UoG-UESTC
Power Engineering 3

Lab 2 Single Phase Transformer Laboratory

Introduction

Transformers are one of the principle reasons why we have AC Power Networks as opposed to DC systems. Their ability to provide a (relatively!) cheap and reliable means of converting AC voltage levels results in high efficiency AC power transmission. In this series of experiments you will investigate the main features of a small single phase transformer, and by the end of the laboratory you should have a good understanding of the following:

- The Ideal Transformer equations
- The equivalent circuit for a practical single phase transformer
- The Open Circuit & Short Circuit Tests to determine equivalent circuit parameters
- Using the equivalent circuit to predict transformer performance
- Transformer Voltage Regulation & Efficiency under load
- The Transformer Voltage and Current Limits

Note:

- Before switching on the power supply, ask the demonstrator to check and ensure your circuit connection is correct **!!!**
- After each experiment measurement, remember to reset the output of the power supply to 0V and turn off the power supply !!!

Assessment

The 3 laboratory sessions account for 15% of your final mark in Power Engineering 3. You should have with you a bound laboratory book (with graph paper). Record ALL your measured results and any subsequent calculations in your bound laboratory book during the laboratory session, also fill out the necessary results in this lab sheet (this makes it easy for me to check your results during the session).

At some point after the lab session you need to write up the results (neatly!) and complete the associated analysis/theory sections before handing in your lab books before the end of the semester.

Note that you will not be assessed during the laboratory session so please communicate freely with supervisor/demonstrators – we are here to help you obtain accurate results and to help with any questions you have relating to the associated theory.

Experiment 1: Determining the Transformer Turns Ratio

The equivalent circuit for an **Ideal** Transformer is shown on figure 1 where N_P is the number of turns on the primary winding and N_S is the number of turns on the secondary. The corresponding relationships between primary and secondary voltages and currents are as follows:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} \qquad \frac{I_P}{I_S} = \frac{N_S}{N_P}$$

N_P/N_S is termed the Turns Ratio

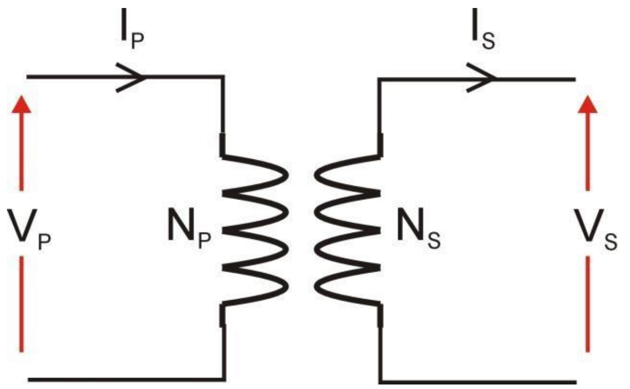


Figure 1: The Ideal Transformer

Clearly the Turns Ratio is very important in defining the operation of a transformer (note: it is used in the equivalent circuit for the practical transformer as well!) and in this first experiment we will determine this turns ratio from measurement:

The experimental setup for this experiment is shown on figure 2. The Turns Ratio can be calculated by measuring the Open Circuit Secondary Voltage (V_{SOC}) at a given Primary Voltage (V_P) and then using the voltage ratio (V_P/V_{SOC}) to calculate the turns ratio.

Experimental Procedure:

1. Set the AC power supply voltage to zero (**Voltage Adjust** knob should be turned fully counter-clockwise until it hits the end-stop).
2. Select one single-phase transformer on Module DJ11, whose nominal parameters are P_N=77V·A， U_{1N}/U_{2N}=220/55V， I_{1N}/I_{2N}=0.35/1.4A. Connect the power supply, meters and transformer as shown in Figure 2, where secondary side of the transformer is open circuit.
3. Turn on the AC power supply.

4. Adjust AC power supply voltage (using Voltage Adjust knob) until approximately the primary side voltage V_p=1.2U_{2N} (about 66V) at the primary side of the transformer is displayed on the Voltmeter. Record the primary side voltage V_P and secondary side voltage V_{SOC} in the Table 1.
5. Gradually reduce the primary side voltage V_P. Record V_P and V_{SOC} within the range of V_p=1.2~0.3 U_{2N}.
6. Adjust the AC power supply voltage to zero.
7. Turn off the AC power supply.

