

**PRINCIPLES OF ELECTRICAL ENGINEERING**

**ELEC 275**

**LABORATORY MANUAL**

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**PLEASE READ IMPORTANT INFORMATION REGARDING  
EMERGENCY PROCEDURES ON THE LAST PAGE**

## **Safety**

Engineers are often required to use hand and power tools in constructing prototypes or in setting up experiments. Specifically, electrical engineers use test instruments to measure the electrical characteristics of components, devices, and electronics systems.

These tasks are interesting and challenging, but they may also involve certain hazards if one is careless in his/her work habits. It is therefore essential that students learn the principles of safety at the very beginning of their career and that they practice these principles.

Safe work requires a careful and deliberate approach to each task. Before undertaking an experiment, students must understand what to do and how to do it. They must plan everything, setting out tools, equipment, and instruments on the workbench in a neat and orderly fashion. Extraneous items should be removed, and all cables should be securely fastened.

### **General Safety Rules**

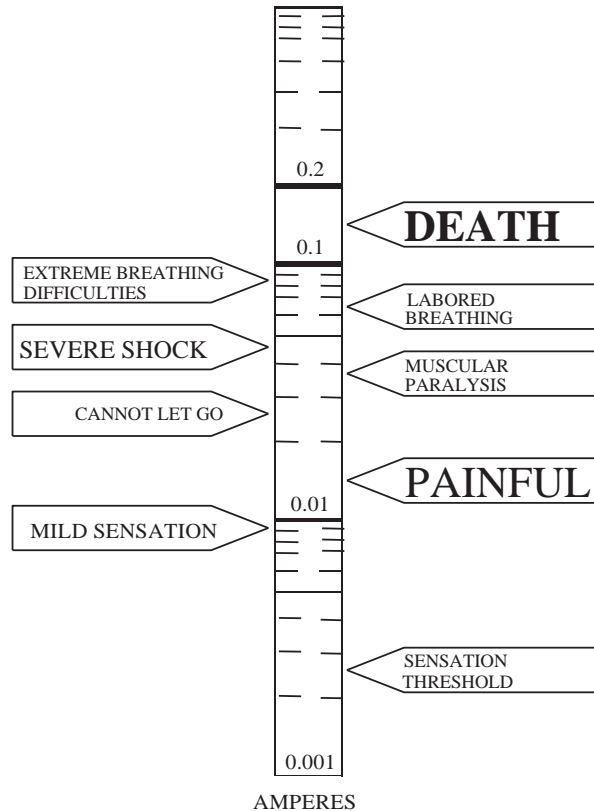
The first rule of personal safety is always:

*Think First!*

This rule applies to all industrial workers as well as to those working with electricity. Develop good habits of workmanship. Learn to use tools correctly and safely. Always study the job at hand and think through your procedures, your methods, and the applications of tools, instruments, and machines before searching. Never permit yourself to be distracted from your work, and never distract another worker engaged in hazardous work. **Don't be a clown!** Jokes are fun and so is "horsing around", but not near moving machinery or electricity. There are generally three kinds of accidents which may occur to electrical students and technicians- electric shock, burns, and equipment-related injuries. You're knowing and studying about them, and observing simple rules will make you a safe person to work with. You could personally be saved from painful and expensive experiences.

## Electric shocks

What about electric shocks? Are they fatal? The physiological effects of electric currents can generally be predicted with the chart shown in Fig. 1:



**Fig. 1** Physiological effects of electrical currents.

Notice that it is the current that does the damage. Currents above 100 mA, or only one tenth of an ampere, are fatal. A workman who has contacted currents greater than 200 mA may live to see another day if given rapid treatment. Currents less than 100 mA can be serious and painful. A safe rule: **Do not place yourself in a position to get any kind of shock.**

## **Nine rules for safe practice and avoiding electric shocks:**

1. **Work with one hand behind you or in your pocket.** A current between two hands crosses your heart and can be more lethal than a current from hand to foot. A wise technician always works with one hand. Watch your TV serviceman.
2. Be sure of the condition of the equipment and the dangers it can present **before** working on it. Many sportsmen are killed by supposedly unloaded guns; many technicians are killed by supposedly "dead" circuits.
3. **Never** rely on safety devices such as fuses, relays, and interlock systems to protect you. They may not be working and may fail to protect you when most needed.
4. **Never** remove the grounding prong of a three-wire plug. This eliminates the grounding feature of the equipment making it a potential shock hazard.
5. **Do not work on a cluttered bench.** A disorganized mess of connecting leads, components and tools only leads to careless thinking, short circuits, shocks, and accidents. Develop systematized and organized work habits.
6. **Do not work on wet floors.** Your contact resistance to ground is greatly reduced on a wet floor. Work on a rubber mat or an insulated floor.
7. **Do not work alone.** It is just good sense to have someone around to shut off the power, to give artificial respiration, or to call a doctor.
8. **Never talk to anyone while working.** Do not let yourself be distracted. Also, don't talk to someone who is working on dangerous equipment. Do not be the cause of an accident.
9. **Always move slowly** working around electrical circuits. Violent and rapid movements lead to accidental short circuits and shocks.

## **Burns**

Accidents caused by burns, although usually not fatal, can be painfully serious. The dissipation of electrical energy produces heat.

Four rules for safe practice and avoiding burns:

1. **Resistors get very hot**, especially those that carry high currents such as the ones in this lab. Watch those five- and ten-watt resistors. They will burn the skin of your fingers. Stay away from them until they cool down.
2. Be on guard for all **capacitors which may still retain charges**. Not only can you get a dangerous and sometimes fatal shock, you may also get a burn from an electrical discharge. If the rated voltage of electrolytic capacitors is exceeded or their polarities reversed they may get very hot and may actually burst.

## General Laboratory Rules

1. Students must treat the lab equipment, their colleagues, and the Lab Demonstrator TA with due respect. No containers of liquids (including water) are allowed on the lab benches. Large personal articles including coats, jackets, bags, etc., should be left under the desk or at the front of the room if necessary. Eating or drinking is strictly forbidden in the lab by university regulations. Telephones should be silenced and no calls are permitted in respect of your colleagues.
2. Every student must prepare for each experiment and must actively participate in performing the experiment. Do not waste your partner's and the Lab Demonstrator's time by being unprepared for the lab. Note that the function of the Lab Demonstrator is to assist and to answer technical questions, but not to perform the experiment for you.
3. The lab bench workspace must be kept clean. Scrap paper, pencil and eraser shavings must be cleaned up and deposited in the appropriate recycling or garbage can. *Disciplinary action will be taken against any student who misuses the lab, such as making marks on lab benches or on equipment, braiding patch cords etc.* Students must not be a disturbance to others in the lab.
4. In the event of a fire or any emergency requiring evacuation of the building, students must follow the Lab Demonstrator's directives and immediately leave the building via the stairwells whose locations are indicated on a map posted in the lab. The emergency procedures are reproduced at the end of this manual for reference.
5. Any apparently faulty equipment should be reported to the Lab Demonstrator. Under no circumstances are students allowed to try to repair any of the lab equipment.
6. All instruments switched on by the student should be switched off at the end of the session. Each station has a designated patch-cord rack and any cords used by the student must be returned to the designated rack. Do not remove any connections that were already made and which you have been instructed not to remove.

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## **Introduction**

The laboratory room is H-822 in the Hall Building.

The purpose of the laboratory portion of the course is to:

- Illustrate the material presented in the ELEC 275 classroom by means of experiment,
- Enable the student to become familiar with basic electrical measurements and measuring instruments
- Give the student practice in engineering data analysis, presentation, report writing and teamwork.

## **Regarding the Schedule and Pre-lab Preparation**

The topic of each laboratory experiment may be ahead of that being studied in the classroom. However the content is not beyond the understanding of an entry-level university student. The student must make a sincere attempt to understand the experiment description and procedure before coming to each lab. The experiment descriptions provided herein should be sufficient introductory material to conduct the experiment, with further relevant information found in the appendices. For best preparation students should additionally consult external references including the course text book or web as needed.

## **Pre-Lab Assignment**

In order to promote the essential preparedness mentioned above, a pre-lab assignment is due upon entry to the lab room.

## **Lab Structure**

The lab has ten bench stations with the same equipment. Students may work in pairs, but not groups of three unless allowed by the TA in cases where more than 20 students attend the session. Five experiments, listed under “Contents” at the beginning of this manual, will be performed in alternate week lab sessions (every two weeks) in the fall and winter terms, or weekly in the summer term.

Although working in groups of two, **each student must individually prepare and submit all lab reports.**

## General Lab Procedure

### Before the Lab

- Read the introductory material so as to be ready to conduct the lab efficiently in the available time.
- Prepare the pre-lab assignment. Consult external references if needed.
- Print the pre-lab and Data Table sheets to bring to the lab if you wish to keep your lab manual intact.

### During the Lab

- Submit your lab report from the previous lab and your pre-lab assignment.
- A brief lecture about the lab is provided by the Lab Demonstrator TA at the start of the lab. Arrive before the lab start time so as not to miss this key presentation.
- Perform the lab experiment and record all the required data into the provided Data Tables.
- Note observations you may want to investigate further or comment on in your report
- Obtain printouts where instructed.
- Obtain the Lab Demonstrator's signature on all your data and printouts.
- Leave the equipment, bench and lab room clean in accordance with the Lab Rules

### After the Lab

- Prepare the report in accordance with the information that follows. It is due at the start of the next lab.

## Lab Report Regulations

Lab reports must use a standard cover page available here:

[http://users.encs.concordia.ca/~pbipin/ELEC275/lab\\_report\\_cover.pdf](http://users.encs.concordia.ca/~pbipin/ELEC275/lab_report_cover.pdf)

All information on the cover page must be completed. The Expectations of Originality statement must be signed and dated. (Refer to Appendix for further detail.) Marks will be deducted for a report submitted without the cover page above, or if it is only partially filled.

The DATA TABLES (complete with the TA's signature) provided in this manual at the end of each experiment should be detached and included with the lab report. Alternatively the blank pre-lab and data table sheets can be obtained here:

<http://users.encs.concordia.ca/~pbipin/ELEC275/ELEC275LabManual/index275LabManual.html>

The rest of the report (Introduction, Procedure, Discussion, etc.) may be either word-processed or hand-written if legible. It is not necessary to write a detailed procedure as it is already stated here in the manual; it should be summarized as much as possible. Instead, the report should concentrate on meaningful Results, Discussion, and Conclusion sections to indicate that the student has grasped the main concepts of the experiment. No photocopied data will be accepted. Additional computer-processed results such as graphs and spreadsheets could also be included.



**Although student pairs will be expected to have similar lab results, no other part of the submitted report is expected to be shared between student bench pairs or class colleagues.**

The paper report must be submitted to the Lab Demonstrator TA at the start of the next lab. No late submissions are accepted and no other manner of submission is possible. The marked report is returned to the student at the following lab session. The last report (#5) has a submission deadline of only one week. It must be submitted at the lab test or by a pre-arranged meeting. The graded last report may be retrieved at the end of the session from the Lab Coordinator's office. Unclaimed reports will be retained for one term (~ 3 months).

## **Lab Report Grading Scheme**

The percent weight assigned to each section (Pre-Lab, Lab Record, and Lab Report) is indicated on the first page of these respective sections.

## **Lab Test**

A mandatory lab test is conducted during the regular lab time in the week following the fifth experiment. Students perform this test individually. Towards the end of the term, the test schedule is announced by email and posted at the lab room. The 45-minute test involves measurements and or calculations that the student should be familiar with from one of the experiments. The lab manual and an ENCS-approved calculator are the only permitted materials. Late arriving students do not receive extra time.

