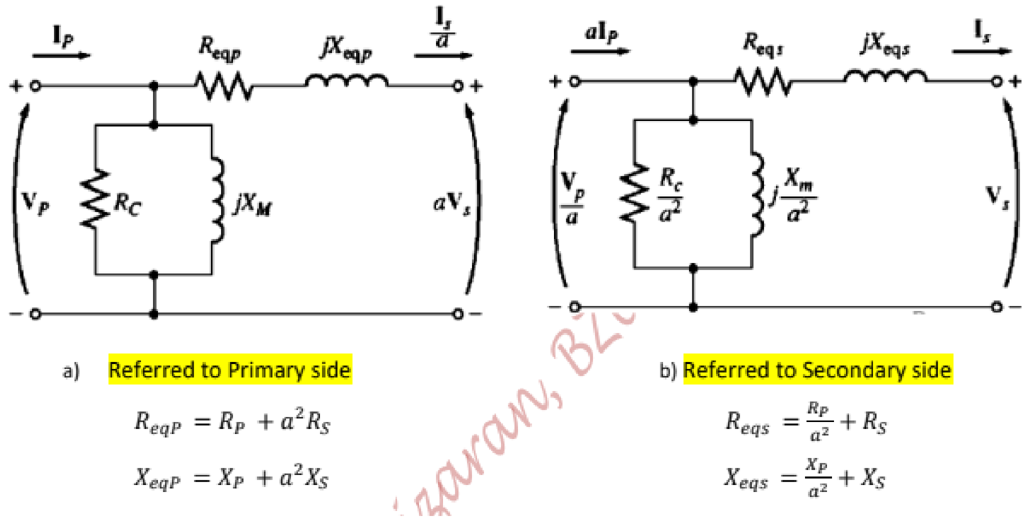

Figure 6: Approximate Equivalent Circuits of a Transformer [1]

➢ Short and open circuit test

To determine the values of the transformer components, two tests are commonly used: the open-circuit test and the short-circuit test.

- **Open test:**

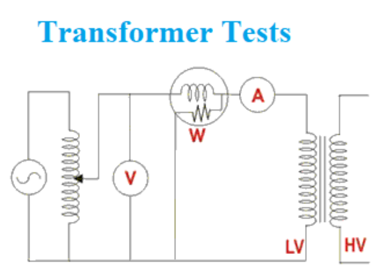

Figure 7: Open Circuit Test on Transformer [10]

We determine the excitation branch characteristics during the open-circuit test. In the open-circuit test, the rated voltage is applied with the load disconnected, measuring IOC, VOC, and POC. Note that 'OC' refers to test parameters, not an open circuit. From this test, we find the excitation branch's magnitude, $GC = (1 / RC)$, $BM = (1 / XM)$, and $YEX = (1 / RC - j / XM)$. The magnitude of YEX referred to the primary side is $|YEX| = (IOC / VOC)$, and its angle is determined by the power factor, $\theta = cos^{-1}(POC / (VOC * IOC))$, where transformer power factors always lag. These measurements are crucial for understanding transformer characteristics and performance.

- **Short Circuit Test**

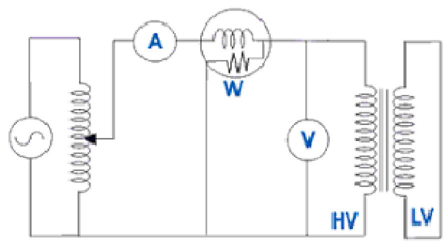

Figure 8: Short Circuit Test [10]

Before conducting the short-circuit test, the voltage source is set to zero. In this test, a very low voltage is applied, and the winding is short-circuited, adjusting the voltage source until the current matches its rated value. During this test, the excitation branch can be ignored as its current is negligible.

The parameters during the Short Circuit test are denoted by 'SC,' but they don't imply a short circuit itself. Measurements include ISC (input current), VSC (input voltage), and PSC (input power). The magnitude of the series impedances referred to the primary side is $|ZSEP| = VSC / ISC$, and the power factor is $pf = cos\ \theta$ (lagging).

ZSEP can be expressed as a combination of resistance and reactance: $ZSEP = (RP + a^2RS) + j(XP + a^2XS)$. Sometimes, it's convenient to conduct these tests on the secondary side due to voltage levels, and the obtained impedances will be referred to the secondary side. The main goal of the short-circuit test is to calculate and establish the values of Req (equivalent resistance) and $jXeq$ (equivalent reactance) as indicated in Figure 6, representing the Approximate Equivalent Circuits of a Transformer.

➢ Transformer on Load Condition

The behavior of the loads and the operation of the transformer may be significantly affected when loads are connected to a transformer. The main variations depending on the kind of load and how it is connected to a transformer are as follows:

1. Resistive Load with Transformer

A resistive load connected to a transformer primarily consumes real power (active power) without affecting the phase relationship between voltage and current. The transformer will step the voltage up or down, as required, but it won't introduce a phase shift. Examples include electric heaters or incandescent lamps.

2. Inductive Load with Transformer:

An inductive load, like an electric motor, can introduce a phase shift between voltage and current. The transformer will step the voltage up or down but doesn't change the fundamental inductive nature of the load. The inductive load can cause reactive power to flow, which requires consideration of power factor correction.

3. Capacitive Load with Transformer:

A capacitive load, when connected to a transformer, may introduce a phase shift, typically in the opposite direction of inductive loads.

Transformers themselves are typically not used to correct power factor issues caused by capacitive loads. Capacitive loads might require additional components like reactors or power factor correction equipment to address power factor concerns.

4. Mixed Loads with Transformer:

Many practical systems have a combination of resistive, inductive, and capacitive loads. Transformers can accommodate these mixed loads but may require additional power factor correction and phase correction equipment to optimize the system's performance.