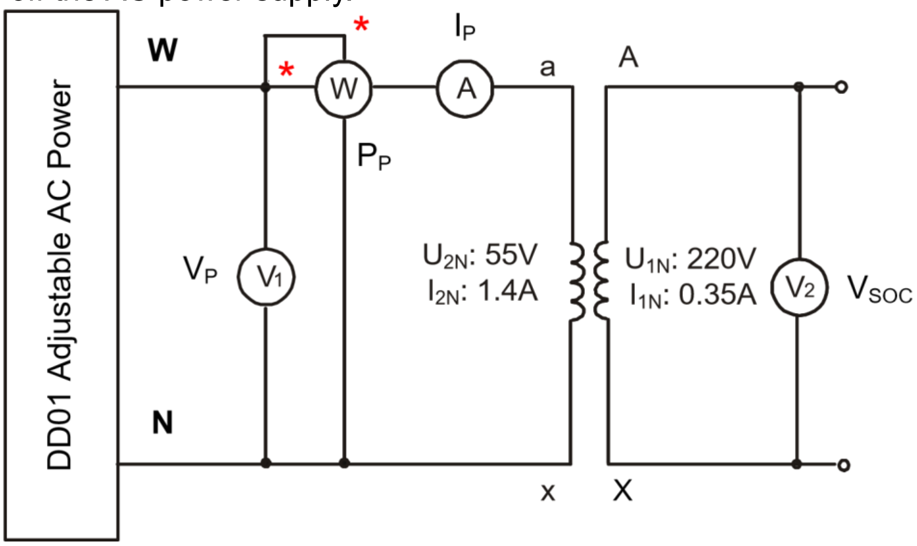


Figure 2: Experiment 1 Setup

Using the measured values of primary and secondary voltages, and the Ideal Transformer voltage equation shown above determine the transformer Turns Ratio:

Table 1. Turns Ratio Test

No.	**1**	**2**	**3**	**4**	**5**	
V_P (V)	16.5	21.5	26.5	31.5	36.5	
V_{soc} (V)	67.3	85.1	104.4	126.2	143.9	
Turns Ratio	0.245	0.253	0.254	0.249	0.253	
No.	**6**	**7**	**8**	**9**	**10**	
V_P (V)	41.5	46.5	51.5	56.5	61.5	66.5
V_{soc} (V)	163.5	183.0	209	225	246	287

Turns Ratio	0.254	0.254	0.246	0.251	0.25	0.232

Note: The low voltage side winding (i.e. primary side nominal values are 55V 1.4A) of the transformer is connected to the power supply, the high voltage side winding acts as the secondary side.

Experiment 2: Determining the practical Transformer Equivalent Circuit

As will be outlined in the lectures the practical transformer has an equivalent circuit which takes into account issues such as wiring copper loss, leakage inductance, magnetising current and iron loss. The complete equivalent circuit for a transformer is shown on Figure 3.