## **Missed Labs and Make-Up Procedure**

Since a lab grade (combination of reports and test) of at least 50% is required to pass the course, it is advisable to avoid missing any labs.

If the student foresees that they will not be able to attend their regular lab section, they should contact the Lab Coordinator as soon as possible to inquire about temporarily joining another section if space permits.

(Always include your name, student ID and course section code in your communications.)

If the student has already missed their section, they should also contact the Lab Coordinator to inquire about any make-up possibility.

A student who is authorized to attend another section, such as in the cases above, should submit their materials (pre-lab or report) to the TA present. The submission must show:

- their registered section code, and
- the code of the section they attended instead, with
- the name of the Lab Demonstrator TA it was submitted to.

In the case of unavoidable grave circumstance such as illness or accident, an absence may be disregarded in calculating the lab grade provided that an authentic document (doctor's or hospital certificate, police report, etc.) is furnished.

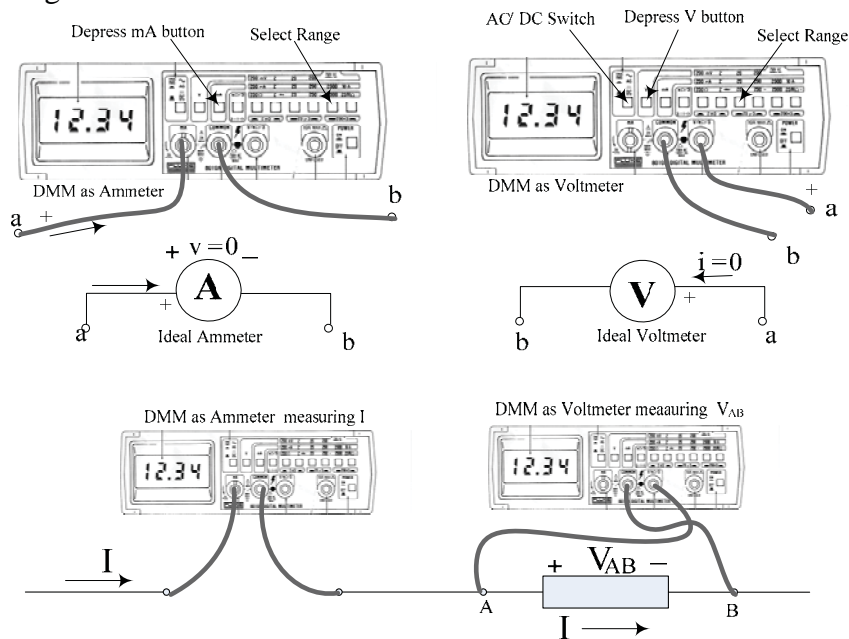
# EXPERIMENT 1 : BASIC DIGITAL MULTIMETER and OSCILLOSCOPE MEASUREMENTS

- OBJECTIVE :** (A) To become familiar with the basic DC Current and Voltage measurements using Digital Multimeters (DMMs).  
 (B) To become familiar with the sinusoidal AC waveform measurements using a Function Generator (FG) and a Digital-Storage-Oscilloscope (DSO) .

- PRE-REQUISITES:** 1. Elementary knowledge of current and voltage variables in electrical circuits and of sinusoidal waveform terminology.  
 2. Reading and making an attempt to understand the tutorial material given below, before coming to the lab session.

## PART (A) : TUTORIAL

Current, Voltage (& Resistance) measurement: Both DC and AC current and voltage measurements are performed in the lab using the Fluke Model 8010A and the Agilent Model 34405A digital multimeters (DMMs) which closely approximate ideal meters. . Ideal ammeters and voltmeters, respectively represented by the circular symbols (with the letters A and V within) shown in Figure 1.1 below, do not disturb circuit conditions when they are connected. The ‘ideal ammeter’, when inserted in the path of the current being measured, behaves like a ‘short circuit’ (ie as if no disruption was made by the insertion). The ideal voltmeter, when connected to the terminals across which the voltage difference is being measured, does not draw any current and is equivalent to an ‘open-circuit’. The front panel connections and general settings of the 8010A DMM, in the ammeter and voltmeter modes, are also shown in the figure.



**Figure 1.1:** Ideal ammeter and voltmeter symbols and their corresponding equivalent connections and settings for the Fluke 8010A DMM

DMMs are also capable of directly measuring other quantities such as resistance, conductance, capacitance, frequency etc. The ‘Ohm-meter’-function is particularly useful to measure the resistance of an isolated resistor as well as for checking open-circuits and short-circuits (continuity checks).

**Resistance measurement:** The Fluke 8010A DMM in its ohmmeter mode is shown in Figure 1.2. The term ‘isolated’ means that the resistor-under-test should be effectively disconnected from any circuit. The 8010A DMM terminals used for R measurement are the same as those used for voltage.

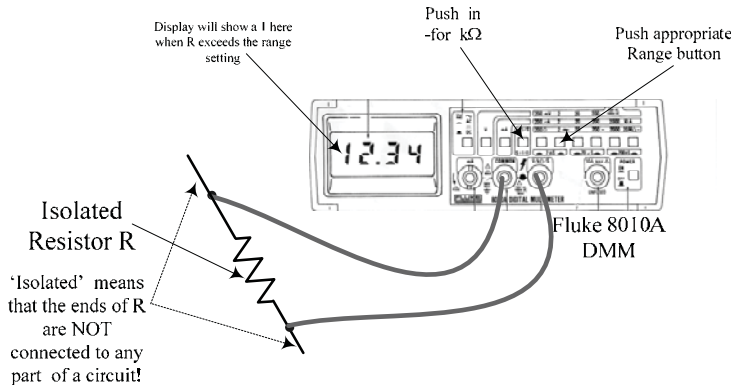


Figure 1.2: Fluke 8010A DMM in the Ohmmeter mode

To avoid possible damage, a DMM should **never** be left in the Ohmmeter-mode, after use.

The Agilent 34405A can also measure resistance, but can additionally measure capacitance, frequency and temperature (using a ‘thermistor’ temperature probe). Another distinction between the above two meters is that the various measurement ranges in the 8010A are manually selected whereas the 34405A is an auto-ranging DMM.

**Current measurement:** The current in any circuit branch (ie through the element constituting that branch) is obtained by inserting an ammeter in series with the branch. It is therefore necessary to break a connection to obtain a current measurement. For example, consider the circuit shown in Figure 1.3. Ammeters P and Q are shown inserted in branches EA and CD to measure the currents  $I_1$  and  $I_4$  respectively.

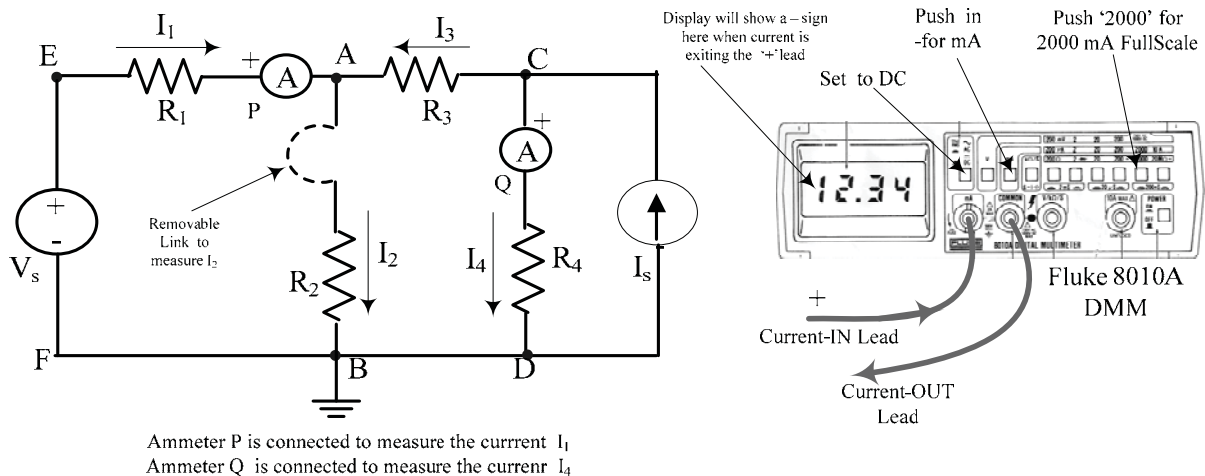


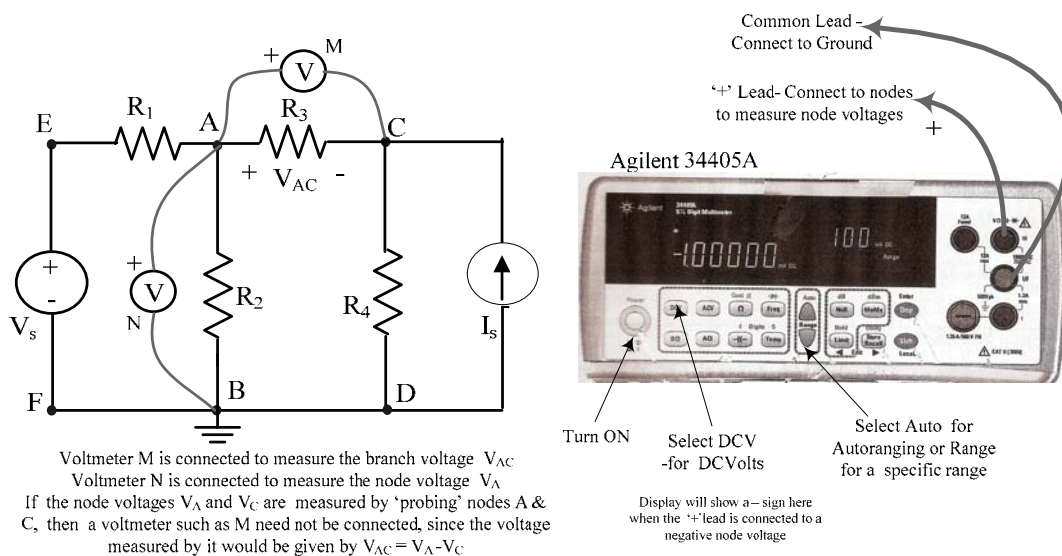
Figure 1.3: DC current measurement [using the Fluke 8010A as example]

To facilitate the ammeter insertion in any branch, a wire-link such as the dotted link shown in the branch AB, may be provided when constructing the circuit. It is then a simple step to remove each link and substitute an ammeter to measure the current at that particular point. The ammeter must be inserted in the proper reference direction to show the correct sign in the display: In DMMs, if the current leaves the '+' ve reference terminal input, a '-' sign will be displayed ahead of the numerical value. **It is very important to orient the 'ammeter' properly so that the indication will have the proper sign.** To measure AC currents, the same DC terminals are used but the DMM must be switched to the AC mode.