5. Load on the Secondary Side of a Transformer:

Loads connected to the secondary side of a transformer inherit the voltage transformation applied by the transformer. The load characteristics themselves remain the same, but they operate at the transformed voltage level. [11]

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4. Procedure

➢ PART A: Single-phase Transformer

- Voltage and Current Transformation & Open Circuit Test

— *Open circuit*

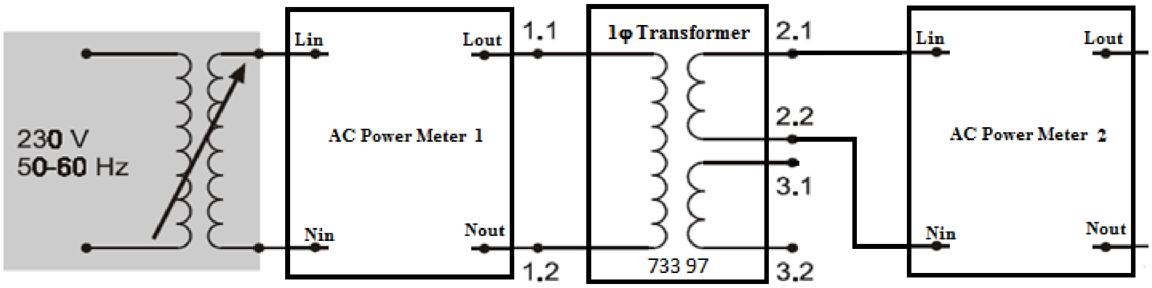

Figure 9: Circuit for Measuring Voltage Transformation in a Single-phase Transformer

Part A	
Nominal voltage (Primary) V_1:	**230 V**
Nominal voltage (Secondary) V_2:	**115V**
Nominal voltage (Secondary) V_3:	**115V**
Nominal current (Secondary) I_2:	**1.36A**
Nominal current (Secondary) I_3:	**1.36A**
Number of Turns N_1:	**408**
Number of Turns N_2:	**214**
Number of Turns N_3:	**214**

Table 1: Nominal Data for the single-phase Transformer under Test

The circuit was connected as shown, with the variable source set at a specific value of 230, as it is a single-phase configuration. The transformer was operated at no load, and the current on the primary side was measured. Additionally, the voltage across the secondaries, denoted as V2 and V3 was measured, along with the voltage V23. The wattmeter reading for the primary side referred to as Poc1 was measured, as well as the readings for Voc1 and Ioc1 when terminals 2.2 and 3.1 were connected.

Measure	Value
I No Load Primary	185.3mA
V_2	120.4 V
V_3	119.8V
V_{23}	240.2V
$P_{O.C}$	10.1W
$V_{O.C}$	229.8V
$I_{O.C}$	185.8mA

Table 2 : The Values measured

$$\theta = \cos^{-1}\frac{Poc}{(Voc * Ioc)}$$

$$\theta = \cos^{-1}\frac{10.1}{(229.8 * 0.1858)} = 84.05$$

$$|YEX| = IOC / VOC$$

$$|YEX| = 0.1858A/229.8V = 0.000808529156$$

$$Rc = 1 / |YEX|$$

$$Rc = \frac{1}{0.000808} = 1237.58$$

$$Xm = 1/(0.000807 * 11.41) = 108.60$$

— *(Resistive load)*

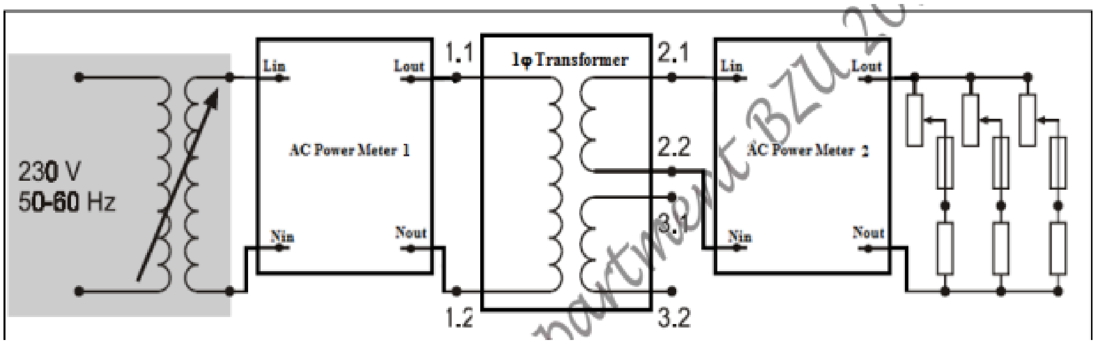

Figure 10: Circuit for Measuring Current Transformation in a Single-phase Transformer

After reducing the input voltage to zero and turning off the power, the circuit was modified, as depicted in Figure 10 below, to determine the current transformation ratio. The resistive load was connected, and a voltage value of 230 was set while maintaining a 90% rating. The resistance rate was subsequently lowered until the secondary rating was achieved, at which point the primary current was measured.

Measure	Value
$I_{\text{primary rated}}$	**0.779A**

Table 3: The Value measured

$$\frac{I1}{I2} = \frac{N2}{N1}$$

$$I1/1.36 = 214/408$$

$$I1 = (1.36 * 214) / 408 = 0.713\ A$$

The measured value of 0.779 A is approximately equal to the calculated value of 0.714 A.

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- Short-Circuit Test and Sustained Short-circuit Current

The investigation of the transformer's behavior when the secondary winding is shorted is undertaken, encompassing the determination of short-circuit voltage and sustained short-circuit current. Furthermore, the assessment of these parameters is influenced by whether one or both of the secondary windings are loaded, with the higher values being observed when both windings are shorted. The use of the rated current for the primary side, as established in the preceding part of the experiment, is necessitated for this measurement.

The circuit is configured in accordance with the illustration in Figure 11. It is paramount to ensure that the power supply is set to zero before activation. Activation is initiated by gradually increasing the voltage of the Variable Transformer from zero, allowing the current in the primary side to reach its rated value (ISC). At this juncture, the corresponding voltage at the primary side (Vsc) and the short circuit power (Psc) are recorded.

Upon the conclusion of the measurements, the input voltage is systematically reduced to zero, and subsequently, the Variable Transformer is turned off. This experimental procedure is executed to thoroughly explore the transformer's response to short-circuit conditions, with a dedicated adherence to the passive voice to convey a formal and objective tone.