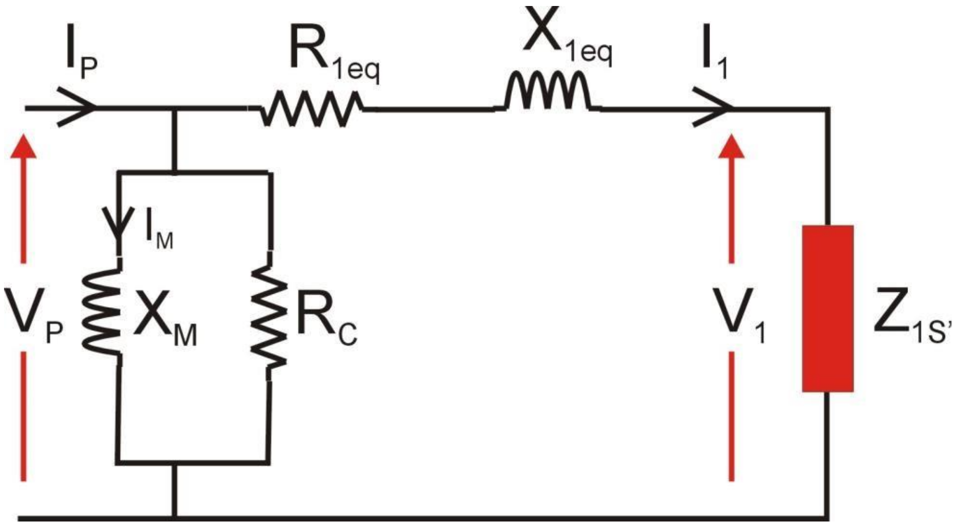


Figure 3: Transformer Equivalent Circuit

The purpose of the next couple of tests is to determine values for the transformer parameters R_{1eq}, X_{1eq}, X_M and R_C.

Experiment 2A: Open Circuit Test (to determine X_M and R_C)

In this experiment the secondary winding is open circuit ($Z_{1S'}$ is Open Circuit) and therefore I_1 = 0A and the equivalent circuit simplifies to that shown on Figure 4.

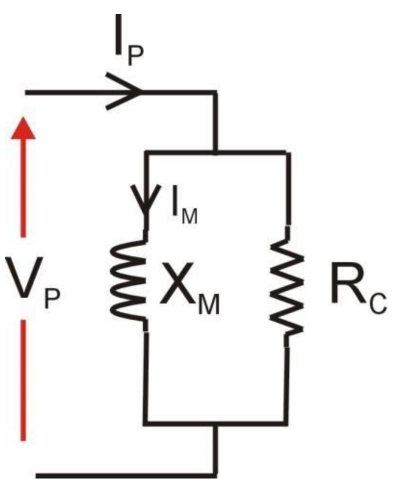


Figure 4: Open Circuit Test Equivalent Circuit

Notice that we have one resistive component R_C and one inductive component X_M. By knowing (hopefully!) that **REAL** Power is associated with the resistance and **REACTIVE** power is associated with inductance we can determine each of these components by simply measuring primary voltage (V_P), primary current (I_P) and primary real power (W) and using the following primary circuit relationships:

Parameter	Units	Equation
Real Power	W	$P_P \quad \frac{V_{P2}}{R_C}$
Apparent Power	VA	$S_P \quad V I_{P P}.$
Reactive Power	VAr	$Q_P \quad \sqrt{S_P^2 \quad P_P^2}$
Reactive Power	VAr	$Q_P \quad \frac{V_{P2}}{X_M}$

For the circuit shown in Figure 2, repeat the test outlined in Experiment 1 but this time record primary voltage (V_P), primary current (I_P) and primary real power (P_P). From test results and above equations determine values for R_C and X_M:

Table 2. Open Circuit Test

No.	**1**	**2**	**3**	**4**	**5**	
V_P (V)	16.5	21.5	26.5	31.5	36.5	
I_P (A)	0.011	0.014	0.016	0.019	0.022	
P_P (W)	0.1	0.3	0.3	0.5	0.7	
S_P (VA)	0.1815	0.301	0.424	0.5985	0.803	
Q_P (VAr)	0.1	0.3	0.3	0.5	0.7	
X_M (Ω)	2722.5	1540.833	2340.833	1984.5	1903.214	
R_C (Ω)	2722.5	1540.833	2340.833	1984.5	1903.214	
No.	**6**	**7**	**8**	**9**	**10**	

V_P (V)	41.5	46.5	51.5	56.5	61.5	66.5
I_P (A)	0.024	0.028	0.034	0.038	0.051	0.067
P_P (W)	0.9	1.1	1.3	1.5	1.7	1.9
S_P (VA)	0.996	1.302	1.751	2.147	3.1365	4.4555
Q_P (VAr)	0.9	1.1	1.3	1.5	2.5	3.9
X_M (Ω)	1913.611	1965.682	2040.192	2128.167	1512.9	1133.91
R_C (Ω)	1913.611	1965.682	2040.192	2128.167	2224.853	2327.5

Note: The Power Meter current and power values may be in milliamps and milliwatts

Experiment 2B: Short Circuit Test (to determine R_{1eq} and X_{1eq})

In this experiment (see next page for setup) the secondary winding is short circuit ($Z_{1s'} = 0\Omega$) and as a result I_1 current will flow in the primary. Under short circuit conditions I_1 is very much bigger than magnetising and iron loss currents and so these elements can be ignored and the equivalent circuit simplifies to that shown on figure 5.