When used in the 'ammeter' mode, DMMs usually have a fuse incorporated for over-current protection. If no indication is obtained in the 'ammeter' mode, this fuse is most probably burnt and must be replaced (by your lab instructor). In the 34405A a separate front-panel 1.25 Amp fuse is used for over-current protection. In the 8010A, a 2A fuse is contained within the '+' reference current terminal, which is a special part [ **Please note: It is important to make sure that this part is always re-inserted in the DMM whenever it is taken out as it is not a replaceable component !** ]

**To avoid possible damage to itself as well as to other circuits, a DMM should never be left in the ammeter-mode, after use.**

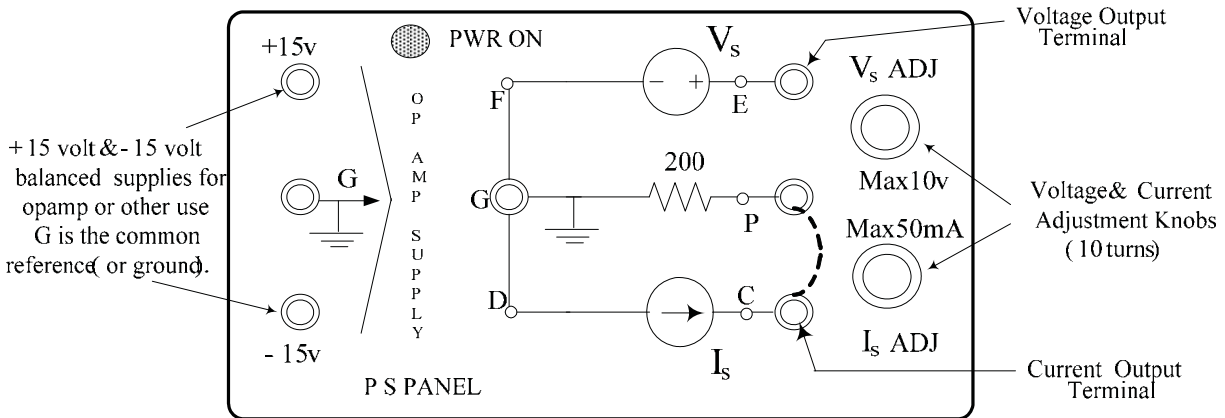
Voltage definitions & measurement: A 'branch voltage' is defined as the voltage across the element constituting the circuit branch. It can be measured by connecting a voltmeter in parallel with the branch. For example in the same circuit as above, shown again in Figure 1.4, voltmeter M is connected to measure the branch voltage between nodes 'A' and 'C', designated by the double-subscripted quantity  $V_{AC}$ , where node 'A' is taken to be positive with respect to node 'C', by convention. Branch voltages can be more conveniently obtained by measuring the node voltages, which are the voltages between every node and an arbitrarily-chosen reference node, called the 'ground' [ In Figure 1.4 node 'B' is indicated as being the 'ground' by its connection to the associated ground symbol.] Node voltages are easily measured by 'probing' every node using a 'grounded' voltmeter such as voltmeter N in Figure 1.4,



**Figure 1.4 : DC voltage measurement [using the Agilent 34405A as example]**

Node voltages are written as single-subscripted voltages such as  $V_A$ ,  $V_C$ ,  $V_E$  etc., where it is understood that  $V_A = V_{AB}$ ,  $V_C = V_{CB}$ ,  $V_E = V_{EB}$  etc. when 'B' is the chosen ground. Using Kirchoff's Voltage Law (KVL) it can be shown that, for any 'non-grounded' branch such as AC, the branch voltage  $V_{AC}$  is given by the difference between the corresponding node voltages, i.e.  $V_{AC} = V_A - V_C$  or  $V_{CA} = V_C - V_A$ . The potential-difference between any pair of nodes, even if there is no element connected between them, can be found by measuring the two node voltages. Node voltages can have positive or negative values. In measuring node voltages, it is important to ground the negative input terminal of the voltmeter so that the correct sign of the node voltage will be displayed ahead of the numerical value.

**DC Voltage & Current Supplies:** The Power Supply Panel (PSP) provides DC source voltages and currents needed in the experiments. It is located on top of the lab station hutch at its center. The PSP is energized by turning on a master power supply (the black-coloured unit located on the centre pillar of the hutch) and it is active when the green PWR ON indicator light is glowing. The front panel of the PSP is shown sketched in Figure 1.5 and a photograph of it is seen in Figure 1.6. The PSP provides a 1.1 volt-to-10 volt continuously variable voltage source and a 5.6-to-50 mA continuously variable current source, each varied by means of a 10-turn control knob.



**Figure 1.5:** Front view of the PSP

The variable current source may be converted into an additional variable voltage source, if necessary, by bridging terminals P and C (shown as a dotted line between P & C in Figures 1.5 & 1.6) using a short patchcord. The PSP also provides 'balanced' +15v / 0 / -15v power supplies required in experiments involving Operational Amplifiers. All the PSP outputs are referenced to the (black) ground terminals labelled G (for Ground)



**Figure 1.6:** Front view photograph of the PSP

**Experimental Circuit for DC experiments:** The resistor circuit shown in Figures 1.3 and 1.4 is available in the lab, constructed on an old-fashioned aluminum chassis (called the ‘R-Chassis’) shown in Figure 1.7. It is used in this experiment for DC measurements. The actual circuit connections between the various terminals on the chassis can be easily examined visually. The circuit diagram of the R-chassis with the resistance values used, is pasted on the top side of the chassis, as seen in the photograph. The resistor values as well as the patch cord connections to be made, including current-measurement links (around the node A), are also shown in both figures above. The value of  $R_L$  in the circuit is variable from  $100\Omega$  to  $300\Omega$  using a 10-turn potentiometer ( $20\Omega$  per turn starting from  $100\Omega$ )

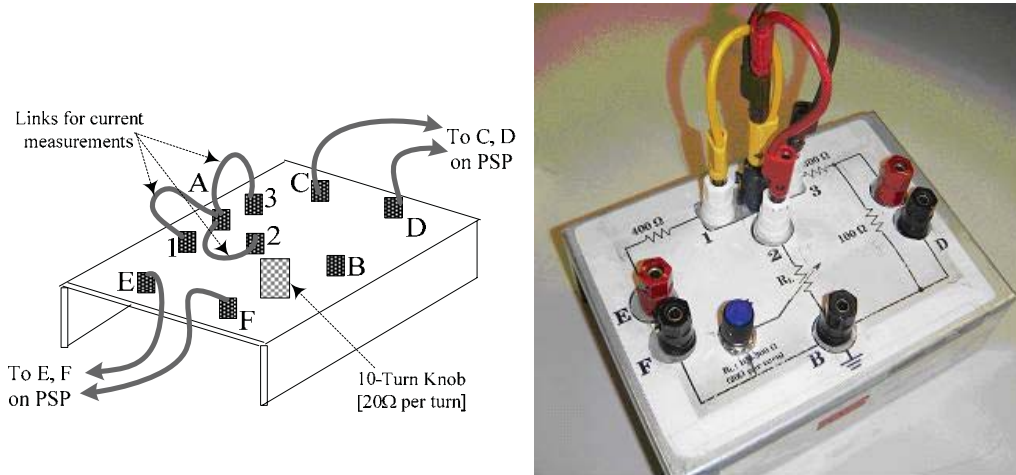


Figure 1.7 : The ‘R-Chassis’

The complete circuit used for DC measurements, showing the exciting voltage and current sources (from the PSP), but not the DMMs, is seen in Figure 1.8. With node B(F,D) used as the ground,  $V_s$  and  $I_s$  are first set to specific known values. The node voltages  $V_E, V_A, V_C$  are then successively measured using the Agilent DMM and the currents  $I_1, I_2, I_3$  are successively measured using the Fluke DMM.

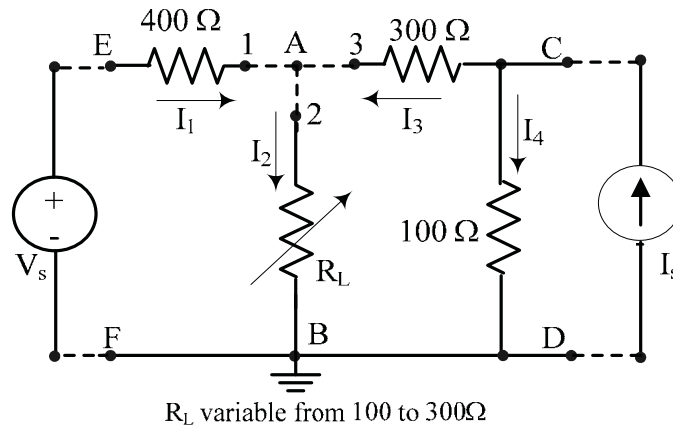
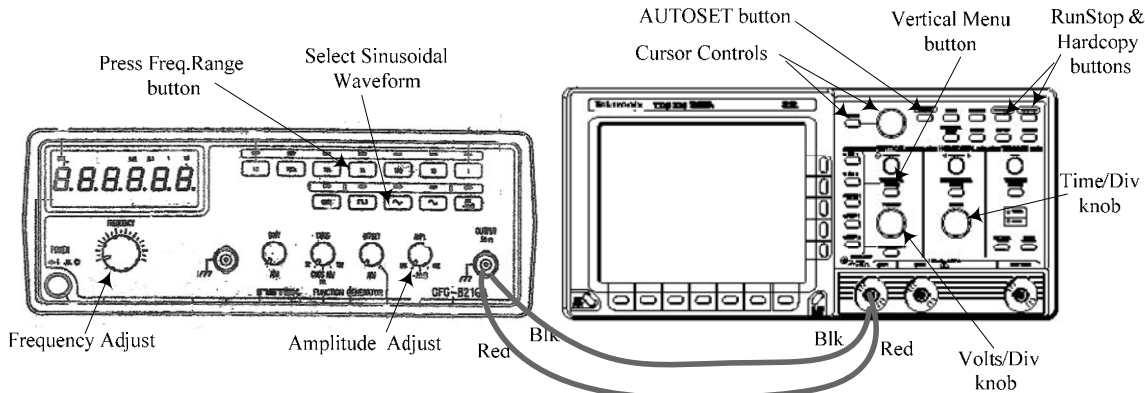


Figure 1.8 : The circuit used for DC measurements



AC (sinusoidal) waveform generation, display & measurement: Periodic voltage waveforms such as square-wave, triangular-wave, sinusoidal and pulse signals produced by electronic function generators (FG) are used as test input signals. The Instek GFG-8216A Function Generator used in the lab can provide sinusoidal (& square-wave) signals upto a frequency of 3 MHz. The signals are displayed and measured using a Tektronix TDS320 Digital Storage Oscilloscope (DSO). Details of both these instruments, such as the function of each button or knob, are given in the Appendix, which the student should read for maximum benefit.



**Figure 1.9:** Main FG & DSO controls identification & basic interconnection

The student should first make the direct connection between the FG and DSO (using banana-plug-ended patch cords) shown in Figure 1.9, switch both instruments on, and obtain a waveform display on the DSO: Pressing CH1 or CH2 on the DSO (on the group of buttons to the left of the VERTICAL MENU button) will cause the corresponding trace to appear. Then pressing the AUTOSET button will produce a display which is ‘optimally sized’ for the applied signal level. Any given trace may be removed by selecting it and then pressing the ‘WAVEFORM OFF’ button. The DC zero level of each trace is indicated by the small arrowhead along the left edge of the graticule. The student should investigate the effects of manipulating the main FG controls identified in Figure 1.9, on the waveform observed on the DSO. The student should also ‘experiment’ with the DSO controls: When the VERTICAL MENU button on the DSO is pressed, various options such as AC/DC input coupling, channel inversion, full or 20 MHz bandwidth, Finescale, DC offset become available for the selected trace. These options are selected using the horizontal and vertical rows of buttons that border the the screen, as well as the GP knob. The DSO also provides two reference channels (to store waveforms for comparison purposes) and a ‘MATH’ channel which displays the result of an arithmetical operation performed on the two active channel signals, such as  $M = Ch1 - Ch2$ .