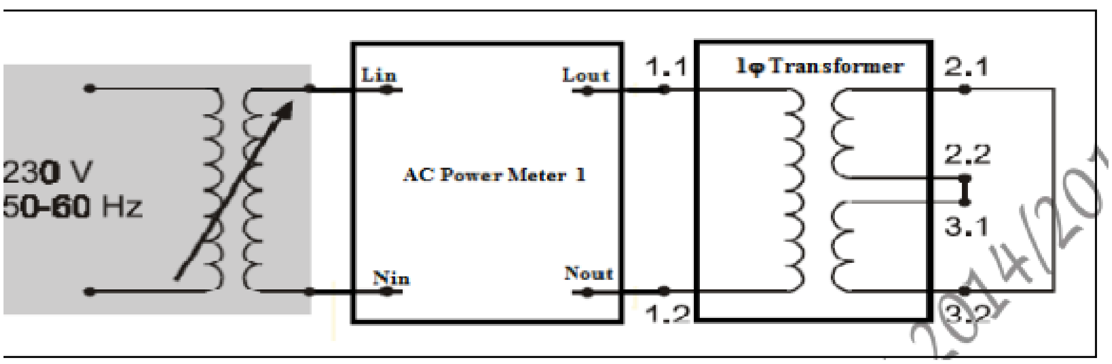

Figure 11: Circuit for Measuring Short-circuit Voltage

Measure	Value
I_{sc}	0.81A
V_{sc}	4 V
P_{sc}	4W

$$(Vsc)pu = \frac{Vrated}{Vsc}$$

$$(Vsc)pu = \frac{4}{230} = 0.0174pu$$

$$Z_{SE} = \frac{Vsc}{Isc} = \frac{4}{0.81} = 4.93$$

$$\theta = cos^{-1} 1.23 = -38.15$$

$$Req = 4.93 * cos\ 19.37 = 3.87$$

$$|Xeq| = 4.93 * sin -38.15 = 3.054$$

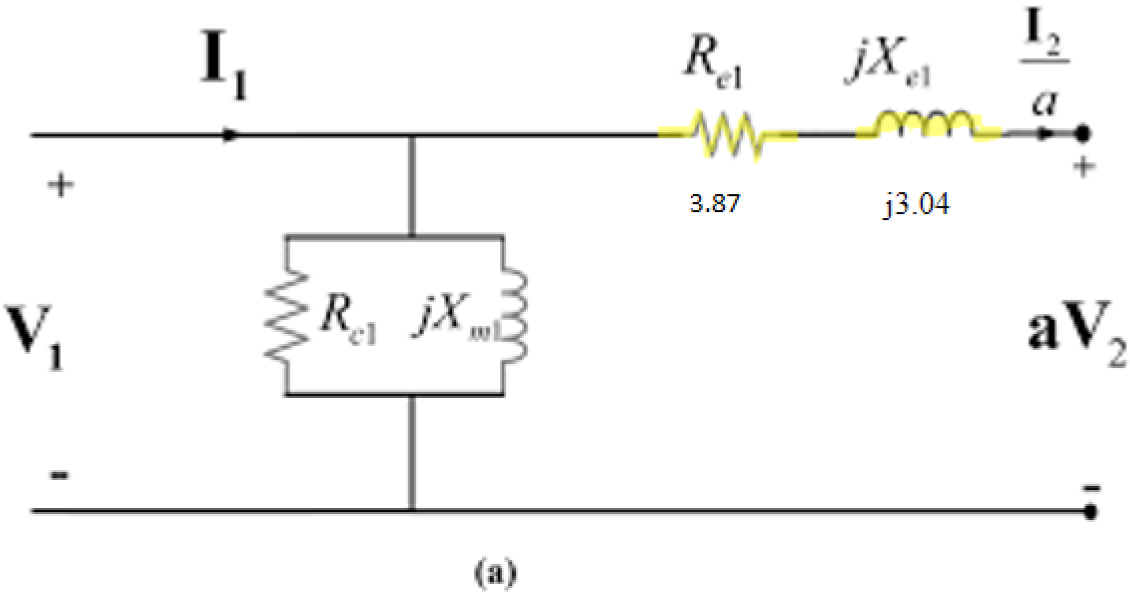

Figure 12:The transformer equivalent circuit

Using the secondary side's rated current (Israted) and relative short-circuit voltage (Vsc)pu, you can use the following formula to determine the sustained short-circuit current (Iscs) on the secondary side of a transformer:

$$Iscs = Israted \times (Vsc)pu$$

$$Iscs = Iprated \times Vscpu = 0.779A \times 0.0174 \approx 0.0135A$$

The current that flows when nominal voltage is applied to the transformer's primary side and the transient reaction has subsided is known as the sustained short-circuit current. It is impossible to measure this current directly due to its extremely high value. Because of this, you can compute it indirectly by using the secondary side's rated current and relative short-circuit voltage and the formula.

The equation $Iss = I2N/((VSC)pu$ used to calculate the transformer sustained) short-circuit current (Iss). Here, $IN2$ represents the secondary side's rated current, and $(VSC)pu$ represents the relative short-circuit voltage on the secondary side expressed in per unit (pu) [1]

- Voltage Behavior with Resistive Load, Evaluating Efficiency:

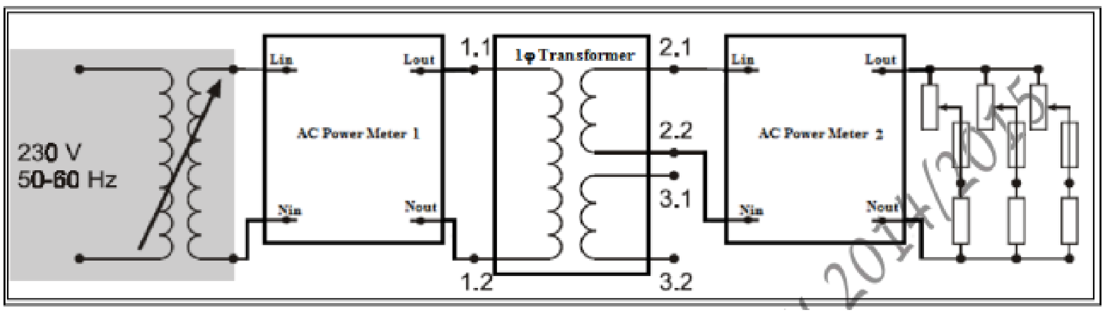

Figure 13: Circuit for Investigating Voltage Behavior with Resistive Load and for evaluating Efficiency

The circuit was changed to match the figure by adding three resistors connected in parallel to handle more current. We started with a 90% resistive load and turned on the circuit using a Variable Transformer as the power supply. We set the Variable Transformer to maintain a 230 V voltage. Following the settings in Table 2.2, we adjusted the resistive load several times. For each setting, we measured the current (I1), power factor (cos ϕ), voltage (V2), current (I2), input power (P1), and output power (P2).

