University of Glasgow
School of Engineering
Power Engineering 3

LAB 1 - Single & Three Phase Systems Laboratory

Introduction

Understanding single and three phase power systems with resistive, inductive and capacitive loads is fundamental to the Power Engineering 3 course. This laboratory has been designed to give you the ability to measure voltages, currents and power in a variety of single and three phase circuits. By the end of the session you will hopefully have a better understanding of the following:

- Single phase voltage, current, power factor and power relationships for resistive, capacitive and complex loads
- Three phase balanced Star connected load: phase power measurement and total supply power
- Three phase unbalanced Star connected load: total supply power measurement using the 3 wattmeter and 2 wattmeter methods

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.

Definitions of Power Factor (PF) & Real Power (P)

Considering the example circuit shown on Figure 1 and the associated phasor diagram, Power Factor and Real Power (measured in Watts) are defined as follows:

Power Factor (PF) = CosΦ where Φ is the angle between V_S and I_S

Real Power (P) = $V_S.I_S.$CosΦ where V_S and I_S are rms values

Note: Real Power (P) and Power Factor are related to Apparent Power (S) and Reactive Power (Q) through the power triangle as shown on Figure 2

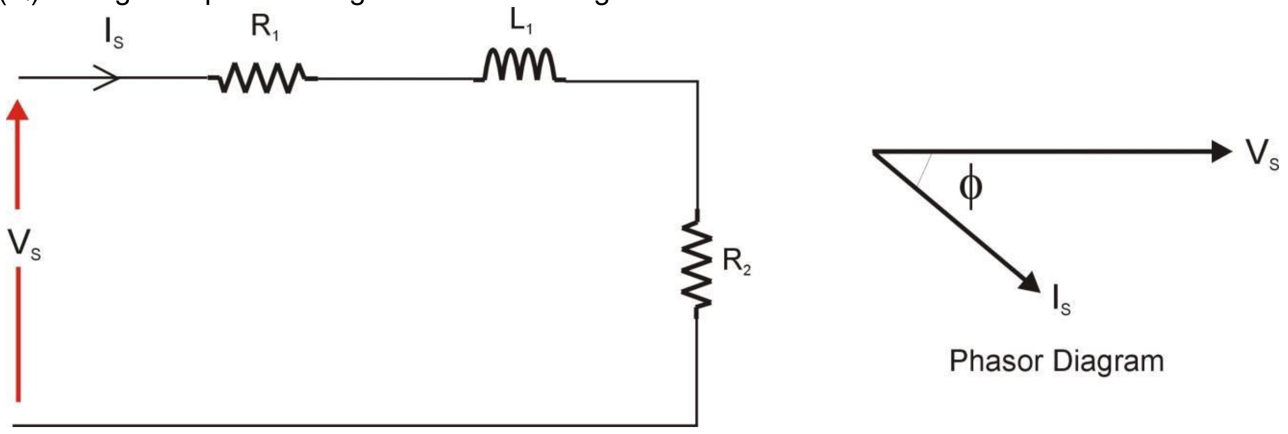


Figure 1: Example Circuit + Phasor Diagram

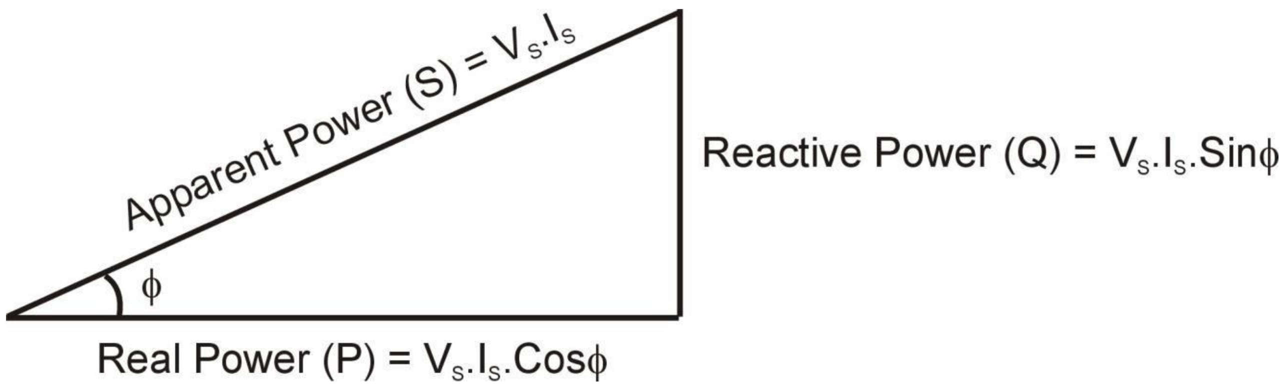


Figure 2: Power Triangle

Three-Meters Method for Single Phase Power Measurement

During this laboratory session you will use **voltmeter**, **ammeter** and **wattmeter** to measure displays the following:

- Voltage (rms)
- Current (rms)
- Real Power (W)
- Power Factor

During this laboratory session you will use all of these except frequency (we assume that the supply frequency is 50Hz mains). Using these measurements you will also be able to calculate the following parameters:

- Apparent Power (VA)

- Reactive Power (VAr)

As ‘proof’ of your understanding indicate on the following table the required **voltmeter or ammeter** placement on Figure 3 (identified by its letter) to measure the following voltages and currents:

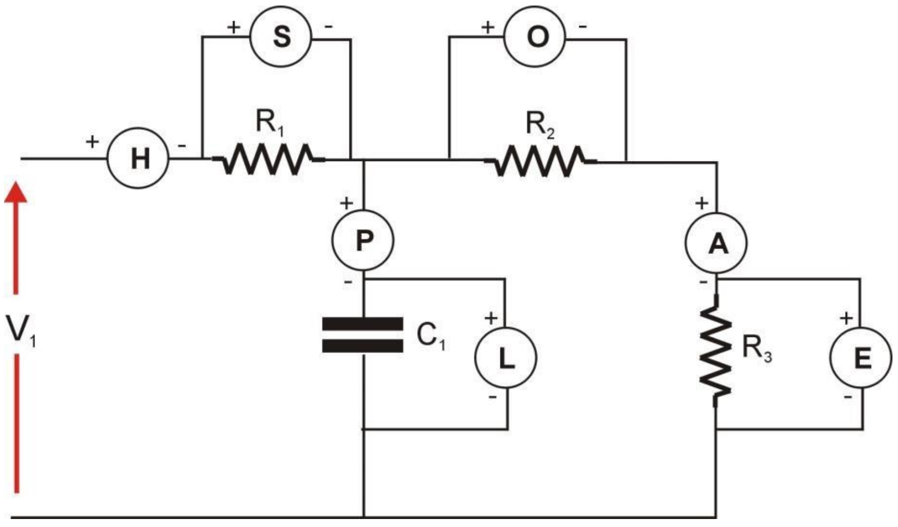


Figure 3: Example Voltmeter and Ammeter Placement

	Meter Requirement	Meter (eg P,E,A etc)
Q1	Measure current through R1	0.079A
Q2	Measure voltage across R2	72.2V
Q3	Measure current through C1	0.043A
Q4	Measure voltage across R3	71.7V

Show answer to laboratory supervisor before continuing.

The key to success in using the Wattmeter is having a good understanding of how to connect the leads to measure voltage and current. To help understand how to connect these voltage and current leads to the circuit to be tested consider the circuit shown on Figure 4. The key concept to remember the polarity conventions of Wattmeter.

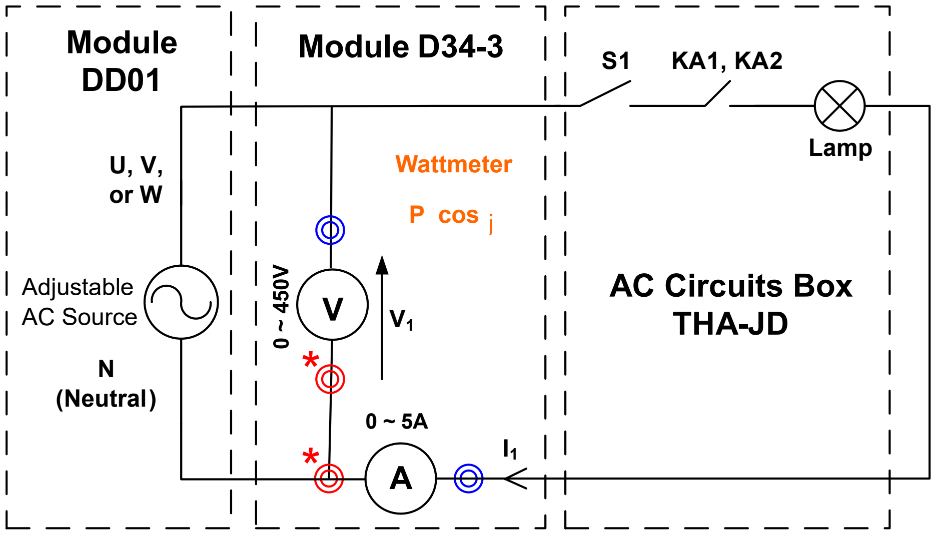
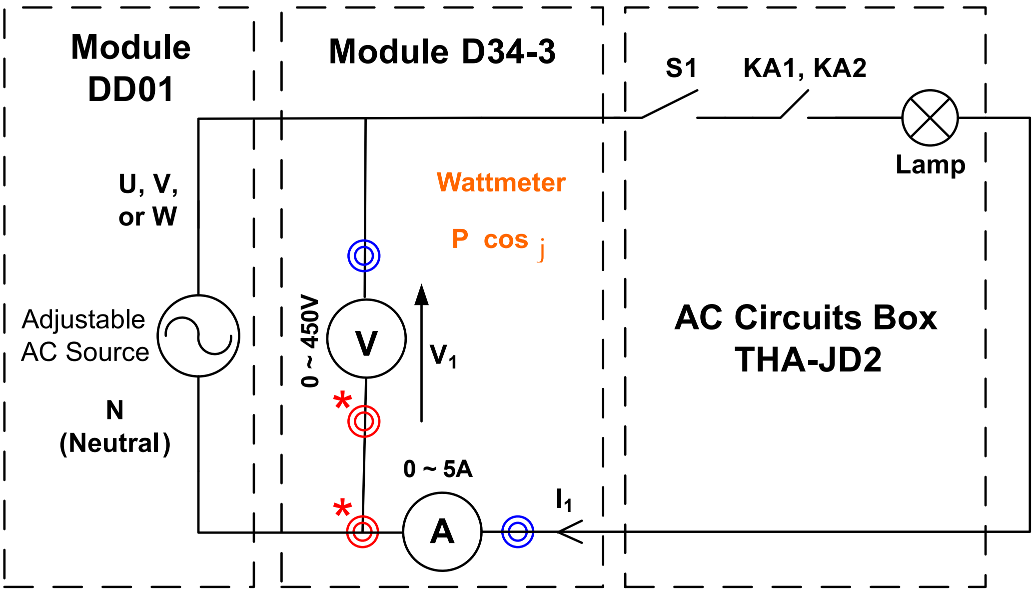