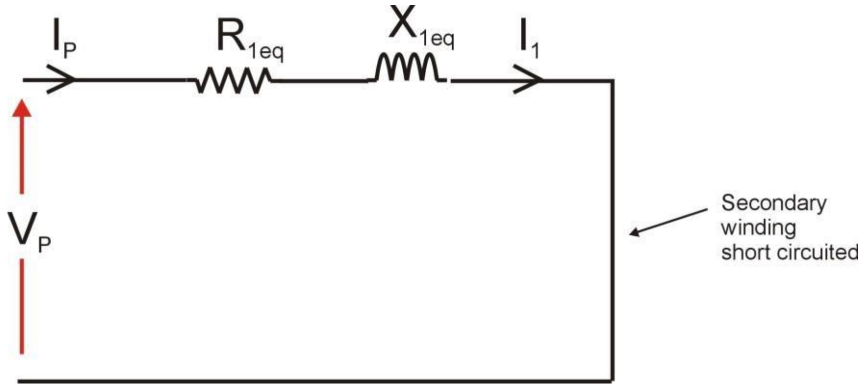


Figure 5: Short Circuit Test Equivalent Circuit

Once again we have one resistive component (R_{1eq}) and one inductive component (X_{1eq}) so knowing that **REAL** Power is associated with the resistance and **REACTIVE** power is associated with inductance we can determine each of these components by simply measuring primary voltage (V_P), primary current (I_P) and primary real power (P_P) and using the following relationships:

Parameter	Units	Equation
Real Power	W	$P_P \quad I_P^{\;2}.R_{1eq}$
Apparent Power	VA	$S_P \quad V I_{P\,P}.$

Reactive Power	VAr	$Q_P \quad \sqrt{S_P^2 \quad P_P^2}$
Reactive Power	VAr	$Q_P \quad I_P{}^{2}.X_{1eq}$

The experimental setup is shown on Figure 6.

Note that this test is carried out at **reduced** supply voltage so ensure the AC power supply voltage is set to **zero** before switching on !!!

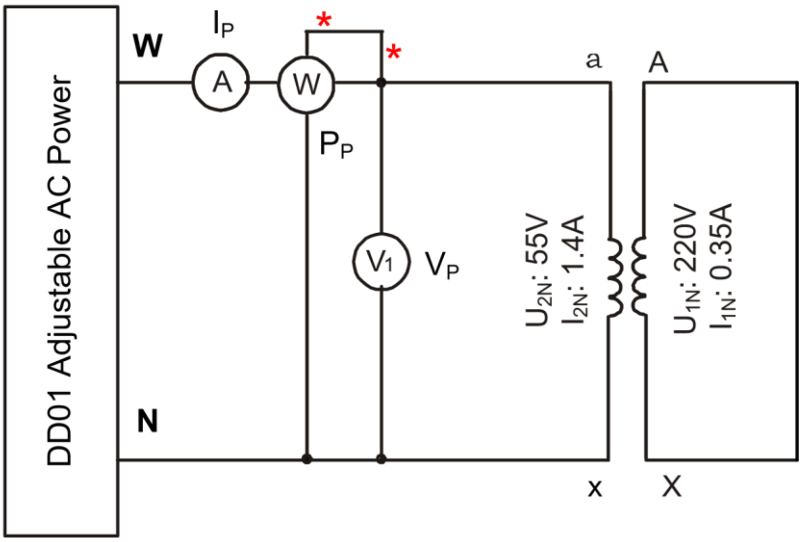


Figure 6: Short Circuit Test Setup

Experimental Procedure:

1. Turn off the AC power supply and set the AC voltage to zero.
2. Connect a short circuit wire across the transformer Secondary winding as shown on Figure 6, where secondary side of the transformer is short circuit.
3. Turn on the AC power supply and slowly increase the voltage until approximately the primary current $I_P=1.1I_{2N}$ 1.54A. (V_p is about 7 volts !!!)