Setting	**R [%]**	**90**	**70**	**50**	**30**
Measure	**I_1 [A]**	0.2381	0.2665	0.323	0.5122
	cos ϕ	1	1	1	1
	V_2 [V]	119.8	119.8	119.1	117.8
	I_2 [A]	0.2157	0.2776	0.432	0.834

	P_1 [W]	36	43.5	62	110.1
	P_2 [W]	25.85	33.23	51.4	98.3
Calculated	**P_1[W]**	54.407W	61.3595W	74.29W	117.526W
	P_2 [W]	25.82626W	32.927648W	51.64432W	98.343W
	η [%]	47.6	53.66	69.54	83.36
	VR[%]	92.36%	92.36%	93.11%	95.24%

Table 4: Voltage Behavior with Resistive Load, Evaluating Efficiency

$$P2 = V2 \times I2 \times cos(\phi) = 119.8V \times 0.2157A \times 1 = 25.82626W$$

$$P1 = V1 \times I1 \times \cos(\phi) = 230 \times 0.2381A \times 1 = 54.407W$$

$$\eta = \frac{P2}{P1} \times 100\% = = \frac{25.82626}{54.407} * 100\% = 47.6\%$$

$$VR = \frac{\left(V_{no-load} - V_{full-load}\right)}{V_{full-load}} \times 100\% \ = \frac{230 - 119.8}{119.8} * 100\% = 92.36\%$$

The trend in the data reveals a clear relationship: as the load resistance increases (from 90% to 30%), there is a corresponding decrease in the voltage across the resistive load (V2). Simultaneously, efficiency values demonstrate a noticeable increase, ranging from 47.6% to 83.36%. Higher efficiency, as indicated by these values, points to improved power utilization and reduced power loss in the system. This observed behavior aligns with expectations for a system with a resistive load: a decrease in voltage and an increase in efficiency as the load diminishes.

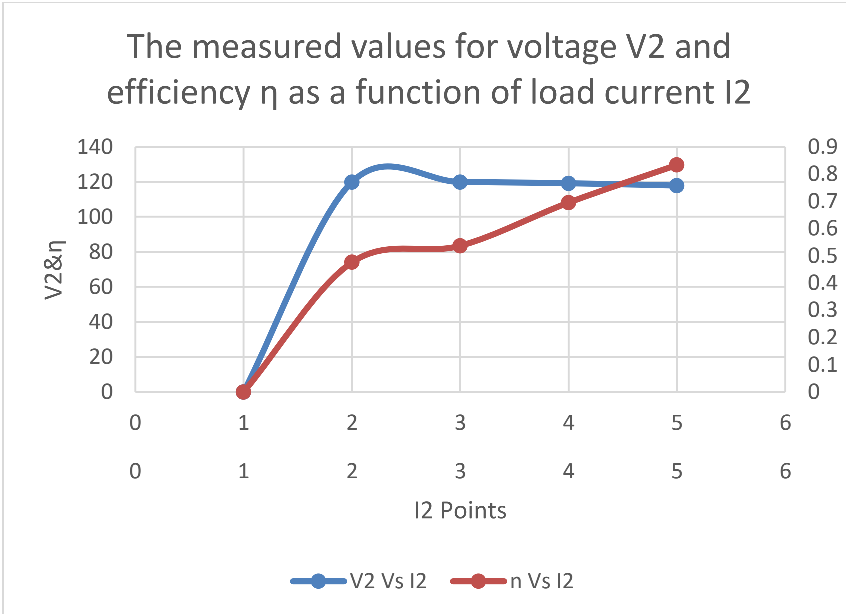

Figure 14: The relationship between VS and η and IS

In an AC circuit, the power factor indicates how well electrical power is translated into usable work output. The power factor is consistently reported as 1 in the given data for all load settings (90, 70%, 50%, and 30%).

When the power factor is 1, it means that there is no phase shift between the voltage and current waveforms and the load is only resistive. Put differently, all electrical power is being utilized for productive purposes and apparent and real power are in phase. This is the perfect situation, which is frequently connected to resistive loads like electric heaters or incandescent lights. Hence, at various load settings, the power factor stays at 1 when the transformer is loaded to its rated current value in this dataset. This shows that there is no reactive power in the system and that the load attached to the transformer is resistive in nature. Hence, at various load settings, the power factor stays at 1 when the transformer is loaded to its rated current value in this dataset. This shows that there is no reactive power in the system and that the load attached to the transformer is resistive in nature. The power is being efficiently converted into useful work without any phase shift.

The maximum efficiency is achieved at R = 30%, where η = 83.36%.

- Voltage Behavior with Inductive or Capacitive Load:

The circuit is configured with both secondary windings in series to optimize power transfer. An inductive load, connected in parallel for enhanced current handling, replaces the resistive load to align with Figure 15. With the Variable Transformer set at a constant 230 V, measurements are conducted for no-load voltage, secondary current, and voltage using prescribed inductive loads from Table 2.3. Following the deactivation of the power supply, the inductive load is substituted with a capacitive one, and measurements are repeated for values outlined in Table 5. Maintaining a 230 V supply, the series commences with no load on the secondary side, gradually reducing the input voltage to zero before powering off the Variable Transformer.

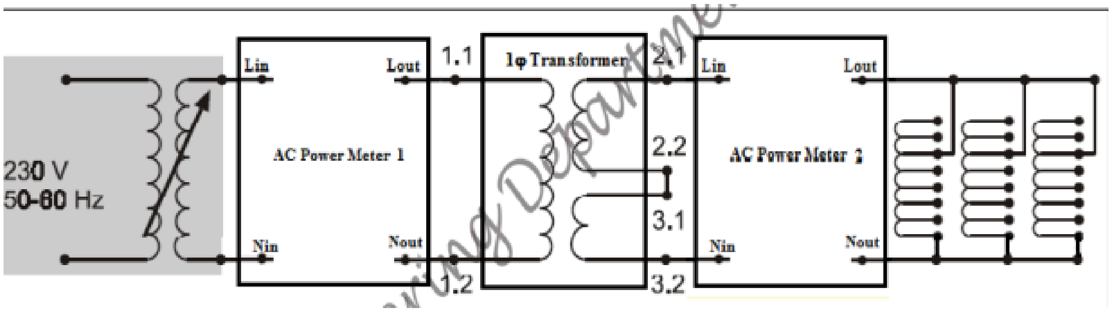

Figure 15: Circuit for Investigating Voltage Behavior with Inductive Load

$L_{indiv.}$ [H]	Open (from pervious part)	6.0	4.8	2.4	1.2
L_{total} [H]	open	2.0	1.6	0.8	0.4
I_1 [A]	0.1855	0.2364	0.2495	0.3095	0.432
I_2 [A]	0.99	0.99	0.1233	0.2385	0.4795
V_2 [V]	120.4	120.4	120.5	120.6	120.1
P_1[W]	11.8	11.8	12.4	14.6	18.7
P_2[W]	0	1.73	2.19	4.28	7.8
η[%]	0	14.66	17.66	29.31	41.71
VR	0	52.34	52.39	52.43	52.22