Figure 4: Voltage & Current Measurement Polarity

Experiment 1: Single Phase Resistive Load

With the power supply turned off, select and connect a 220V 40W lamp (THA-JD2 AC Circuit Box) to one phase of the secondary side of 3 phase power supply (Module DD01) as shown on Figure 5. The output of the power supply is set to 220V.



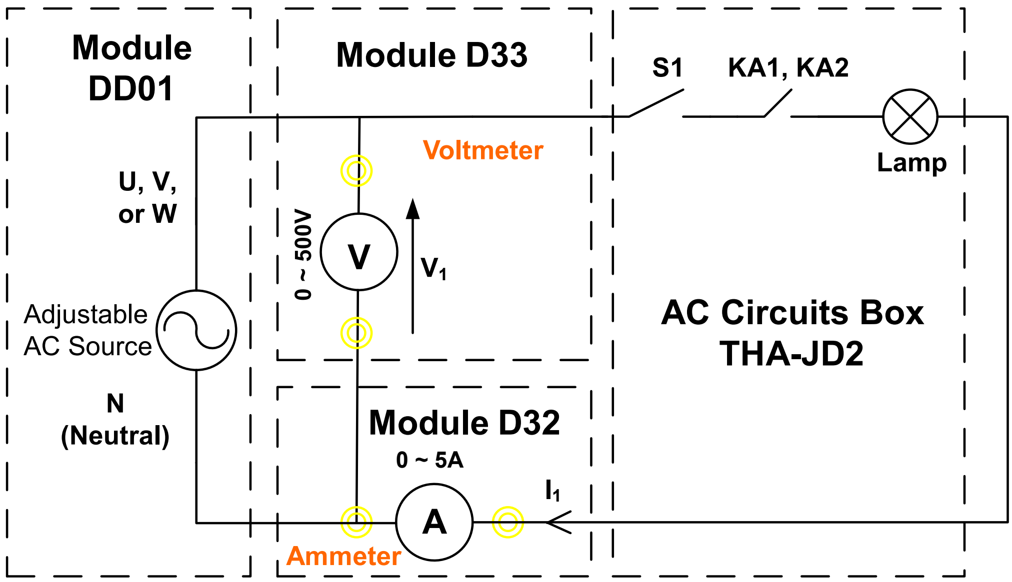


Figure 5: Resistive Load

Use three-meter method to measure the resistor current, voltage, real power and power factor.

Experimental Results:

Parameter	Value	Units
V_R	220	V
I_R	0.187	A
Power Factor	1	
Real Power (R)	40.5	W

Verify the Real Power Measurement by calculating the I^2R power loss in the circuit:

$$R = \frac{V_R}{I_R} = \frac{220V}{0.187A} = 1176.5\Omega$$
$$\text{Real Power} = I^2R = 0.187A^2 \times 1176.5\Omega = 41.1w$$

Experiment 2: Single Phase Resistive + Capacitive Load

With the power supply turned off, select and connect 220V 40W lamp in series with a 4.7μF capacitor (THA-JD2 AC Circuit Box) to a single phase of the secondary side of 3 phase power supply (Module DD01) on Figure 6. Draw a wiring diagram (similar to Figure 5) for this new load configuration including three meters; the current through the resistor and capacitor, and the voltage across both the resistor **and** the capacitor. The output of the power supply is set to 220V.

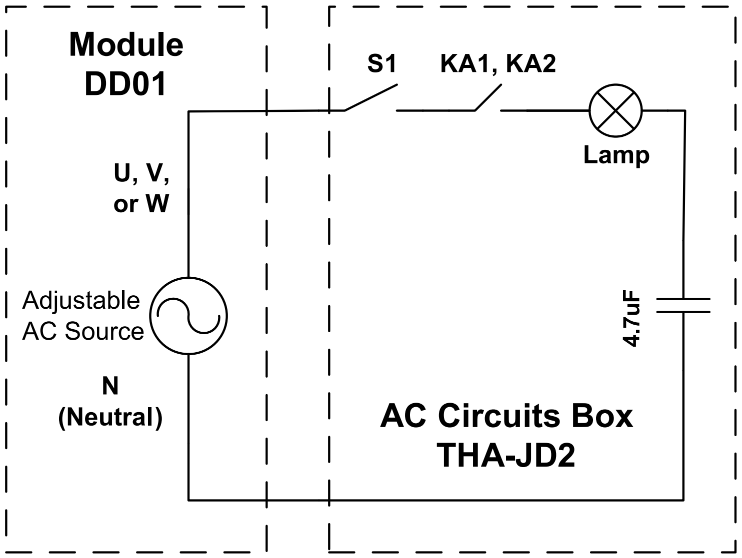


Figure 6: RC Series Load

Wiring Diagram:

Switch on the power supply and determine the following:

Experimental Results:

Parameter	Value	Units
V_{ZT}	220	V
I_{ZT}	0.171	A
Power Factor	0.84	
Real Power	32.3	W

Verify the Real Power Measurement by calculating the I^2R power loss in the circuit:

$$\mathrm{R} = \frac{V_R}{I_R} = \frac{220V}{0.171A} = 1176.5\Omega$$

$$\text{Real Power} = I^2R = 0.171A^2 \times 1176.5\Omega = 34.4\text{w}$$

Three Phase Systems – Balanced Loads

The majority of long distance AC power generation and transmission uses a 3 phase system. The three phase generator voltages are equal in magnitude but are phase shifted by 120º (see Figure 7). The basic idea is that we can connect three phase loads to the three phase generator in one of two ways; Star or Delta. A star connected load is shown on Figure 8 and a delta connected load is shown on Figure 9, with all phase and line voltages and currents shown. In our analysis we will assume that the phase voltages (V_{RN} etc) are equal in magnitude and 120º apart, and the line voltages (V_{RY} etc) are equal in magnitude and 120º apart. A Balanced load condition is when the three load impedances are equal, therefore for a Star connected load $Z_{RS} = Z_{YS} = Z_{BS}$, and for a Delta connected load $Z_{RY} = Z_{YB} = Z_{BR}$. For a balanced load the respective line currents (I_R etc) are equal in magnitude and 120º apart, and the load phase currents (I_{RY} etc, Delta only) likewise.

The result of this is that for a balanced 3 phase load we need only measure voltage, current, power factor and power in one phase as the power in the three phases is identical and total power is simply three times the phase power.