AUTOMATIC MEASUREMENT: In addition to displaying waveforms, the DSO can automatically measure periodic- signal parameters such as peak or RMS amplitudes, Period and Frequency. In the above setup, although the FG has its own frequency display, it is preferably to use it only as a guide, and to obtain the actual frequency from a DSO measurement.

To investigate the automatic periodic-signal measurement capability of the DSO, obtain a **sinusoidal** display showing a few cycles of the waveform: Press the MEASURE button on the DSO and then press the “Select Measurement for CH1” on the bottom menu buttons. Measurement choices appear alongside the vertical menu buttons. Press the last button

(‘More 1 of 6’) to see other measurement choices. The onscreen measurement readings will appear within the graticule area, but they can be moved off-screen to the right of the graticule (by pressing CLEAR MENU) before a printout is made. **The indicated ‘measured’ values are the correct values to be used, as they are averaged over several cycles of the signal.**

**CURSOR MEASUREMENTS:** By pressing the CURSORS button, manually adjustable Vertical, Horizontal & Paired ‘cursors’ are available for the measurement of time-difference, voltage-difference or both, respectively. In particular, the V-bar cursors can be used to find the time-difference between two reference points which are on the same waveform or on different waveforms. Paired cursors have tiny H-bars ‘riding’ on the waveform at the location of the V-bars. **Paired cursors can only be used on a single waveform**

To activate and use the **cursors**, press CURSORS. A choice of H-bar(to measure voltage differences),V-bar (to measure time differences) or Paired Cursors (to measure both voltage and time differences on a single waveform) is available. The cursors are selected and positioned using the TOGGLE button and the GP knob, respectively, the solid-line cursor being the ‘active’ one. The above  $\Delta V$  or  $\Delta t$  differences measured by the cursors appear on the top-right end of the screen, but may be moved off-screen by pressing CLEAR MENU. A typical display showing automated measurements of Peak-to-Peak and RMS magnitudes, Period, Frequency and Paired-cursor data is shown in Figure 1.10.

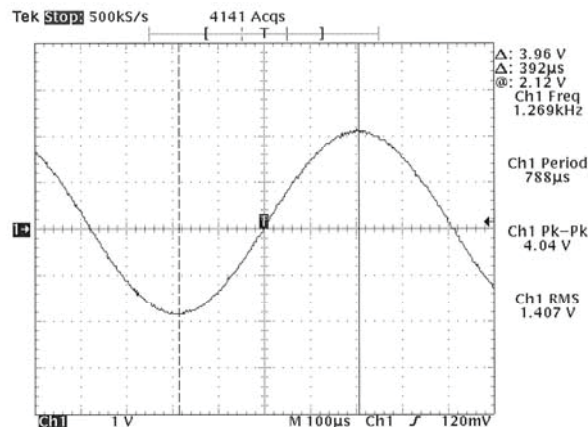


Figure 1.10: Typical display showing automated measured values and Paired-cursor data.[ The small arrowhead appearing along the left edge of the graticule indicates the zero-position of each trace.]

The cursor data “@ 2.12V” indicates that the voltage level on the waveform at the location of the solid-line(active) cursor is 2.12 volts. Note that paired cursors can only be used on a single waveform.

**DATA PRINTOUT:** Every DSO in the lab is interfaced through a serial-data switch to the common printer.To obtain printout of a display, first ‘freeze’ the display by pressing RUN/STOP and then press HARDCOPY. **The printer is programmed to print two copies of the ‘frozen’ display, together with station-identification.**



**Experimental Circuit for AC experiments:** An aluminum chassis (the ‘RLC Chassis’) on which R, L and C elements are mounted, as shown in Figure 1.11, is used in the lab for familiarization with the use of the FG and the DSO in AC measurements.

The value of R in the circuit is variable from  $100\Omega$  to  $10100\Omega$  using a 10-turn potentiometer ( $\sim 1\text{ k}\Omega$  per turn, starting from  $100\Omega$ ). The nominal values of L & C are  $L = 47\text{ mH}$  and  $C = 22\text{ nF}$ . An RLC-meter (located on the Printer table) can be used to measure exact values.

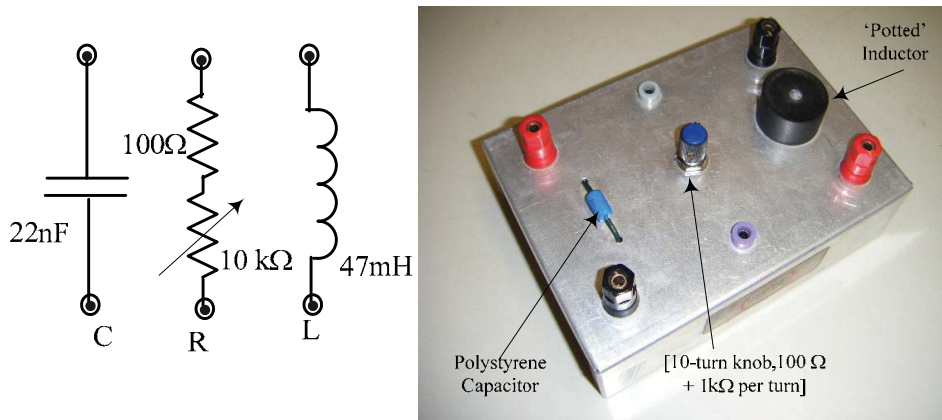


Figure 1.11 : RLC-Chassis and component values

**PART (B): Procedure & Results**

**DC voltage & current measurements :**

1. **Make sure that the PSP is turned OFF.** Make the patchcord connections shown in Figure 1.12 between the PSP and the R-Chassis using available banana-plug patchcords of appropriate lengths and colours\*

[ \* It is good practice to ‘colour-code’ your connections. Try to use different coloured cords and certain ‘standard’ colour-associations., eg Black or Brown for Ground , Red for ‘+’ power , and other colours for the other interconnections.]

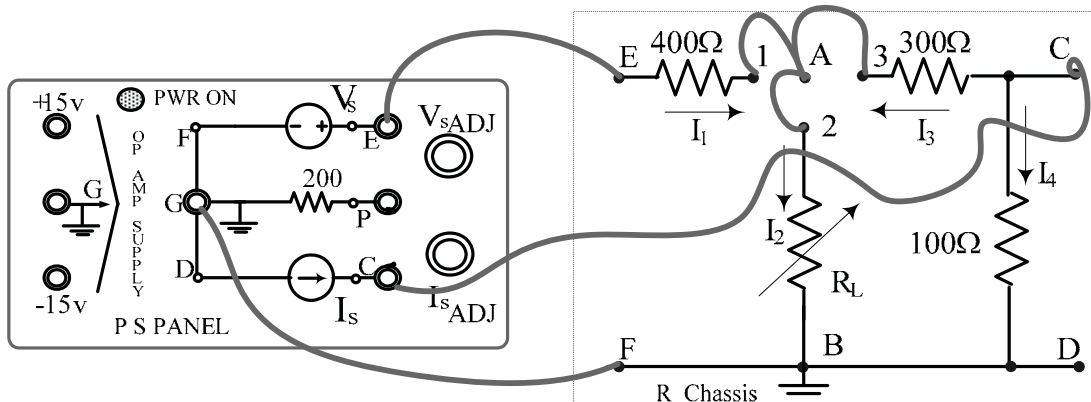


Figure 1.12

2. Set the value of  $R_L$  to a known value between  $200\Omega$  to  $300\Omega$  and then **turn the PSP ON**. Set the 'V<sub>s</sub> ADJ' and 'I<sub>s</sub> ADJ' knobs at 4 -to-8 turns from the extreme CCW (stop) position. This will result in V<sub>s</sub> and I<sub>s</sub> outputs in the range of 4~9 Volts and 8~9 mA , respectively.
3. Set the Fluke 8010A DMM as an ammeter in the 200 mA DC range Measure the branch currents I<sub>1</sub>, I<sub>2</sub> and I<sub>3</sub> ( by successively replacing the links around terminal A with the ammeter connected in the proper direction ) and enter their values in the data tables provided. [Recall the current measurement method given earlier in Figure 1.3]
4. Set the Agilent 34405A DMM to the DCV-Auto mode and measure the node voltages V<sub>E</sub>, V<sub>A</sub> and V<sub>C</sub> [with F(B,D) as ground ] and enter their values in the LAB RECORD. [Recall the node voltage measurements given earlier in Figure 1.4]
5. **Results (DC) :**
  - (a) Use the current measurements of Step 3 to verify the KCL equation :  $I_2 = I_1 + I_3$
  - (b) Use the node voltage measurements of Step 4 to obtain the branch voltages V<sub>EA</sub>, V<sub>AB</sub>, V<sub>AC</sub> and V<sub>CD</sub>; hence verify the validity of the KVL relations :
 
$$V_{EF} = V_{EA} + V_{AB} = V_{EA} + V_{AC} + V_{CD} \quad \text{and} \quad V_{AC} + V_{CD} + V_{BA} = 0.$$
  - (c) Use all the measured data (voltages & currents) to calculate I<sub>s</sub> ,the current delivered by the current source.[Hint:  $I_4 = V_c / 100, A$ ] and hence determine the total power P<sub>del</sub> delivered by the PSP sources.
  - (d) Use all the measured data (voltages & currents) to calculate the total power dissipated P<sub>diss</sub> by elements in the circuit and show that P<sub>diss</sub> = P<sub>del</sub> [of Step 5(c)] Give possible reasons for any difference observed in the two values of power.

=====

## AC (sinusoidal) waveform measurements :

- Make the banana-plug patch cord connections shown in Figure 1.13 between the FG, the DSO and the RLC-Chassis using appropriate lengths and colours. The circuit obtained is a **series-RLC** circuit excited by a voltage source, with the voltage across C being the output voltage  $V_{out}$ . [Note that after connecting the FG to the DSO, as in Figure 1.9, all the other connections are made at the DSO terminals alone, since this results in minimum wiring clutter].

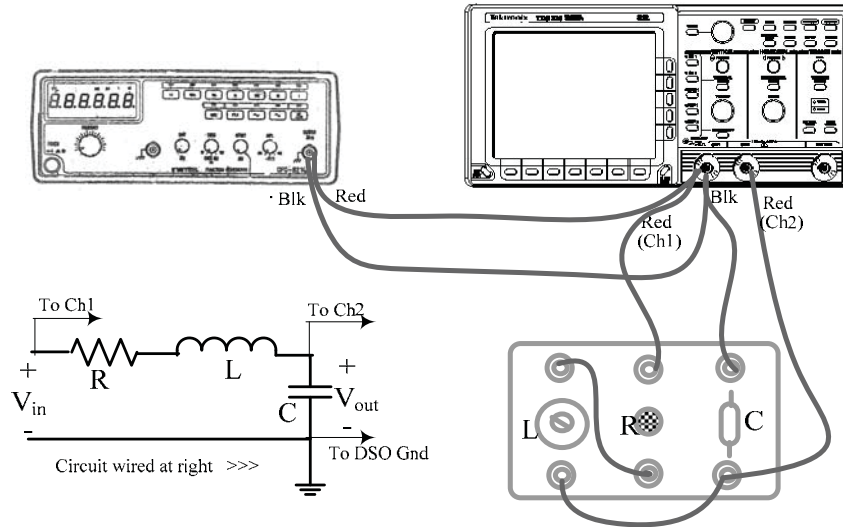


Figure 1.13

- Set the DSO to display Channels 1 and 2, with DC input coupling. Press the MEASURE button and successively select the following measurements to be displayed: Ch1 frequency and the RMS amplitudes of both channels. Also press CURSORS and select the V-bar cursors. Move the displayed values to the right by pressing CLEAR MENU.
- Set the FG output amplitude and frequency controls to display a sinusoidal Ch1 signal of about 2 volts RMS at a frequency of about 100 Hz. (Press AUTOSSET if necessary to obtain an optimally-sized display). Position the two traces so that there is no overlap. Set the R control on the RLC-Chassis to the minimum (ie 100 $\Omega$ ).
- Vary the FG frequency over the range of 100 Hz to 10 kHz (as read on the DSO) and observe the changes in the output voltage (Ch2) amplitude and its phase, relative to the input signal. [It will be observed that significant changes in both voltage and phase-shift occur around and above the 'series resonant-frequency' given by  $f_n = \frac{1}{2\pi\sqrt{LC}}$ , Hz which is approximately 5 kHz for the LC values used in the RLC-Chassis.].
- Obtain two typical printouts, one at  $f_1 (\approx f_n)$ , Hz and the other at  $f_2 (\approx 1.5f_n)$ , Hz. Both printouts must show the two RMS amplitude values and the V-bar cursors positioned to read the time-shift  $\Delta t$  between two adjacent waveform maxima (peaks) [or at minima (troughs), or at zero-crossings]. The phase-shift  $\phi$  is then given by  $\phi = 360 f \Delta t$ , degrees, where  $f$  is in Hz. and  $\Delta t$  in sec. In each case, adjust the SEC/DIV knob until

only one or two cycles of the waveform are displayed, so that the cursors may be positioned more precisely to find  $\Delta t$ .