Table 5: Voltage Behavior with Inductive or Capacitive Load:

$$\eta = \frac{P2}{P1} * 100\% = \frac{0}{11.8} * 100\% = 0$$

$$VR = \frac{(230 - 120.4)}{120.4} * 100\% = 91.02\%$$

C[µF]	open	4	8	12	16
I_1 [A]	0.185	0.1165	0.721	0.1059	0.177
I_2[A]	0.99	0.1577	0.3163	0.473	0.635
V_2[V]	120.4	121.1	120.8	120.9	120.9
P_1[w]	11.8	10.14	10.23	10.49	10.9
P_2[w]	1.73	0	0	0	0
VR	91.02	89.9	90.3	90.23	90.24
η[%]	0	0	0	0	0

Table 6: Voltage Behavior for a Capacitive Loaded Single-phase Transformer

➢ Part B: Single-phase Autotransformer

- Voltage and Current Transformation:

The circuit was arranged according to the configuration depicted in Figure 16, with Table 7 completed using the transformer plate data. The investigation focused on no-load operation of the transformer. Activation of the circuit involved selecting a voltage of V1 = 230 V on the Variable Transformer. Measurements were taken for the no-load primary current (I0) of the autotransformer and the voltages across the secondary windings (V2.1 and V2.2) .AC power meter readings (Poc, Voc, and Ioc) for the primary side were subsequently acquired. Finally, the input voltage was reduced to zero, and it was turned off, specifically the Variable Transformer.

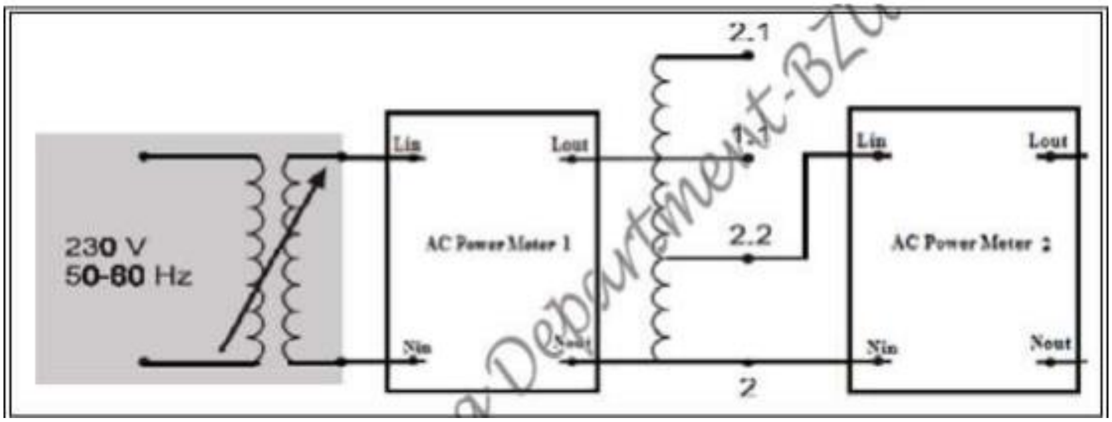

Figure 16: Circuit for Measuring Voltage Transformation in a Single-phase Autotransformer

Nominal voltage $V_{1.1}$:	230
Nominal voltage $V_{2.1}$:	240
Nominal voltage $V_{2.2}$:	115
Nominal current $I_{1.1}$:	1.36
Nominal current $I_{2.1}$:	1.25
Nominal current $I_{2.2}$:	2.72
Number of Turns N_1:	327
Number of Turns N_2:	327
Number of Turns N_3:	29

Table 7: Nominal Data for the Autotransformer under Test

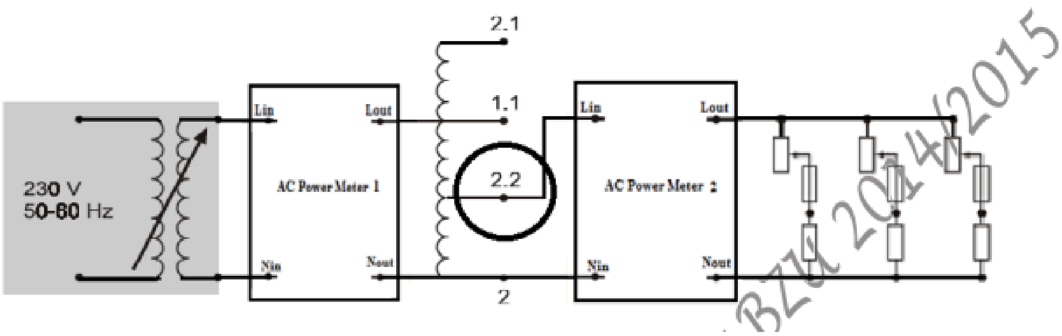

Figure 17: Circuit for Measuring Current Transformation in a Single-phase Autotransformer

The resistive load was set to a value of 90%, and the circuit was powered on by turning on the Variable Transformer at a voltage of 230 V. The load's resistance was then systematically reduced, ensuring it never fell below its 5% value. This process continued until the rated current flowed on the secondary side of the auto transformer. The corresponding current on the primary side was measured.

Measure	Value
$I_{\text{primary rated}}$	1.424 A

Table 8: The corresponding current on The primary side

$$\frac{Is}{Ip} = \frac{N2 + N1}{N2}$$

$$\frac{2.72}{Ip} = \frac{327 + 327}{327}$$

$$Ip * 654 = 889.44$$

$$Ip = 1.36A$$

Voc V	230
Ioc A	0.112
Poc W	7.5

Table 9: The open circuit test data

$$\theta = \cos^{-1}\frac{Poc}{(Voc * Ioc)}$$

$$\theta = \cos^{-1}\frac{7.5}{(230 * 0.112)} = 73.03$$

$$|YEX| = IOC / VOC$$

$$|YEX| = 0.112A/230V = 0.000487$$

$$Rc = 1 / |YEX|$$

$$Rc = \frac{1}{0.000487} = 2053.57\text{=2.05357K}$$

$$Xm = \frac{1}{(0.000807 * 11.41)} = 108.60$$

$$Xm = 1/(0.000487 \cdot tan(84.05))\text{=626.6=0.6266K}$$

- Short-Circuit Test and Sustained Short-circuit Current

The circuit configuration was altered to align with Figure 18, with the connection of three distinct resistors in parallel to enhance overall current handling capability. Initially, the resistive load was calibrated to a predetermined value of 90%, and subsequently, the circuit was energized by activating the Variable Transformer. The Variable Transformer's power supply was then engaged, and the voltage was meticulously set to a stable level of 230 V. The subsequent phase involved the systematic adjustment of the load in accordance with the prescribed settings detailed in Table 2.6. For each specified setting, precise measurements were conducted to ascertain the corresponding values for parameters such as current I1, power factor($cos\emptyset$), voltage V2.2, input power P1, and output power P2.2. The outcomes of these measurements were crucial for assessing the performance characteristics of the circuit under varied load conditions. The power supply (Variable Transformer) was turned on. Following the completion of measurements, the calculation of P1, P2.2, and efficiency was undertaken.