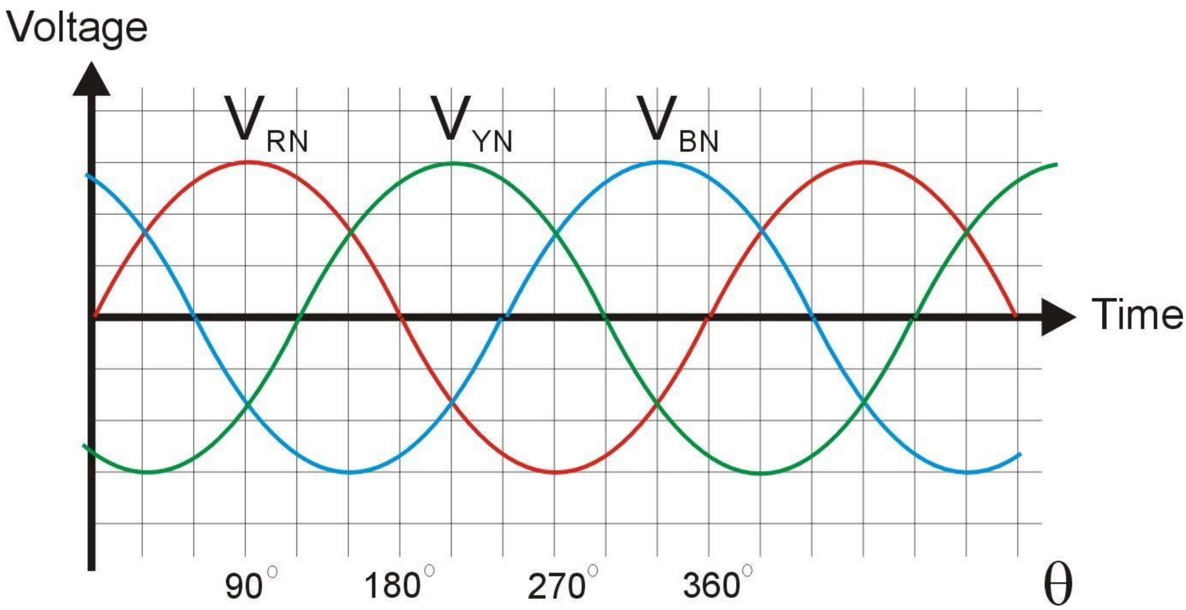


Figure 7: Three Phase Voltage Supply

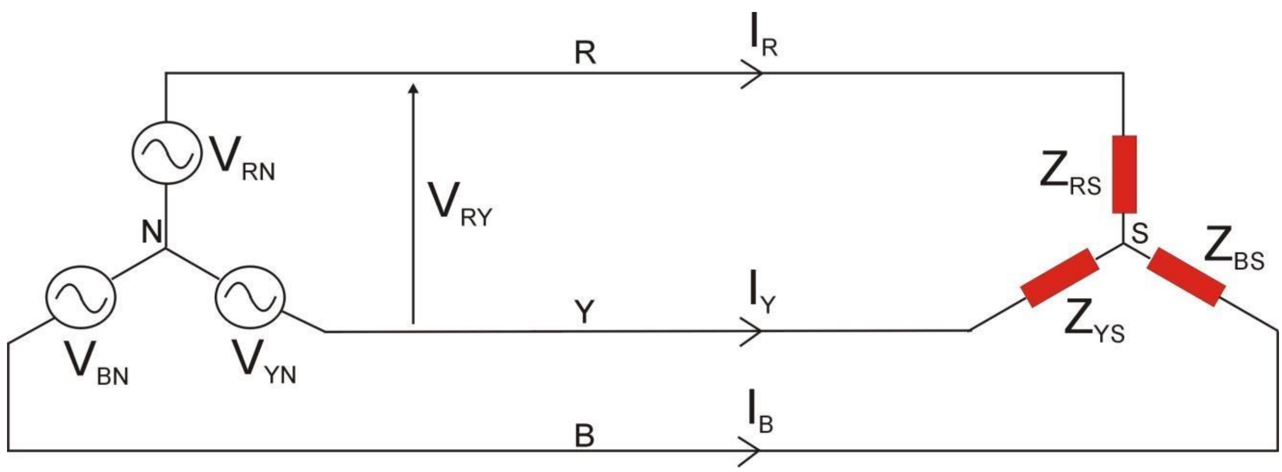


Figure 8: Star connected (balanced) load

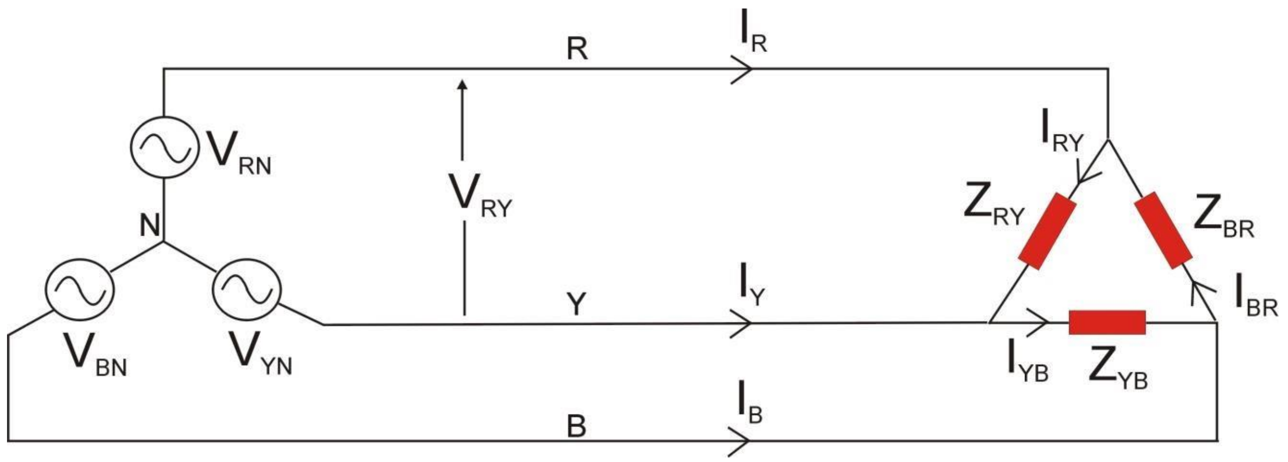


Figure 9: Delta connected (balanced) load

Parameter			
Phase Voltages	V_{RN}	V_{YN}	V_{BN}
Line Voltages	V_{RY}	V_{YB}	V_{BR}
Line Currents	I_R	I_Y	I_B
Load Phase Currents (Delta Only)	I_{RY}	I_{YB}	I_{BR}

Experiment 3: Balanced 3 Phase Star connected load

We will now use all three outputs of the 3 phase Power Supply at the secondary sides of autotransformer (Module DD01). The three phase voltages are output on the red, yellow and blue terminals and the neutral point is also available on the black terminal (but not connected to the load!).

Now wire up (using colour coded wiring would be beneficial) a balanced Star connected load consisting of a lamp in series with a 4.7μF capacitor as per Figures 10. The output line voltage of the power supply is set to 380V.

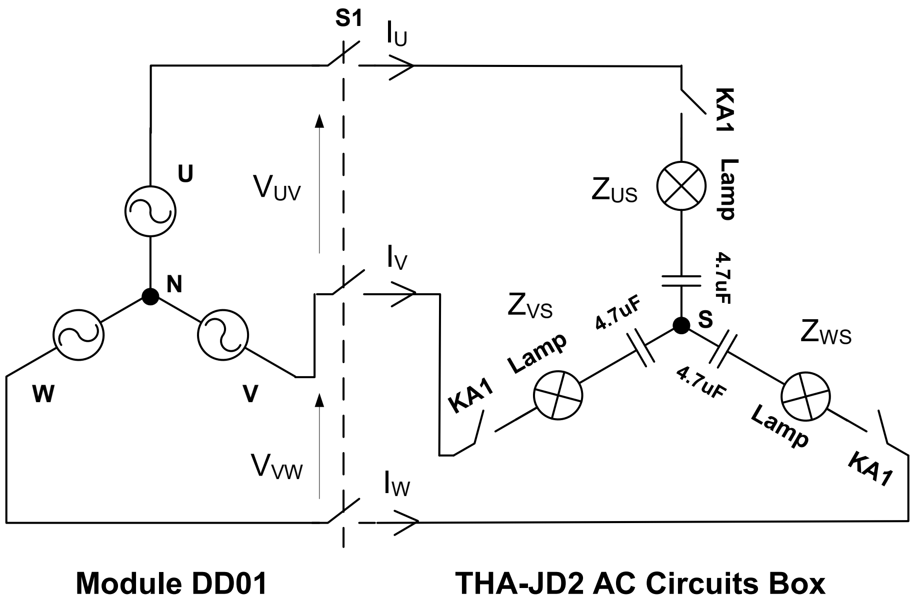


Figure 10: Star connected RC load

A useful check to see if the wiring is correct is to measure the voltage between the load star point and the generator neutral (V_{SN}). If the load is perfectly balanced then V_{SN} = 0V but due to resistor tolerances it will measure a small voltage. Connect the voltmeter (Module D33) leads to points (S) and (N) respectively and verify the voltage is as expected:

Measured	V_{SN}	3.1v

In power systems the utility companies are generally interested in measuring and monitoring the Phase Power output from the three phase supply. To do this connect the Wattmeter to measure the RED Phase Voltage V_{WN} and the RED Line Current I_W and record the results:

Experimental Results:

Parameter	Value	Units
V_{WN}	220	V
I_W	0.172	A
Power Factor	0.84	
Real Power	32.6	W

From this determine the total real power taken from the 3 phase supply:

Total Real Power	97.8	W

Verify the Real Power Measurement by calculating the TOTAL I^2R power loss in the circuit:

$$\mathrm{R} = \frac{V_R}{I_R} = \frac{220V}{0.172A} = 1176.5\Omega$$

$$\text{Real Power} = I^2R = 0.172A^2 \times 1176.5\Omega = 34.8\text{w}$$

Three Phase Systems – Unbalanced Loads

This is the condition where the three load impedances are no longer equal and therefore the output power from each of the three phases is now no longer equal. As a result we can no longer simply measure the power in one phase and then multiply this by 3. There are two methods to measuring power in unbalanced systems (note: these methods are also valid for balanced load conditions):

1. 3 Wattmeter Method
2. 2 Wattmeter Method

(the obvious advantage of the latter is that in an actual permanent monitoring setup we now require only 2 wattmeter's instead of 3)

An Example of the connections for the two wattmeters are shown on Figure 11.

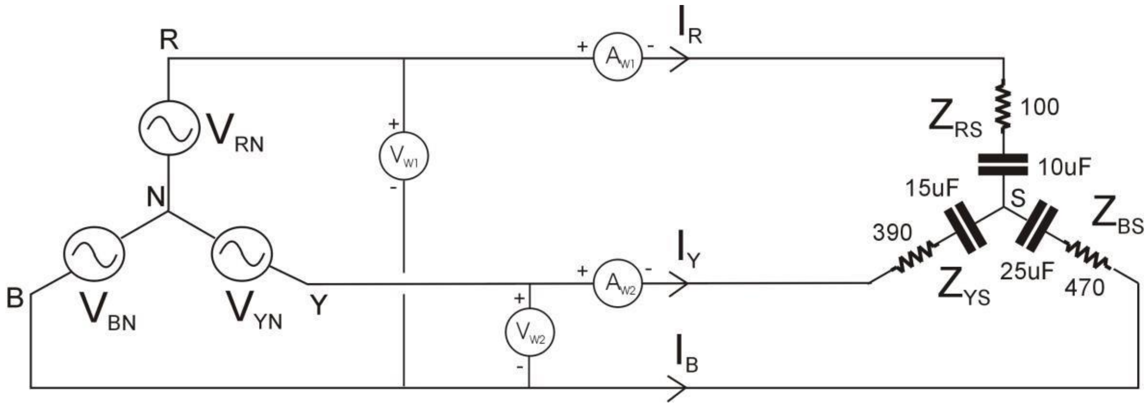


Figure 11: An Example of 2 Wattmeter Placement

Experiment 4: Unbalanced 3 Phase Star connected load – 3 Wattmeter Method

Connect the unbalanced star connected circuit shown on Figure 11. In the three wattmeter method a wattmeter is placed on each of the three phases (we will have to make do with using one wattmeter in each location in turn though!). The output line voltage of the power supply is set to 380V.

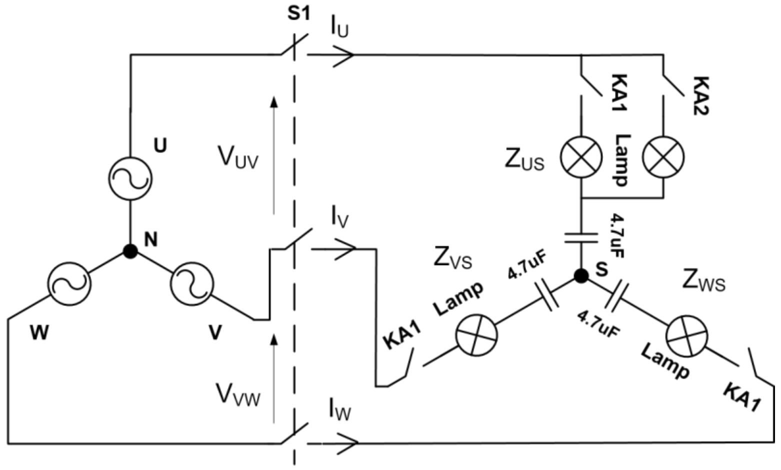


Figure 11: Star connected unbalanced RC load

Before making the actual wattmeter reading measure the voltage V_{SN}:

Measured	V_{SN}	64.4v

Now wire up the meters to measure V_{WN} and I_W and record the results:

V_{WN}		I_W		Real Power (P_{W1})		Power Factor
(V)		(A)		(W)		
220		0.164		25.4		0.64