A typical trace near the resonant frequency, with the cursors placed at the troughs, is shown in Figure 1.14. [ For the waveforms in Figure 1.14,  $V_{out}$  (Ch2) lags  $V_{in}$  (Ch1) by  $360(4866)(44 \times 10^{-6})$  degrees or  $\sim 77^\circ$ ]

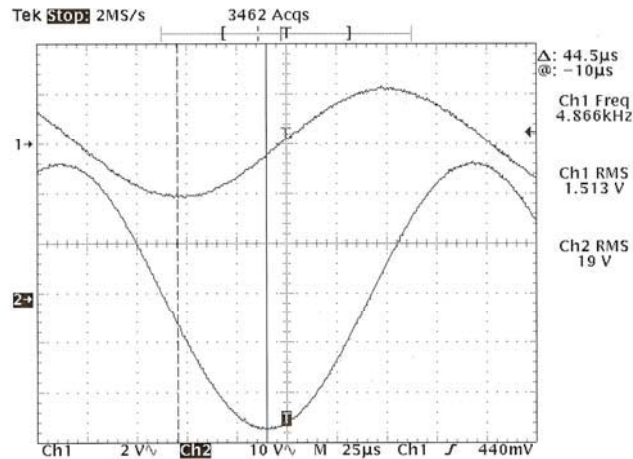


Figure 1.14

11. **Results (AC) :**

- The amplitude ratio  $V_{out}/V_{in}$  in Fig 1.14 is called the Voltage Gain  $A_v$ . From the two printouts of Step 10, obtain the values of  $A_v$  at the two frequencies  $f_1$  &  $f_2$  used.
- Calculate the phaseshift  $\phi$  (in degrees) at the above two frequencies, from the cursor readings.
- Compare the results of (a) and (b) with the corresponding theoretical values which are given by the following equations:

$$A_v = \frac{\frac{1}{\omega C}}{\sqrt{R^2 + [\omega L - \frac{1}{\omega C}]^2}} \quad \text{and} \quad \phi = -90^\circ - \tan^{-1} \frac{(\omega L - \frac{1}{\omega C})}{R}, \text{ degrees.}$$

where  $\omega = 2\pi f$  where  $f$  is in Hz. . Use the radian frequencies  $\omega_1$  and  $\omega_2$  and nominal values given for  $L$  &  $C$  given in Figure 1.11 and value used for  $R$ . Calculate the percent difference between the measured and theoretical values using the latter as reference.

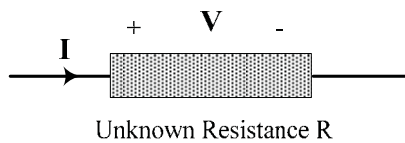
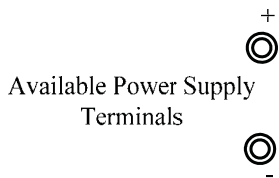
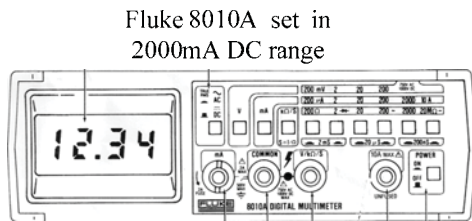
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Name: \_\_\_\_\_ ID# \_\_\_\_\_ Lab Section: \_\_\_\_\_

**PRE-LAB** [ To be completed and submitted before performing Lab#1 ]  
 (Weight: 20%)

Question#1 (a) Physical representations of the digital multimeters used in the lab (Fluke Model 8010A & Agilent Model 34405A) and a resistance element of unknown value are shown below. Also shown are power-supply terminals from which a voltage supply is available. Show (by drawing lines) how you would connect the DMMs and the resistance R to the available power supply terminals, to measure the voltage V across the resistance and the current I through it.



(b) Assuming that you have made the proper connections and that the Fluke 8010A and Agilent 34405A read

..... mA\* and ..... volts\* , respectively, determine the following:

Value of the resistance ,  $R = \dots\dots\dots$  Ohms/  $k\Omega$

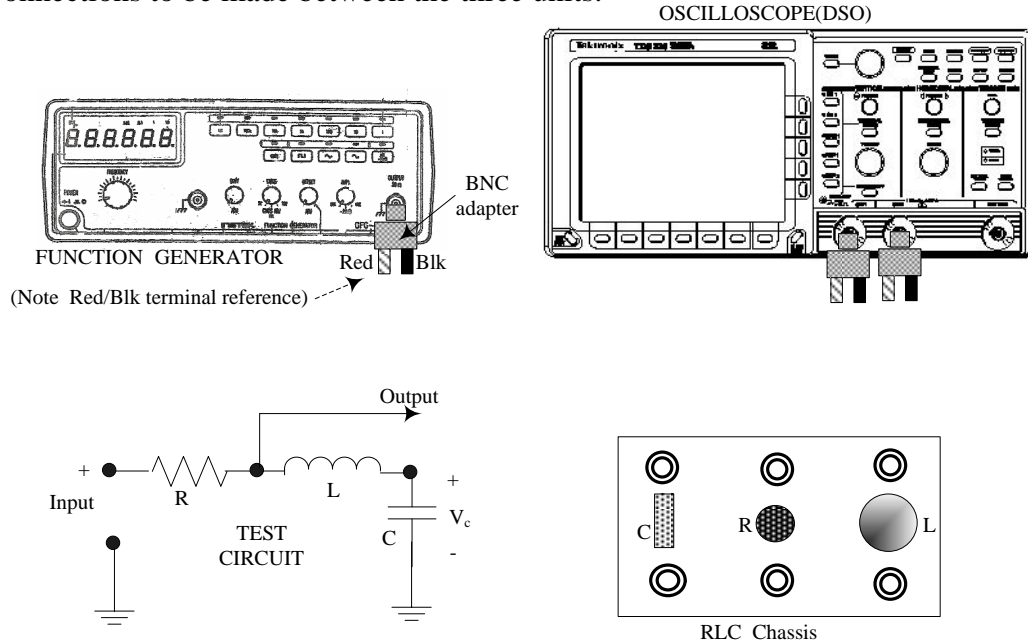
Power dissipated in R ,  $P_R = \dots\dots\dots$  Watts / mW

\* Fill in values of your choice for I & V

continued overleaf >>>>>

**Question #2**

(a) Physical representations of the Instek GFG-8216A Function Generator (FG) and the Tektronix TDS-320 Oscilloscope (DSO) are shown below. The test circuit shown at the lower left is to be implemented using the RLC-chassis, the FG and the DSO. Show (draw) the necessary connections to be made between the three units.



(b) Assume that you have made the proper connections for (a) above and that you next wish to change the test circuit to have only R and C in series, with  $V_c$  as the output. Using a dashed line, show the (single) additional connection required which will accomplish the change.

(c) Two sinusoidal waveforms of the same frequency,  $f$ , are displayed on the oscilloscope. The waveforms are not in phase and the cursors were used to measure the following values:

Time between two adjacent peaks of the same waveform = .....  $\mu s$   
 (choose between 200 to 400  $\mu s$ )

Time between adjacent peaks of the first and second waveform = .....  $\mu s$   
 (choose between 10 to 40  $\mu s$ )

With the values that you have chosen, the frequency is  $f = \dots\dots\dots$  Hz

and the phase-shift between the two waveforms is  $\phi = \dots\dots\dots$  degrees.

## **LAB RECORD (Weight: 30 %)**

### **DC Circuit**

From Step 2: Reference values used :

$R_L \approx \dots\dots\dots$  Ohms ,  $V_s$  knob at  $\approx \dots\dots\dots$  Turns,  $I_s$  knob at  $\approx \dots\dots\dots$  Turns.

From Step 3 : DC Currents:

$I_1 = \dots\dots\dots$  mA,  $I_2 = \dots\dots\dots$  mA,  $I_3 = \dots\dots\dots$  mA.

From Step 4 : DC Node Voltages :

$V_A = \dots\dots\dots$  Volts,  $V_E = \dots\dots\dots$  Volts,  $V_C = \dots\dots\dots$  Volts.

### **AC Circuit [Steps 6 to 11]**

Values of elements used [The RLC meter located on the Printer table can be used to measure the exact values of L and C. Use the available measurement frequency of 1 kHz) :

$R = \dots\dots\dots$ ,  $L = \dots\dots\dots$ ,  $C = \dots\dots\dots$

**[ Make sure to also obtain your TA's signature on the printouts of Step 10 ]**

TA Signature : .....



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## **LAB REPORT** (Weight: 50%)

**DC Results** (See Step 5)

(a) **KCL Verification** :

(b) **KVL Verification** :

(c) **Calculation of  $I_s$** :

(d) **Power Balance**:

Total Power Dissipated  $P_{diss} =$

Total Power Delivered  $P_{del} =$

### **AC Results**

(Step 11)

Amplitude Ratio  $A_v =$  .....

Phase Shift  $\phi =$  .....at frequency  $f_1 =$  .....Hz

Amplitude Ratio  $A_v =$  .....

Phase Shift  $\phi =$  .....at frequency  $f_2 =$  .....Hz

**Attach a final page to the report , summarizing what was learnt in the experiment and adding any comments that you may wish to make about it.**

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## EXPERIMENT 2

### DC CIRCUITS : EQUIVALENT RESISTANCE THEVENIN'S THEOREM and THE MAXIMUM POWER TRANSFER THEOREM

**STUDY OBJECTIVES** : (A) Concept and determination of Equivalent Resistance  
(B) Verification of Thevenin's Theorem & the Maximum Power Transfer Theorem

**PREREQUISITES**: 1. Complete familiarity with the use of the lab instruments, as acquired Experiment #1.  
2. Reading & making an attempt to understand the tutorial and descriptive material given below.

#### **TUTORIAL**

##### **PART (A)**:

**Resistance R and Ohm's Law**: The resistance element R is defined by the DC voltage/current ratio:  $R = V/I$ . This relation between V, I and R is known as Ohm's Law (OL). The law can be also expressed as  $V = IR$  or  $I = V/R$ , where V is the voltage across the terminals of the defined resistance element and I is the current entering the positive terminal, as shown in Figure 2.1(a). R is a dissipative element, and the power P is dissipated as heat energy, raising the temperature of the component.