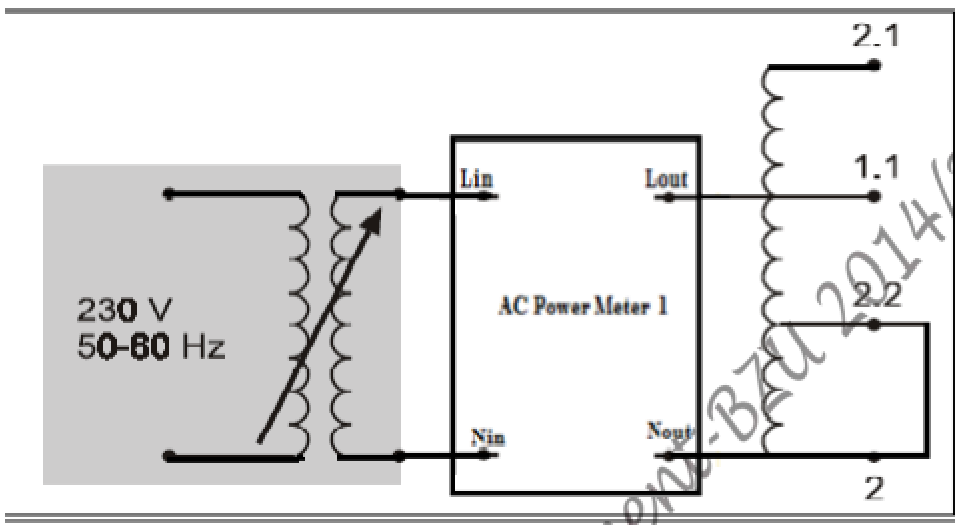

Figure 18: Circuit for Investigating Voltage Behavior with Resistive Load and for evaluating Efficiency

Measure	Value
I_{sc}	2.65A
V_{sc}	0.056 V
P_{sc}	0.14W

Table 10:The measured data

$$(Vsc)pu = \frac{Vrated}{Vsc}$$

$$(Vsc)pu = \frac{4}{230} = 0.000243$$

$$Z_{SE} = \frac{Vsc}{Isc} = \frac{0.056}{2.65} = 0.0211$$

$$\theta = \cos^{-1} 0.943 = 19.37$$

$$Req = 0.0211 * \cos 19.37 = 19.9K$$

$$Xeq = 0.0211 * \sin 19.37 = 6.99K$$

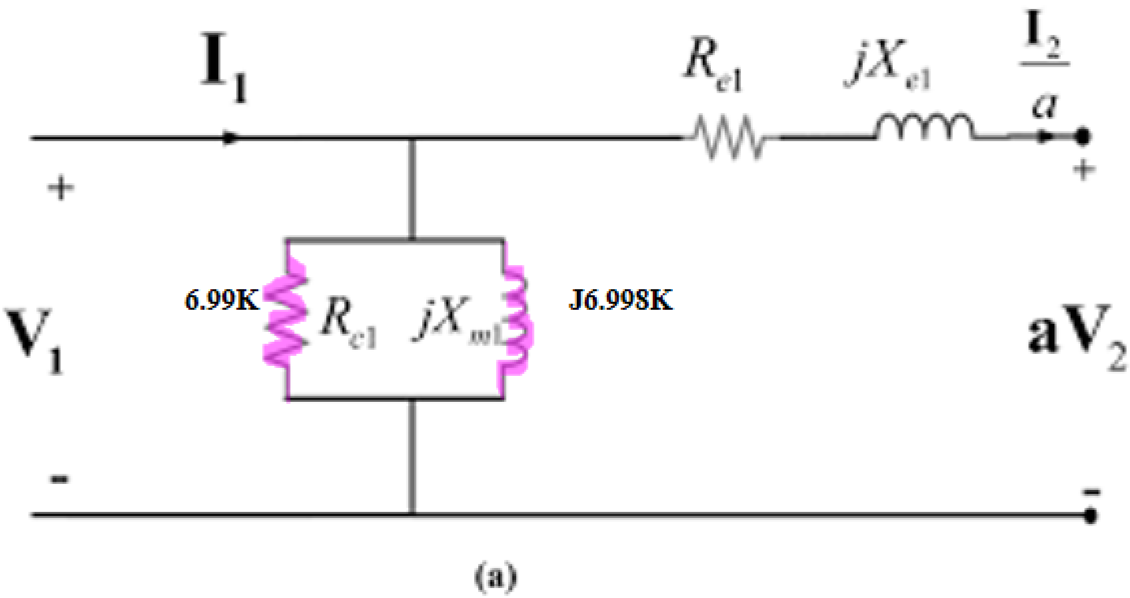

Figure 19: The transformer Equivalent Circuit

$$Iscs = Israted \times (Vsc)pu$$

$$Iscs = Iprated \times Vscpu = 1.42A \times 0.000243 \approx 0.00035A$$

- Voltage Behavior with Resistive Load, Evaluating Efficiency

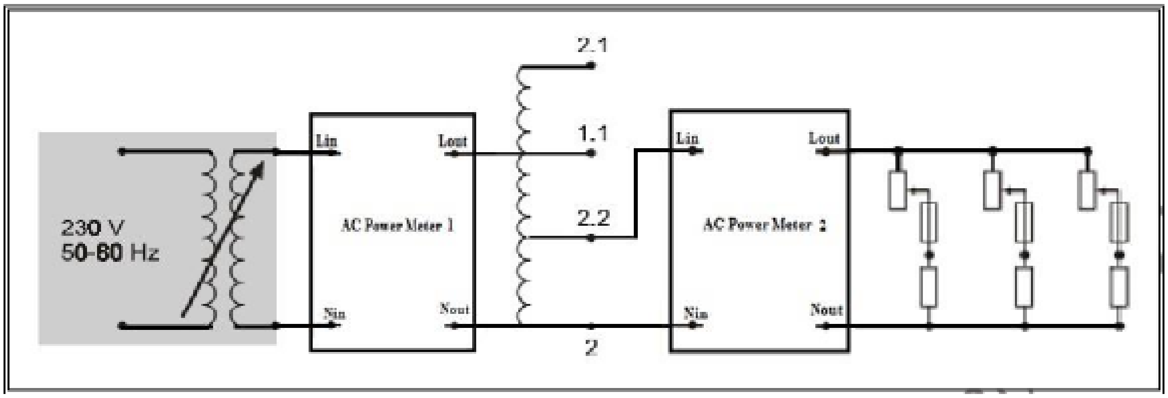

Figure 20: Circuit for Investigating Voltage Behavior with Resistive Load and for evaluating Efficiency