Wire up the meters to measure V_{UN} and I_U and record the results:

V_{UN}		I_U		Real Power (P_{W2})		Power Factor
(V)		(A)		(W)		
220		0.239		45.6		0.70

Wire up the meters to measure V_{VN} and I_V and record the results:

V_{VN}		I_V		Real Power (P_{W3})		Power Factor
(V)		(A)		(W)		
220		0.164		25.6		0.65

The Total Real Power supplied by the three phase generator is $P_{W1} + P_{W2} + P_{W3}$:

Total Real Power	96.6	(W)

Experiment 5: Unbalanced 3 Phase Star connected load – 2 Wattmeter Method

We now want to repeat the measurement of total 3 phase power in the circuit shown on Figure 11 but this time using the 2 wattmeter method. The output line voltage of the power supply is set to 380V.

Wire up the meters to measure V_{WV} and I_W and record the results:

V_{WV}		I_W		Real Power (P_{W1})		Power Factor
(V)		(A)		(W)		

38.7		0.168		72.5		0.96

Wire up the meters to measure V_{UV} and I_U and record the results:

V_{UV}		I_U		Real Power (P_{W2})		Power Factor
(V)		(A)		(W)		
384.6		0.244		23.1		0.24

The Total Real Power supplied by the three phase generator is $P_{W1} + P_{W2}$:

Total Real Power	95.6	(W)

Verify the Real Power Measurements by calculating the TOTAL I^2R power loss in the circuit:

$$\mathrm{R} = \frac{V_R}{I_R} = \frac{220V}{0.172A} = 1176.5\Omega$$

$$\mathrm{R}' = \frac{1176.5}{2} = 588.3\Omega$$

$$\text{Real Power(v)} = {I_v}^2 R = 0.164A^2 \times 1176.5\Omega = 31.6\text{w}$$

$$\text{Real Power(w)} = {I_w}^2 R = 0.164A^2 \times 1176.5\Omega = 31.6\text{w}$$

$$\text{Real power(z)} = {I_z}^2 R' = 0.239A^2 \times 588.3\Omega = 33.6\text{w}$$

$$\text{Total Power} = \text{Real Power(v)} + \text{Real power(w)} + \text{Real Power(z)} = 31.6\text{w} + 31.6\text{w} + 33.6\text{w} = 96.8\text{w}$$

Comment on how the results from the two different methods compare.

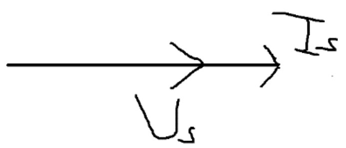
The total powers measured by those two methods are almost the same, with 95.6w in three phase generator and 96.8w in the TOTAL I^2R power loss in the circuit respectively.

Post Laboratory Theoretical Calculations and Analysis:

For the subsequent calculations assume a 110V/50Hz supply (phase) voltage.

Experiment 1:

1. Calculate the supply current (I_S) for the given load
   $R=\frac{U^2}{P}=\frac{220V^2}{40W}=1210\Omega$
   $I_S=\frac{U}{R}=\frac{110V}{1210\Omega}=0.091A$
2. Calculate the Real Power, Apparent Power and Reactive Power.
   Real Power=${I_s}^2R$=$0.091A^2 1210\Omega$=10w
   Apparent Power= I_S U =0.091A110v=10.01w
   Reactive Power=$\sqrt{10.01w^2-10w^2}$=0
3. Draw the resultant Phasor Diagram indicating the supply voltage and current
   Real Power= I_S U CosΦ
   Φ=arccos($\frac{\text{Real Power}}{\text{IS U}}$)= arccos($\frac{10}{10.01}$)=0



4. Create a table comparing the measured and calculated results and comment.

Experimental Results:

Parameter	Value	Units
V_R	220	V
I_R	0.187	A

Power Factor	1	
Real Power (R)	40.5	W

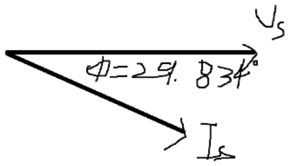
Calculated Results:

Parameter	Value	Units
V_R	110	V
I_R	0.091	A
Power Factor	1	
Real Power (R)	10	W

Although the voltage and current of the circuit have changed, the Power Factor remains the same. Moreover, the results are almost linear, which means the calculated real power is 1/4 of the experimental real power because the voltage and current of the circuit in the calculated results equals half of those in the experimental results.

Experiment 2:

1. Calculate the total impedance for the series RC circuit.
   Z_c =1/jwC=
   Z= R+Z_c=1210-693.626j
2. Calculate the supply current (I_S).
   $I_S=\frac{U}{Z}$=1210-693.626j=
   $\frac{110\times1210}{1210^2+693.626^2}+\frac{110\times693.626}{1210^2+693.626^2}j$
   =0.068+0.039j=0.10$\angle 29.834°$
3. Calculate the Power Factor, Real Power, Apparent Power and Reactive Power.
   Power Factor =CosΦ= Cos$\angle 29.834°$ =0.867
   Real Power= I_S U CosΦ=9.537w
   Apparent Power= I_S U=11w
   Reactive Power= I_S U sinΦ=5.472w
4. Draw the resultant Phasor Diagram indicating (to scale) the supply voltage, supply current, resistor voltage and capacitor voltage.