4. Gradually reduce the primary voltage V_P, record voltage (V_P), current (I_P) and power (P_P) within the range of I_P=0.2~1.1 $\mathbf{I}_{2N}$.
5. Reduce the AC voltage to zero and turn off the AC power supply.
6. From the test results and above equations determine values for R_{1eq} and X_{1eq}.

Note: If Primary Real Power > Primary Apparent Power then assume Q_P = 0 (this is a result of some assumptions in the equivalent circuit which are not valid for a transformer this size)
If you found any meter reading is weird (too larger or smaller than expected value), please turn off the power supply and set the AC voltage to zero immediately!!! Recheck your circuit connection!!!

Table 3. Short Circuit Test

No.	**1**	**2**	**3**	**4**	**5**	
V_P (V)	4.7	4.5	4.5	4.7	5.6	
I_P (A)	0.28	0.41	0.54	0.67	0.80	
P_P (W)	0.175	0.175	0.22	0.5	0.7	
S_P (VA)	1.316	1.845	2.43	3.149	4.48	
Q_P (VAr)	0.438	0.433	0.36	1.4	2.4	
X_{1eq} (Ω)	5.586735	2.575848	1.234568	3.118735	3.75	
R_{1eq} (Ω)	2.232143	1.041047	0.754458	1.113834	1.09375	
No.	**6**	**7**	**8**	**9**	**10**	
V_P (V)	5.3	5.8	6.2	6.9	7.2	7.8
I_P (A)	0.93	1.06	1.19	1.32	1.45	1.58
P_P (W)	1.7	2.5	3.2	4.1	4.6	5.6
S_P (VA)	4.929	6.148	7.378	9.108	10.44	12.324

Q_P (VAr)	3.6	4.8	5.7	7.4	8.3	10.2
X_{1eq} (Ω)	4.162331	4.271983	4.025139	4.247016	3.947681	4.085884
R_{1eq} (Ω)	1.965545	2.224991	2.259727	2.353076	2.187872	2.24323

Note: The low voltage side winding (i.e. primary side nominal values are 55V 1.4A) of the transformer is connected to the power supply, the high voltage side winding acts as the secondary side.

From your results fill in the component values of the complete transformer equivalent circuit shown on Figure 7. Also note that the value of $Z_{1s'}$ (secondary load impedance REFERRED TO THE PRIMARY SIDE) is equal to the (turns ratio)^2 x Secondary Impedance (Z_s). Calculate the value for (turns ratio)^2 based on your measured value for turns ratio and put this value in the box below $Z_{1s'}$ in Figure 7.