**The power dissipated in R** is given by  $P = VI$  Watts, with the abovementioned current direction and voltage polarity. Using OL,  $P = I^2R = V^2/R$ , Watts. Since R is always a dissipative element, the current-voltage reference of Figure 2.1(a) is defined as a 'power convention', called the "Passive Sign Convention"(PSC), which is applicable to all dissipative elements.

According to the PSC, power calculated using the current direction/voltage polarity of Figure 2.1(b) will yield a positive value if the circuit within the block is dissipative. If the power calculated in this manner yields a negative value, then the circuit concerned is behaving like a source. It should be noted that the current direction in R is always into the positive terminal signifying a drop in potential (ie a 'voltage drop').

**Equivalent Resistance**: Based on Ohm's Law, an equivalent resistance  $R_{eq}$  may be defined between any two terminals 'A' & 'B' of a network, shown as a rectangular block in Figure 2.1(b). The network may consist of a single resistor or a circuit composed of many arbitrarily connected resistors.

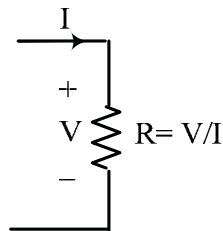


Figure 2.1(a)

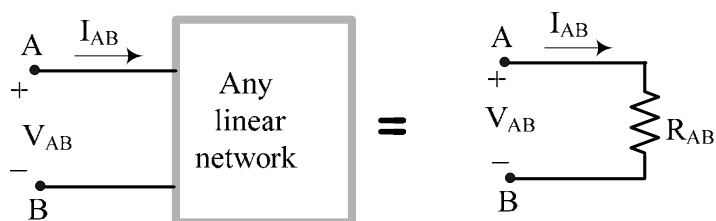


Figure 2.1(b)

The equivalent resistance  $R_{AB}$  between terminals ‘A’ and ‘B’ of the network in Figure 2.1(b) is given by  $R_{AB} = V_{AB} / I_{AB}$ , where  $V_{AB}$  is the voltage across the terminals (‘A’ being positive with respect to ‘B’) and  $I_{AB}$  is the current entering terminal ‘A’. Thus, if  $V_{AB}$  and  $I_{AB}$  are found, either by measurement or by analysis, the equivalent resistance  $R_{AB}$  can be calculated from the ratio  $V_{AB} / I_{AB}$ .

**In this experiment, students will construct a 5-resistor series-parallel network and determine the resistance  $R_{AB}$ , with respect to two specified terminals of the network in three different ways: (i) by theoretical calculation, using nominal values of the resistors, (ii) by current-voltage measurements to determine  $R_{eq}$ , and (iii) by direct Ohmmeter measurement.**

PART (B): Thevenin’s Theorem & the Maximum Power Transfer Theorem are two important and affiliated theorems in linear circuit analysis. A ‘linear’ circuit is one which contains only elements that are defined by mathematically linear current-voltage relationships, such as R and the ideal voltage and current sources. The two theorems are concerned with the behaviour of any given linear network acting as a source. Thevenin’s Theorem states that any linear network containing sources and resistances [Figure 2.2(a)] can be reduced to a simple equivalent circuit [Figure 2.2(b)] consisting of a single independent constant voltage source  $V_T$  in series with a single resistance  $R_T$ , with respect to a specified pair of terminals ‘a’ and ‘b’. This equivalent circuit is called the “Thevenin Equivalent Circuit (TEC) with respect to terminals a & b”.  $V_T$  and  $R_T$  are respectively called the Thevenin Equivalent Voltage and the Thevenin Equivalent Resistance. In circuit analysis, replacing a large network (or even a section of it) with a TEC can result in considerable simplification. For example, if it is required to find the current  $I_L$  or the voltage  $V_L$  associated with a specific resistance  $R_L$ , then replacing the remainder of the network connected to  $R_L$  with a TEC will result in the simple circuit shown in Figure 2.2(c), from which the current  $I_L$  and the voltage  $V_L$  are easily found, using OL and the voltage-division rule, respectively, as

$$I_L = \frac{V_T}{R_T + R_L} \quad \text{and} \quad V_L = V_T \left[ \frac{R_L}{R_T + R_L} \right]$$

The resistance  $R_L$  connected to the TEC is called the ‘load’. [Note: The load need not be a single resistance; it can be the ‘equivalent resistance’ of another network]. Regarding the rectangular block in Figure 2.2(a) as a ‘real source’ (such as a battery or a power supply), it can be seen that the TEC of Figure 2.2(b) is in fact the *equivalent circuit* of the real source. Specifications of real sources list the ‘open circuit voltage’  $V_o$  or ‘terminal voltage’  $V_t (=V_T)$  and the ‘internal resistance’  $R_i$  or ‘source resistance’  $R_s (=R_T)$ .

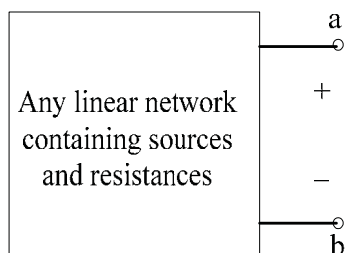


Figure 2.2(a)

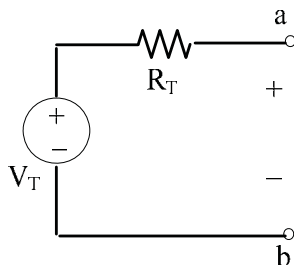


Figure 2.2(b)

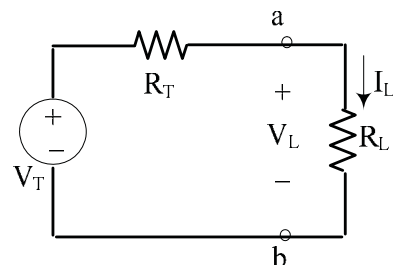


Figure 2.2(c)

Both  $V_T$  and  $R_T$  can be obtained from just two measurements made at the terminals ‘a’ and ‘b’ of the linear network of Figure 2.2(a) as can be seen from the following reasoning : From

the TEC of Figure 2.2(b), the ‘open-circuit voltage’  $V_{ab}(oc)$  [ie the voltage  $V_{ab}$  when nothing is connected to the terminals a-b] is equal to the Thevenin voltage  $V_T$  since the voltage drop across  $R_T$  will be zero as a result of there being no current through the open-circuited terminals, ie  $V_{ab}(oc) = V_T$ . Further, if the terminals a-b are short-circuited, the resulting current in the short-circuit from ‘a’ to ‘b’ will be  $I_{ab}(sc) = V_T/R_T = V_{ab}(oc)/R_T$ , from which we obtain  $R_T = V_{ab}(oc)/I_{ab}(sc)$ . Thus, only two measurements,  $V_{ab}(oc)$  and  $I_{ab}(sc)$ , are sufficient for the determination of the TEC with respect to the terminals a-b.

The above “ $V_{ab}(oc)$ - $I_{ab}(sc)$  method”, as this method is called, is generally used only for the theoretical determination of the TEC, for the following reason : While it is easy to measure the “open-circuit voltage”  $V_{ab}(oc)$  of the network, short-circuiting its terminals to measure  $I_{ab}(sc)$  could result in a destructively high current if the value of  $R_T$  (which is unknown) happens to be small ! Therefore, instead of trying to measure  $I_{ab}(sc)$ , the voltage  $V_x$  developed across a known load resistance  $R_x$  placed across the reference terminals is measured. The load resistance value used must result in a reduction of the terminal voltage, however small. Then, by voltage-division,  $V_x = V_T R_x / [R_T + R_x]$ , from which we obtain:

$$R_T = R_x \left[ \frac{V_T}{V_x} - 1 \right]$$

Since the values of  $V_T$ ,  $V_x$  and  $R_x$  are known,  $R_T$  can be found .

A theoretical calculation of  $R_T$  can also be made, using the following reasoning: Considering again the circuit of Figure 2.2(b), it is seen that  $R_T = R_{ab}$  if the source  $V_T$  is ‘killed’ by setting its value to zero. Thus , if the circuit within the network block shown in Figure 2.2(a) is known,  $R_T$  is equal to the ‘dead resistance’  $R_{ab}(dead)$ , between the reference terminals ‘a’ and ‘b’, when all the independent voltage sources (and current sources ) within the network are reduced to zero (ie ‘killed’).

{ To ‘kill’ a voltage source, replace it with a short-circuit(sc) and to ‘kill’ a current source replace it with an open-circuit (oc) } .

It is important to remember that finding  $R_{ab}(dead)$  is only possible if all the sources internal to the network can be ‘killed’. Since the discrete internal structure of the network is not generally accessible, finding  $R_T = R_{ab}(dead)$  remains an analytical procedure applied to the actual circuit constituting the network.

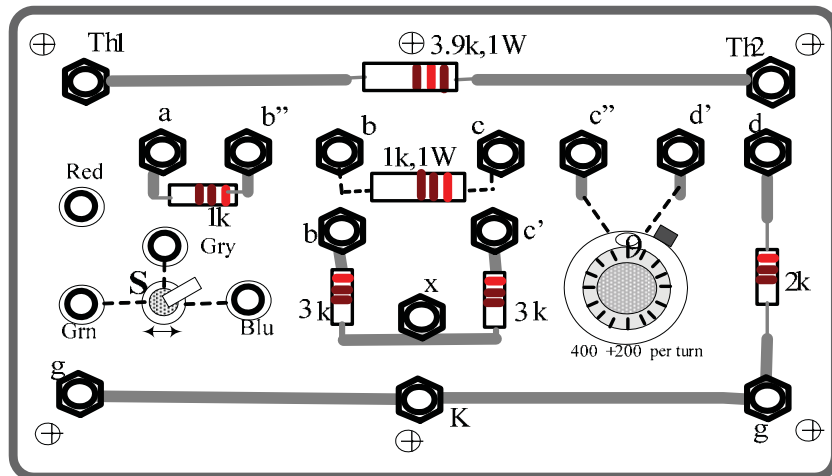
The Maximum Power Transfer (MPT) theorem answers the question of how a load resistance  $R_L$  can be selected so that the maximum power  $P_L(max)$  can be drawn from a real source that is represented by a TEC. The MPT theorem can be considered to be a corollary of Thevenin’s theorem. It states that maximum power is transferred to  $R_L$  [see Figure 2.2(c)] from the TEC (and hence from the original network or ‘real source’ ) when  $R_L = R_T$ .

When the MPT condition  $R_L = R_T$  is satisfied,  $I_L = V_T/2R_T$  and the maximum power is given by  $P_L(max) = (V_T)^2 /4R_T$ . **Note that when  $R_L = R_T$ , the load voltage  $V_L = V_T/2$ .** This last result suggests yet another ‘non destructive’ way of finding  $R_T$ : Use a calibrated, variable load resistance  $R_L$  and , starting from a high value, reduce  $R_L$  until the load voltage falls to exactly one-half of the ‘open circuit’ value, ie until  $V_L = V_{ab}(oc)/2$ . The value of  $R_L$  at this setting is the value of  $R_T$ . **In the lab experiment, this method will be used to obtain the TEC of a network.**

## EXPERIMENTAL

The experiments are performed using a component box whose photograph is shown in Figure 2.3 together with an outline drawing of the panel. Several components [also listed in the figure] are mounted on the box along with banana-jack terminals, which are used both for onboard and

other interconnections. Some internal connections are already made between the terminals as seen in the outline drawing of Figure 2.3. Banana-plug patch cords of various lengths and colours, which are available in the lab, are used to make all interconnections. The box has 6 resistors of fixed value and one variable resistor (potentiometer) fitted with a 10-turn, turns-counting dial from which the value of the latter resistance can be obtained.