5. Create a table comparing the measured and calculated results and comment.

Experimental Results:

Parameter	Value	Units
V_{ZT}	220	V
I_{ZT}	0.171	A
Power Factor	0.84	
Real Power	32.3	W

Calculated Results:

Parameter	Value	Units
V_{ZT}	110	V
I_{ZT}	0.068	A
Power Factor	0.867	
Real Power	9.537	W

Although the voltage and current of the circuit have changed, the Power Factor remains almost the same. Moreover, the results are nonlinear owing to the capacitor, which means half the voltage will not bring the half current in the same circuit, and thus the ratio of two real power results cannot be an integer.

Experiment 3:

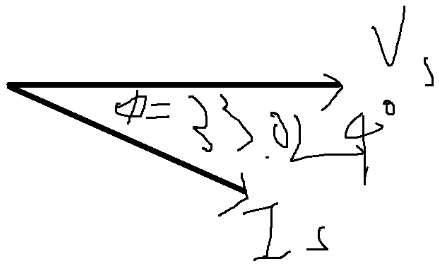
1. Calculate the impedance in each phase.
   Since each phase are in the same situation, so their impedance are all the same
   $Z= 2(R+Z_c)=(1210-693.626j)\times 2=2420-1387.252j$

2. Calculate the line voltage V_{WU}.
   $V_{WU}=110\times\sqrt{3}=190V$
3. Calculate the Red line current.
   $I_R=\frac{U}{Z}=\frac{190V}{(2420-1387.252j)\Omega}=$
   $0.060+0.039j=0.072\angle 33.024°$

4. Calculate the Power Factor of each phase.
   Power Factor $=\cos\Phi= \cos\angle 33.024° =0.838$

5. Calculate the per phase Real Power, Apparent Power and Reactive Power.
   Real Power= I_R U CosΦ=6.637w
   Apparent Power= I_R U=7.92w
   Reactive Power= I_R U sinΦ=4.316w

6. Draw the resultant 3 phase Phasor Diagram indicating all phase and line voltages and the 3 line currents.



7. Create a table comparing the measured and calculated results and comment.
   Experimental Results:

Parameter	Value	Units
V_{WN}	220	V
I_W	0.172	A
Power Factor	0.84	
VSN	3.1	V
Real Power	32.6	W

Calculated Results:

Parameter	Value	Units
V_{WN}	110	V
I_W	0.072	A
Power Factor	0.838	
VSN	0	V
Real Power	6.637	W

Experiment 4 & 5:

1. Calculate the impedance in each phase.
   Z_{UV}= R+R'+2Z_c=1815-1387.252j
   Z_{VW} = 2(R+Z_c)=(1210-693.626j)×2=2420-1387.252j
   Z_{WU}= R+R'+2Z_c=1815-1387.252j
2. Calculate the voltage V_{SN} and compare with the measured value.
   V_{SN} =(R+Z_c)/(R+R'+2Z_c) V_{VU} + V_{VN} =-110.623+61.435j
3. Calculate the voltages V_{WS}, V_{US} and V_{VS}.
   V_{WS} =- V_{SW} =-V_{VW} (R+Z_c)/ 2(R+Z_c)=-95.263V
   V_{US} =V_{UV} (R'+Z_c)/ (R+R'+2Z_c)= 110.623-61.435j
   V_{VS} = V_{VW} (R+Z_c)/ 2(R+Z_c)= 95.263V

4. Calculate the supply line currents.
   I_U= V_{UN}/ [(R'+Z_c)+ (R+Z_c)|| (R+Z_c)] =0.119∠40.893°
   I_V= V_{VN}/ [(R+Z_c)+ (R+Z_c)|| (R'+Z_c)]= 0.098∠32.862°
   I_W= V_{WN}/ [(R+Z_c)+ (R+Z_c)|| (R'+Z_c)]= 0.098∠32.862°

5. Calculate the Real Power in each Phase.
   Real Power:
   P_U= V_{UV} I_U Cos Φ_U =190×0.119×COS40.893° =17.093W
   P_V= V_{VW} I_V Cos Φ_V =190×0.098×COS32.862° =15.641W
   P_W= V_{WU} I_W Cos Φ_W =190×0.098×COS32.862° =15.641W

6. Calculate the total Real Power in each Phase.

   P= P_U+P_V+P_W=17.093W+15.641W +15.641W =48.375W

7. Compare calculated Real Power with measured values and comment.
   Experimental results:

V_{WN}		I_W		Real Power (P_{W1})		Power Factor
(V)		(A)		(W)		
220		0.164		25.4		0.64

V_{UN}		I_U		Real Power (P_{W2})		Power Factor
(V)		(A)		(W)		
220		0.239		45.6		0.70

V_{VN}		I_V		Real Power (P_{W3})		Power Factor
(V)		(A)		(W)		

220		0.164		25.6		0.65

Calculated results:

V_{WN}		I_W		Real Power (P_{W1})		Power Factor
(V)		(A)		(W)		
110		0.098		15.641		0.84

V_{UN}		I_U		Real Power (P_{W2})		Power Factor
(V)		(A)		(W)		
110		0.119		17.093		0.756

V_{VN}		I_V		Real Power (P_{W3})		Power Factor
(V)		(A)		(W)		
110		0.098		15.641		0.84