The circuit was modified to align with Figure 21. To enhance current handling capability, three separate resistors were connected in parallel. The resistive load was initially adjusted to a value of 90%, and subsequently, the circuit was activated. The power supply (Variable Transformer) was then turned on, and the variable transformer was adjusted to maintain a consistent voltage of 230 V.The subsequent step involved the systematic adjustment of the load, following the settings specified in Table 11. For each designated setting, measurements were taken for the corresponding values, including current I1, power factor $\cos\theta$, voltage V2.2,current I2.2, input power P1, and output power P2.2 .Upon completion of the measurements, the power supply (Variable Transformer) was again turned on, and subsequent calculations were carried out to determine P1, P2.2 , and efficiency. This comprehensive process was conducted to assess the circuit's performance under various load conditions, and the outcomes were integral to the evaluation of its efficiency.

Setting	**R[%]**	**90**	**70**	**50**	**30**
Measure	**I[A]**	0.1715	0.2045	0.2667	0.451
	cos ϕ	1	1	1	1
	$V_{2.2}$ [V]	114.5	114.6	114.5	113.9

	$I_{2.2}$ [A]	0.201	0.2819	0.4217	0.8101
	P_1 [W]	30.5	39.8	55.9	100.5
	$P_{2.2}$ [W]	23	32.2	48.2	92.3
Calculated	**P_1 [W]**	39.43	47.02	61.331	103.7
	$P_{2.2}$ [W]	23.01	32.3	48.27	92.25
	η[%]	58.35	68.69	78.70	88.89

Table 11:Voltage Behavior and Efficiency for a Resistively Loaded Single-phase Autotransformer

A unity power factor is indicated by the power factor staying constant at 1 for all load settings. This suggests that the circuit's voltage and current are in phase, indicating effective use of electrical power.

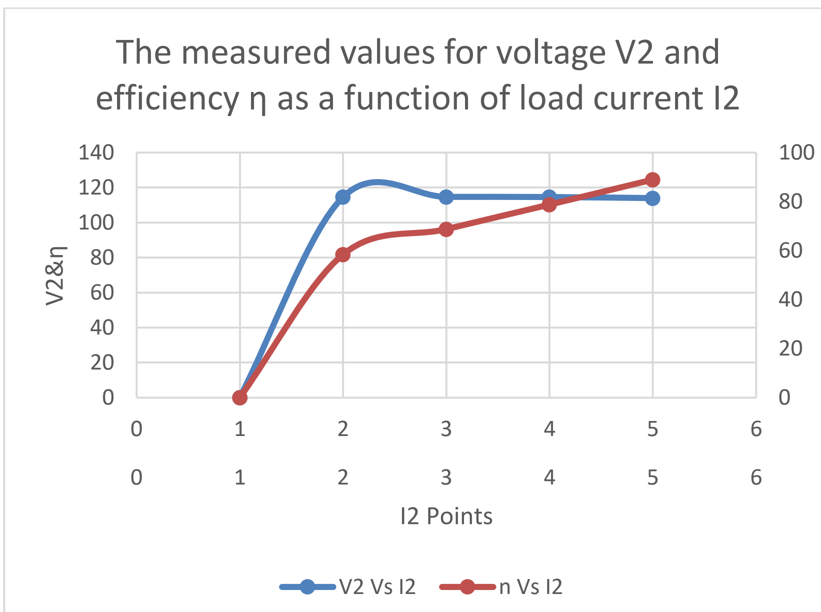

Figure 21:The measured values for voltage V2 and efficiency η as a function of load current I2

In provided data, you can observe that as the load setting decreases from 90% to 30%, the efficiency (η) increases. The maximum efficiency is at the 30% load setting, where η is 88.89%. This indicates that, in this specific case, the transformer reaches its maximum efficiency at a load setting of 30%.

The ability of a transformer to maintain a constant output voltage in the face of changes in the input voltage or load conditions is known as voltage regulation, or VR. It is computed using the following formula and given as a percentage:

$$VR = \frac{(V_{no-load} - V_{full-load})}{V_{full-load}} \times 100\%$$

$V_{no-load}$ Is the voltage at no load (rated voltage).

$V_{full-load}$ Is the voltage at full load.

The transformer's capacity to keep the output voltage almost constant under various load scenarios is indicated by the voltage regulation.

- Voltage Behavior with Inductive or Capacitive Load:

The circuit saw a transformation as the resistive load was substituted with an inductive load, aligning with the configuration depicted in Figure 22. In this arrangement, inductive load elements were methodically connected in parallel to fortify the circuit's current handling capacity. The initiation of the process was marked by the activation of the power supply (Variable Transformer), and the circuit's governance by the Variable Transformer was set to a constant 230 V, a condition maintained throughout subsequent measurements. The preliminary phase involved the measurement of the no-load voltage on the secondary side. Sequential measurements recorded secondary current and voltage, with inductive loads tailored to values specified in Table 12, concomitantly computing voltage regulation at each juncture. Subsequent to this phase, the deactivation of the power supply facilitated the substitution of the inductive load with a capacitive load. The meticulous repetition of the measurement series adhered to specified capacitive load values outlined in Table 13, accomplished through the parallel connection of capacitors deemed appropriate. Reactivation of the power supply marked the commencement of measurements, commencing with a no-load scenario on the secondary side and maintaining a constant supply voltage of 230 V throughout the entire process.