### Terminal Connection Reference

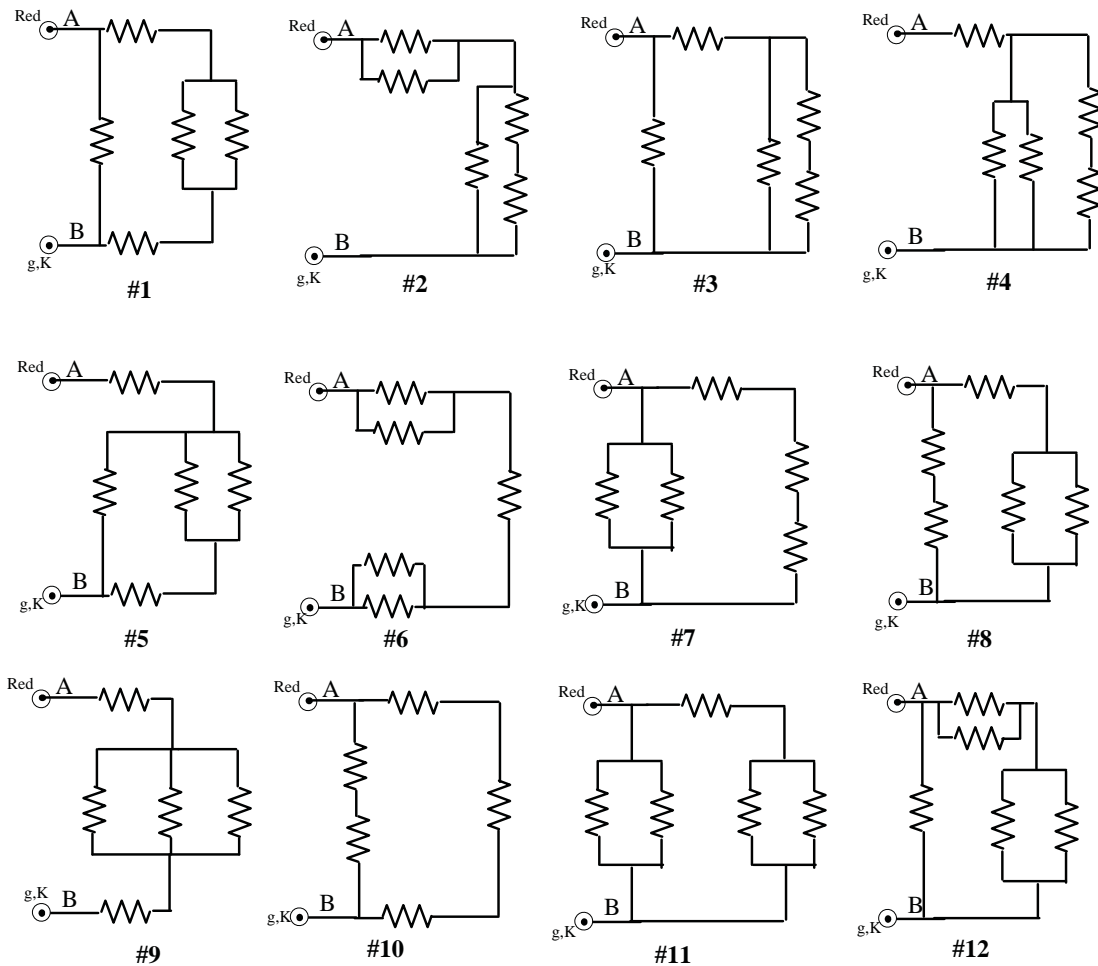
<u>Terminals</u>	<u>Component Connected</u>
g-K-g	Ground bus (internally interconnected)
a – b''	1 kΩ , 0.25 W resistor
d – g (Gnd)	2 kΩ , 0.25 W resistor
b' - x - c'	3 kΩ , 0.25 W resistors are connected between b' & c' and an unmarked terminal(x)
c'' – d'	400 Ω resistor in series with a 2kΩ potentiometer fitted with a 10-turn dial [Total range : 0.4 to 2.4 kΩ ]
b-c	1 kΩ , 1W resistor
Th1-Th2	3.9 kΩ ,1W resistor
Red	Unconnected [Use as <u>input</u> anchor terminal]
Grn,Gry,Blu	SPDT switch S [Gry connects to Grn when toggled to the left. Gry connects to Blu when toggled to the right.]

Figure 2.3

The six fixed value resistors, together with the (400Ω + 2 kΩ) potentiometer are to be interconnected using available short banana plug patch cords to construct various **5-resistor networks** in this experiment. Typical 5-resistor series-parallel networks are shown in Figure 2.4.

**Note:** The component values given in Figure 2.3 are nominal standard values. The actual values should be measured (& recorded) using the bench DMMs and/or the RCL-Meter which is located on the printer table in the lab.

**Typical Series-Parallel Resistor Circuits using 5 Resistors**



**BASIC RESISTANCE-COMBINATION RULES:**

For resistors connected in series,  $R_{eq} = R_1 + R_2 + R_3 + \dots$  Etc

For resistors connected in parallel,  $1/R_{eq} = (1/R_1) + (1/R_2) + (1/R_3) + \dots$  Etc

For TWO resistors connected in parallel,  $R_{eq} = R_1R_2/(R_1 + R_2)$

**Figure 2.4**



## PROCEDURE & RESULTS :

### [PART (A)]: Equivalent Resistance of a network

1. Select a circuit from the collection in Figure 2.4 and label the resistances for your reference. Assign available resistance values to the various resistors and construct the chosen network on the Expt#2 box with the 'Red' and (g,K) terminals as 'input terminals' A and B respectively. Use the shortest banana-plug patchcords available to interconnect the various onboard components.
2. **Make sure that the PSP is switched OFF.** Connect the Expt#2 box to the two DMMs and to the PSP as shown in Figure 2.5 with the DMMs set in the indicated modes/ranges. Note that the nominal +15v output of the PSP is connected to the 'Red' input terminals through the Fluke DMM set in the ammeter mode and the PSP ground is connected to the (g,K) terminals on the box. The Agilent DMM is connected to measure the voltage at the above input terminals.
3. Neatly redraw the circuit which you selected in the area provided in the Lab Record section, showing all resistor values. Then, enter\* the calculated value of the input resistance  $R_{in}$  between the 'Red' and (g,K) terminals] using the nominal values of the resistors that were selected. **\*Use the data tables provided in the Lab Record to record these values as well as all subsequent experimental data.**

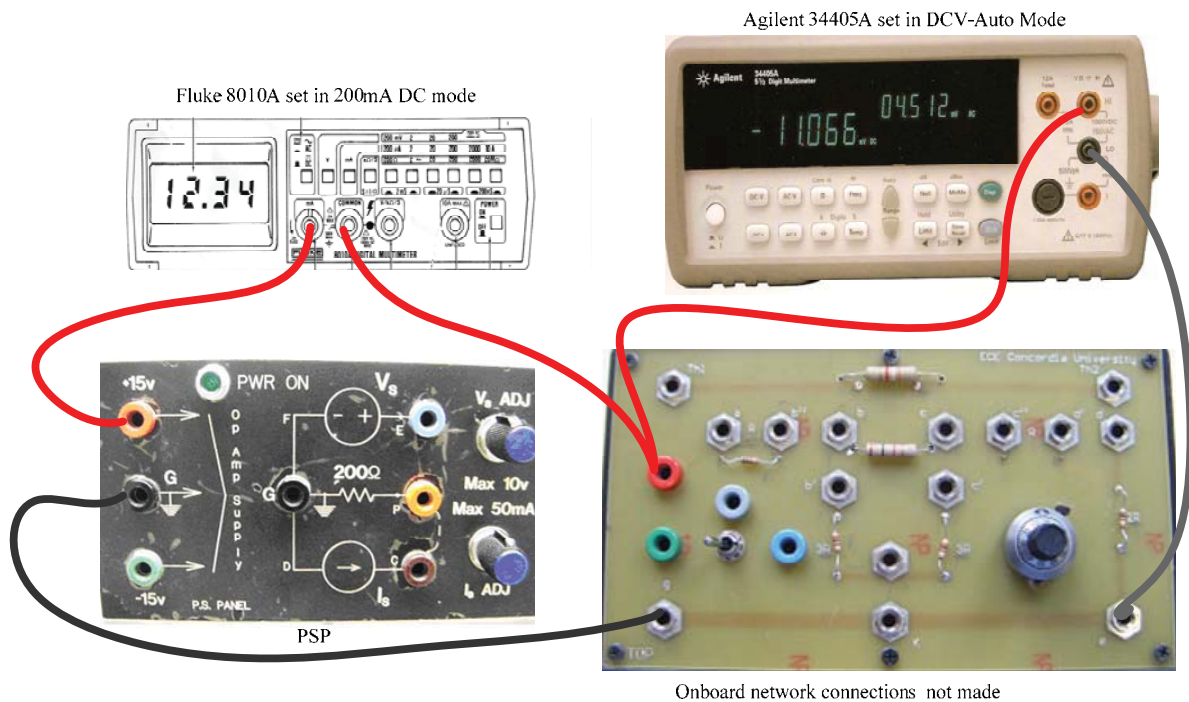


Figure 2.5

4. **Switch ON the PSP** using the switch on the master power supply .The Agilent DMM should indicate a voltage  $V_{in}$  of 15 volts nominal and the Fluke DMM will display the current  $I_{in}$  being drawn by the selected network. Record their exact values.
5. **Switch OFF the PSP** and **remove the patchcords connected to the PSP and to the Fluke DMM.** Then switch the Agilent DMM to function as an Ohmmeter. This meter should now display the directly measured value of the equivalent resistance of the network between terminals A (Red) and B (g,K). Record its value.

**Results:** Determine the ratio  $R_{in} = V_{in}/I_{in}$  in the Lab Report and compare its value with the corresponding calculated ('theoretical') value obtained in Step 3 and the Ohmmeter-measured value of Step 5.

=====

[PART (B)]: **Thevenin Equivalent Circuit (& Maximum Power Transfer verification):**

The circuit shown in Figure 2.6 will be used for the verification of the Thevenin and MPT theorems. The network is constructed using the fixed resistors for  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$ . The variable resistor (400  $\Omega$  to 2400  $\Omega$ ) is used as a variable load  $R_L$ . The Gray and Green terminals of the on-board SPDT switch  $S$  are connected together so that  $S$  acts as a SPST switch which can be used to connect or disconnect the load  $R_L$  from the circuit to the left of terminals a-b, whose TEC is to be determined.. The +15 volt output from the PSP is to be connected to the 'Red' terminal , as in Part A, and the Gry-Grn terminal of effective SPST switch  $S$  is designated as the output terminal of the complete circuit to the left of terminals a-b . The Blue terminal of  $S$  is connected to the load so that toggling  $S$  to the right will connect the load to the TEC while toggling it to the left will disconnect the load from the TEC.