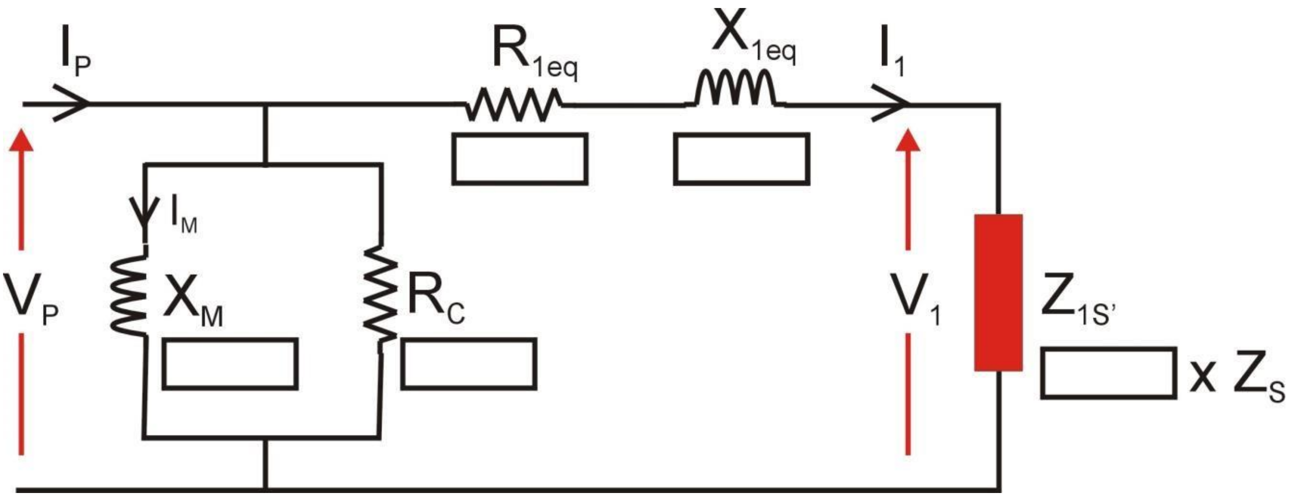


Figure 7: Measured Transformer Equivalent Circuit

Using the Equivalent Circuit to Predict Transformer Performance

The purpose of the equivalent circuit is to be able to predict transformer performance (output voltage, current, power, efficiency etc) for a given load. You can therefore use your equivalent circuit to calculate transformer performance for a given secondary load impedance and input voltage.

Theory:

Calculate the following parameters using your equivalent circuit for a primary voltage (V_p) of 55V and a 628Ω load resistance (Z_s) connected across the secondary winding:

1. Output Current (I_S)

2. Output Voltage (V_S) - plot this value on the previous graph of Output Voltage v Output Current
3. Output Power
4. Voltage Regulation
5. Transformer Copper Loss (W) (hint: associated with R_{1eq})
6. Transformer Iron Loss (W) (hint: associated with R_c)
7. Transformer Efficiency

Note: **The low voltage side winding (i.e. primary side nominal values are 55V 1.4A) of the transformer is connected to the power supply, the high voltage side winding (i.e. secondary side nominal value is 220 0.35A) is connected to the load resistance.**

Steps:

1. Calculate $Z_{1s'}$ based on (turns ratio)^2 x 628Ω
2. Using the equivalent circuit on Figure 7 calculate I_1 (hint: ignore X_m and R_c components)
3. Using the equivalent circuit on Figure 7 calculate V_1 (hint: $V_1 = I_1 . Z_{1s'}$)
4. The secondary output voltage and current are derived from I_1 and V_1 through the following relationships (where Np/Ns is the turns ratio):

$$V_S \quad \frac{N_S}{N_P}.V_1 \qquad I_S \quad \frac{N_P}{N_S}.I_1$$

Parameter	Value	Units
Output Current (I_S)	0.308	A
Output Voltage (V_S)	193.554	V
Output Power	59.615	W
Voltage Regulation *1	12.373%	
Transformer Copper Loss	2.713	W

Transformer Iron Loss	1.441	W
Transformer Efficiency [*1]	77.487%	

[*1] See next page for definitions of Voltage Regulation & Efficiency

AVE turns ratio=1/11(0.245+0.253+0.254+0.249+0.253+0.254+0.254+0.246+0.251+0.25+ 0.232)=0.249

1. $Z_{1s'}$= (turns ratio)^2 x 628Ω=38.937Ω

2.Ave $\mathbf{X_{1eq}}$=3.727811

Ave $\mathbf{R_{1eq}}$=1.76997

$I_1 = V_P/ (\mathbf{X_{1eq}} + \mathbf{R_{1eq}} + Z_{1s'})$=55/(38.937+3.727811+1.76997)=1.238A

3.$V_1 = Z_{1s'} I_1$=38.937×1.238=48.195V

4.$V_S = V_1 N_S / N_P = V_1$ /turns ratio=48.195/0.249=193.554V

(where Np/Ns is the turns ratio)

$I_S = I_1 N_P / N_S = I_1$ x turns ratio=1.238 x 0.249=0.308A

(where Np/Ns is the turns ratio)

Transformer Copper Loss= I_1^2 *$\mathbf{R_{1eq}}$=1.238^2*1.76997=2.713W

Transformer Iron Loss= V_P^2 /$\mathbf{R_C}$= 55^2 /2099.262=1.441W

(for ave $\mathbf{R_C}$=2099.262Ω)

Np/Ns is the turns ratio= Vp/Vsoc=0.249= 55/Vsoc

Vsoc=220.884V

Voltage Regulation = ($V_{SOC} - V_S$) / V_{SOC} x 100% = (220.884 – 193.554) / 220.884 x 100%=12.373%

Efficiency = Output Power (W) / Input Power (W) x 100% = 193.554 x0.308/55 x1.4=77.487%