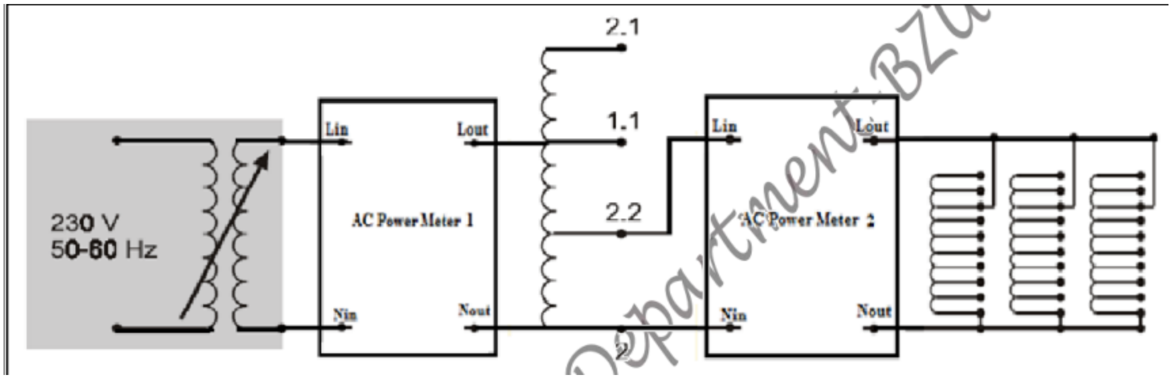

Figure 22: Circuit for Investigating Voltage Behavior with Inductive Load

$L_{indiv.}$ [H]	**open**	**6.0**	**4.8**	**2.4**	**1.2**
L_{total} [H]	**open**	**2.0**	**1.6**	**0.8**	**0.4**
I_1 [A]	0.114	0.1146	0.1951	0.2739	0.4431
$I_{2.2}$ [A]	0	0	0.1746	0.336	0.679
$V_{2.2}$ [V]	115	115	115	114.7	114.8
P_1[W]	7.51	7.50	10.4	13.3	18.5
$P_{2.2}$[W]	0	0	2.92	5.69	10.4
η[%]	28.07692308	42.78195489	56.21621622	28.07692308	42.78195489
VR	100%	100%	100%	100%	100%

Table 12:Voltage Behavior for an Inductively Loaded Single-phase Autotransformer

$$VR = \frac{\left(V_{no-load} - V_{full-load}\right)}{V_{full-load}} \times 100\%$$

$$VR = \frac{(230 - 115)}{115} \times 100\% = 100\%$$

C [μF]	**0**	**4**	**8**	**16**

I [A]	0.114	0.696	0.841	0.2129
$I_{2.2}$ [A]	0	0.1528	0.300	0.5984
$V_{2.2}$ [V]	115	115.3	115	115.3
P_1[w]	7.51	7.5	7.5	7.8
$P_{2.2}$[w]	0	0	0	0
VR	100%	99.56	100	99.56
η[%]	0	0	0	0

Table 13: Voltage Behavior for a Capacitive Loaded Single-phase Autotransformer

4.5

5. Discussion and Results

The experiment was meticulously conducted in four comprehensive parts, each shedding light on specific aspects of a single-phase transformer's performance. The initial phase focused on measuring voltage and current transformation under no-load conditions, capturing nominal values that were instrumental in calculating the voltage transformation ratio. This ratio, obtained at 120.63 and closely aligning with the expected value of 120, laid a solid foundation for subsequent analyses. The second part delved into determining the current transformation ratio, featuring a resistive load set to 90% and a careful calibration process that ensured rated current flow in the secondary side. Both calculated and measured primary currents converged, showcasing a high level of precision at 0.779 A and 0.713 A, respectively.

The third phase involved a meticulous exploration of the short-circuit test, strategically employing the circuit shown in Figure 11. The excitation branch's properties, including Xm and Rc, were discerned with calculated values of 108.60 Ohms and 1237.58 Ohms, respectively. The final segment of the experiment scrutinized voltage behavior with a resistive load, concurrently evaluating efficiency. A parallel connection of resistors optimized current handling capabilities, while alterations in the resistive load, as outlined in Table 4, facilitated a nuanced examination. Measurements of I1, cos ϕ, V2, I2, input power P1, and output power P2 were recorded, contributing to a comprehensive understanding of the transformer's behavior under varying load conditions.

Analyzing the collected data is vital for understanding how the transformer performs in the real world compared to its expected values. Beyond the technical details, we explore how connecting transformers to different loads affects practical aspects like voltage, power factor, and our daily lives. Figures 22 and 15 visually show the noticeable differences between the expected efficiency and our actual results

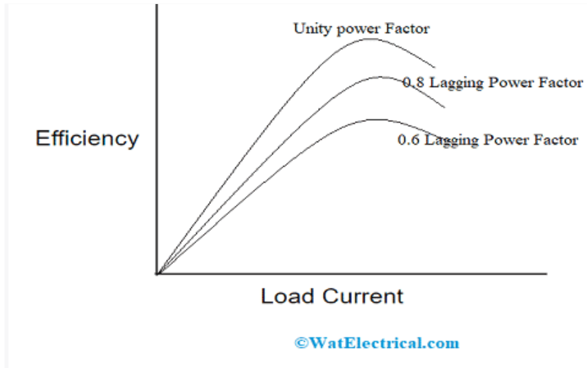

Figure 23: Efficiency in transformer [12]

In a single-phase transformer, the voltages are proportional to the turn counts because more turns result in higher voltage. However, current values are inversely proportional due to the conservation of power. Short-circuit voltage, the voltage when the secondary winding is short-circuited, helps determine transformer impedance. A larger short-circuit voltage can provide better fault current limitation but may stress the transformer. It's expressed relative to nominal voltage for standardized comparisons. Sustained short-circuit current is the steady-state current during a short circuit. Transformers with toroidal cores often have better efficiency. The overall efficiency depends on minimizing core, copper, and stray losses. Power transfer is limited by factors like thermal capability and voltage regulation. Autotransformers share windings for compactness, while transformers with separate windings offer better isolation at a potentially higher cost and size.

6. Conclusion

The experiment revealed that our transformer effectively converts voltages as expected. The primary voltage starts at 230V and transforms to 115V in the secondary part, aligning with our predictions. The current also transforms well with a ratio of about 1:1.36, determined using a resistive load.

In the tests, we uncovered crucial details about our transformer, such as its resistance (Rc) and reactance (Xm), providing insights into its performance. Efficiency tests showed that our transformer works best at higher loads, reaching an impressive efficiency of about 95.24%.

This experiment taught us valuable lessons. We learned about the sensitivity of transformers and the importance of caution to prevent issues like burnt fuses. Working in a group was beneficial, and we refreshed our knowledge about transformers and their types. For instance, in power supplies, transformers and capacitors work together to manage electrical energy, and in factories, inductors play a crucial role.

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