Experiment 3: Transformer Regulation & Efficiency

We'll leave the equivalent circuit for the time being and now look at transformer operation with an actual load connected to the secondary winding. Invariably we want the load to dissipate real power so we will represent this with a simple value of resistance. When we investigate transformer performance we are primarily interested in the following:

- Transformer Voltage Regulation
- Transformer Efficiency

Voltage Regulation is a measure of how well the output voltage (V_S) remains constant from no load (open circuit) to full load (maximum I_S). It is expressed mathematically as:

$$\text{Voltage Regulation} = \frac{V_{SOC} - V_{SL}}{V_{SOC}} \times 100\%$$

where:

V_{SOC} = Open Circuit Secondary Voltage V_{SL} = Secondary Voltage under load

Given that we want the output voltage to remain as close as possible to the open circuit voltage we therefore want the Regulation value to be as low as possible (typically <5%).

Transformer Efficiency is expressed mathematically using any one of the following equations:

$$\text{Efficiency} = \frac{\text{Output Power (W)}}{\text{Input Power (W)}} \times 100\%$$

$$\text{Efficiency} = \frac{\text{Output Power (W)}}{\text{Output Power (W)} + \text{Losses (W)}} \times 100\%$$

$$\text{Efficiency} = \frac{\text{Input Power (W)} - \text{Losses (W)}}{\text{Input Power}} \times 100\%$$

The aims of the following series of tests is to measure performance at four different resistive load points, and from the results calculate the Voltage Regulation and Efficiency at each point. The experimental set up is shown on Figure 8. The general idea is to measure input and output voltages, currents and powers over the load range for a constant input voltage (V_P).

Note: **The low voltage side winding (i.e. primary side nominal values are 55V 1.4A) of the transformer is connected to the power supply, the high voltage side winding (i.e. secondary side nominal value is 220 0.35A) is connected to the load resistance R_L via Switch S_1**. R_L is the series four 900 Ω (max current 0.41A) variable resistors in Module D42, Switch S_1 is the switch S_1 in Module D51.

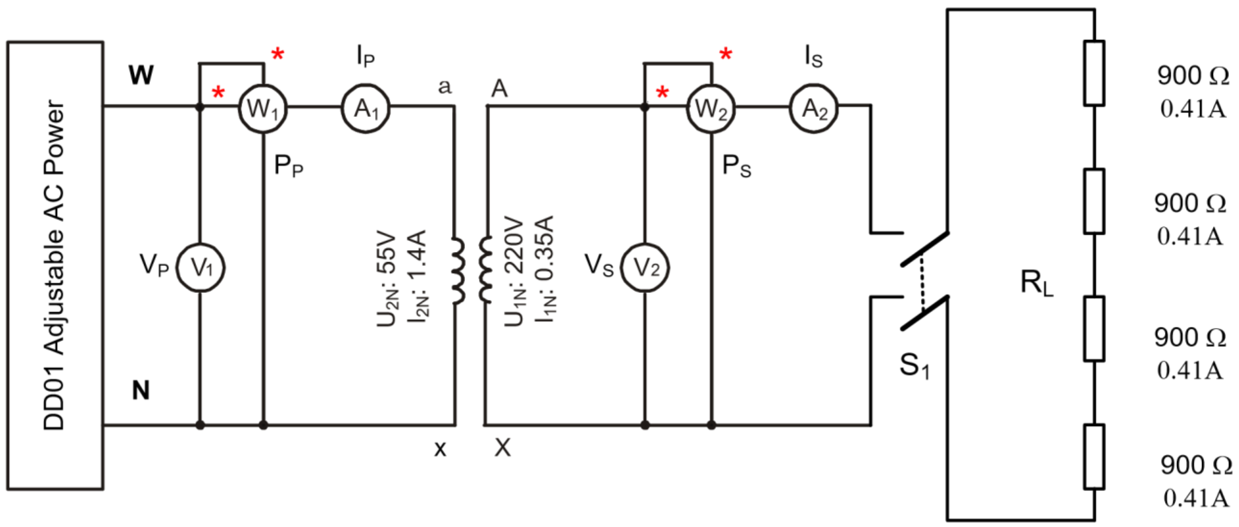


Figure 8: Transformer Regulation & Efficiency Tests

Experimental Procedure:

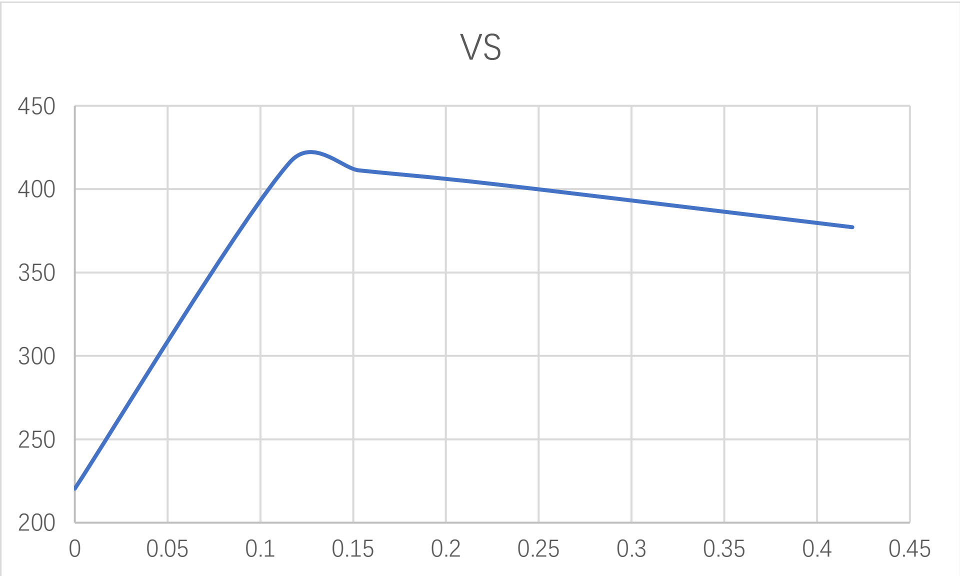
1. Turn off the AC power supply and set the AC voltage to zero.
2. Connect the resistors to the Secondary winding as shown on Figure 8. Adjust the value of the series four resistor R_L to its maximum value (about 3600Ω)
3. Turn on the AC power supply and adjust until approximately 55V. Gradually reduce the resistor the value of resistor R_L until the secondary current $I_S=I_{1N}/4$, $I_{1N}/2$, $3*I_{1N}/4$, and I_{1N}, measure primary circuit parameters: voltage (V_P), current (I_P) and real power (P_P) and secondary circuit parameters: voltage (V_S), current (I_S) and real power (P_S), respectively.
4. Repeat for Open Circuit Secondary condition (no resistors connected) but only measure the Secondary voltage (V_{SOC}).
5. Turn off the AC power supply.

From your test results and associated equations calculate the Voltage Regulation and transformer Efficiency at each of the four load points:

V_{SOC}	220V

Load Point	V_P	I_P	P_P		V_S	I_S	P_S		Regulation	Efficiency
	(V)	(A)	(W)		(V)	(A)	(W)		(%)	(%)
R_L=900	55	1.765	169.3		377.2	0.419	158.9		71.45455	93.857%
R_L=1800	55	1.050	99.9		403.03	0.226	91.9		83.19545	91.992%
R_L=2700	55	0.818	70.5		411.3	0.153	63.7		86.95455	90.355%
R_L=3600	55	0.714	55.7		416.3	0.116	49.1		89.22727	88.151%
Open Circuit	55	0.038	1.3		220.4	0	0		0.181818	0%

From the results plot Secondary Voltage (V_S) and Efficiency against Output Current I_S (note using a false zero on the Y axis values is recommended to maximise resolution):



Analysis of Results and Comparison with Theory

Using your results for $I_S=I_{1N}$ (i.e. 628Ω load) complete the following table of comparison between your measured results and your theoretical values calculated earlier from your equivalent circuit:

Parameter	Measured	Theory	Units
Output Current (I_S)	*0.308*	**0.35**	**A**
Output Voltage (V_S)	*193.554*	**220**	**V**
Output Power	59.615	**77**	**W**
Voltage Regulation	12.373%	**0%**	
Transformer Efficiency	**77.487%**	**100%**	