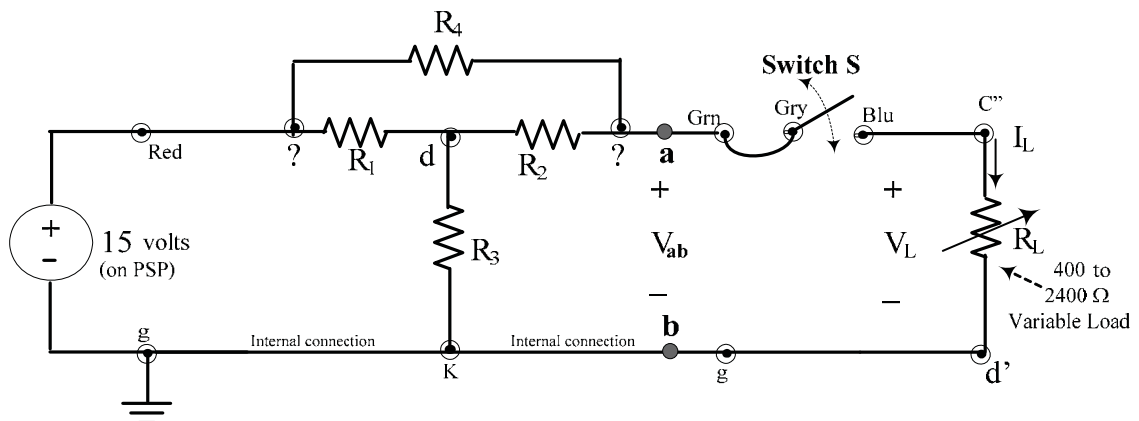


Figure 2.6: Circuit used for verification of Thevenin's & the MPT Theorems

The theoretical Thevenin resistance  $R_T$  for the circuit of Figure 2.6 is the resistance seen from the right (between the Gry/Grn terminal of  $S$  and 'g'), with  $R_L$  disconnected and with the 15v source **replaced by** a short-circuit [Do not short circuit the source !]. That is,

$$R_T = R_4 \parallel [R_2 \parallel (R_1 \parallel R_3)]$$

where P stands for ‘is in parallel with’ and S stands for ‘is in series with’. The corresponding theoretical Thevenin voltage  $V_T$  can also be obtained by analysis. For example, using mesh analysis to find the voltage drops across  $R_2$  and  $R_3$  and summing them, we obtain:

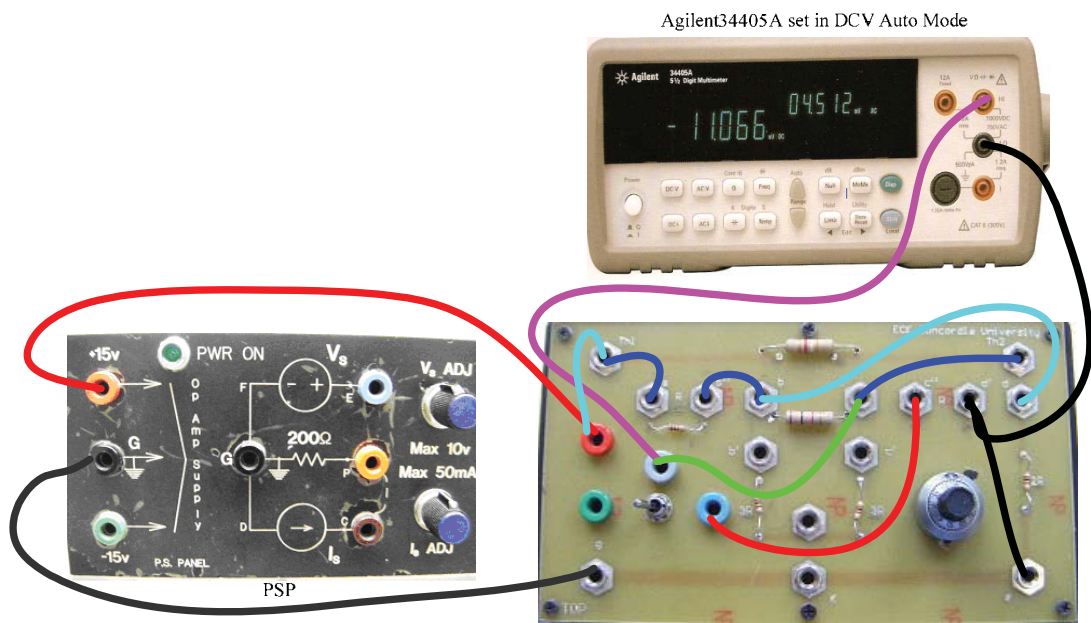
$$V_T = 15 \left[ \frac{R_3(R_1 + R_2 + R_4) + R_1 R_2}{(R_1 + R_3)(R_1 + R_2 + R_4) - R_1^2} \right]$$

The table below gives the calculated values for  $R_T$  and  $V_T$  corresponding to some chosen sets of the available resistor values.

$V = 15$  volts

$R_1$ k $\Omega$	$R_2$ k $\Omega$	$R_3$ k $\Omega$	$R_4$ k $\Omega$	Resulting $R_T$ k $\Omega$	Resulting $V_T$ volts
3	3	2	1	~ 0.81	13.27
3	1	2	3	1.27	9.81
1	3	2	3	1.65	12.75
3	3	2	3.9	2.02	10.67
3	3	1	2	1.30	11.09
1	1	2	3.9	1.17	11.5

- Construct the circuit of Figure 2.6 using any of the sets of values given in the table above. A typical setup (showing onboard connections corresponding to the last set in the table) is shown in Figure 2.7. **Make sure the PSP is turned OFF** and switch S is toggled to the left.



Onboard network connections shown correspond to the last set in the table

**Figure 2.7**

7. Set the variable load to its maximum by turning the dial to its extreme CW position. Then **turn ON the PSP**. The meter should display the corresponding 'open circuit' voltage,  $V_{ab}(oc)$  [≡ the Thevenin voltage  $V_T$ ]. Record its exact value.
8. Toggle the switch  $S$  to the right and then progressively decrease  $R_L$ , by turning the 10-turn dial CCW, until the value of  $V_L$  displayed by the DMM falls to exactly one-half of  $V_{ab}(oc)$ . Note the dial reading and record the corresponding value of  $R_T$ . [This is the experimental value of  $R_T$  and it should correspond with the corresponding 'theoretical' value of  $R_T$  given in the table]

{ Alternatively, set the 10-turn dial to obtain a known value of  $R_L = R_x$  which is in the range of 40 to 60% of the 'theoretical'  $R_T$ . Note the corresponding load voltage  $V_x$  and determine  $R_T$  from the voltage-division rule as explained in the tutorial. }

- 9 **MPT Verification:** Using the 10-turn dial, set the variable load value ( $R_L$ ) first to two values  $R_b, R_a$  which are progressively lower than  $R_T$  ( which is the value of  $R_L$  which results in  $V_L = 0.5V_T$  ) and next, to two values  $R_c, R_d$  which are progressively higher than  $R_T$  and record the load voltage in each case in the data table of the Lab Record (p39). The settings chosen must be such that a small but significant change occurs in the load voltage value.

**Results:** Compare the experimentally obtained values of  $V_T$  &  $R_T$  with the 'theoretical' values. Use the data of Step 9 above to plot the experimental load power in the coordinate space provided in the Lab Report to show that the load power is a maximum when  $R_L = R_T$ . The experimental load power is obtained from  $P_L = (V_L)^2 / R_L$  where  $V_L$  is the load voltage measured in Step 9 for each value of  $R_L$  used.

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**PRE-LAB** [ To be completed and submitted before performing Lab # 2 ]  
**(Weight: 20%)**

**PART (A): (i)** Ohm's Law (OL) defines the element R (resistance) as  $R = V/I$ , where V is the voltage (Volts) and I is the current (Amps) and R is the resistance(Ohms)  
From this definition, we have  $V=IR$  and  $I=V/R$ . The power P (Watts) dissipated in a resistance R is given by  $P = VI = I^2R = V^2/R$ .  
In the four cases below, arbitrarily assign numerical values for the first two quantities and then use OL to fill in the value for the third (dependent) quantity.:

- (a)  $I = \dots\dots\dots \text{mA}$ ,  $V = \dots\dots\dots \text{volts}$ ,  $R = \dots\dots\dots \text{ohms}$
- (b)  $R = \dots\dots\dots \text{k}\Omega$ ,  $V = \dots\dots\dots \text{volts}$ ,  $I = \dots\dots\dots \text{mA}$
- (c)  $V = \dots\dots\dots \text{volts}$ ,  $R = \dots\dots\dots \Omega$ , Power  $P = \dots\dots\dots \text{Watts}$ .
- (d)  $P = \dots\dots\dots \text{kW}$ ,  $V = \dots\dots\dots \text{volts}$ ,  $I = \dots\dots\dots \text{A}$ ,  $R = \dots\dots\dots \Omega$

**(ii)** Choose any **one** of the 5-resistor series-parallel circuits in Figure 2.4 and redraw the chosen circuit in the space below. **Assign resistance values** in the 1 k $\Omega$  to 3 k $\Omega$  range to the various resistors in each case (mark the values on the circuits) and calculate the input resistance  $R_{AB}$  of your chosen circuit .

$R_{ab} = \dots\dots\dots$

(Continued Overleaf >>>> )

Name: \_\_\_\_\_ ID# \_\_\_\_\_ Lab Section: \_\_\_\_\_

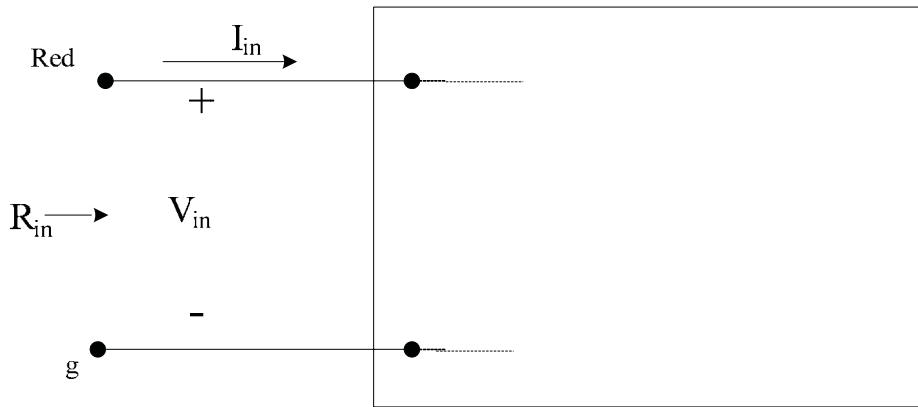
**PART (B): TEC & MPT**

(i) For the circuit that you selected in PART (A), Sec (ii) of this pre-lab, consider that a 15 volt DC source is connected to terminals A & B (with A positive). Then choose any one of the resistances in the circuit to be the load and re-draw the 'source-load' circuit in the space below. **Analytically** determine the TEC with respect to the chosen load. [ Clearly specify the resistance which is selected as the load.]. Draw the TEC showing  $V_T$ ,  $R_T$  and  $R_L$ .

(ii) Find the maximum power that can be drawn from the above TEC.

**LAB RECORD (Weight: 30 %)**

**PART A** [Step 3] : Draw the series-parallel circuit, which you have selected in the space within the dotted outline showing all resistance values clearly. **Calculate the theoretical value of  $R_{in}$  for your network., ie  $R_{in}$  (calc). This will be used as a ‘reference’ value .**



[Neatly draw your selected circuit within the block and indicate all R values used]

Measurements [Steps 1 to 5] :

Calculated Value of  $R_{in}$  (calc) = .....  $\Omega$ . (for the above circuit)

Exact input voltage  $V_{in}$  = ..... volts ,  $I_{in}$  = ..... A / mA

$R_{in}$  value (from current/voltage measurements)

$R_{in}$  (expt) =  $V_{in}/I_{in}$  = .....  $\Omega$ .

Ohmmeter-measured Value of  $R_{in}$ (OM) = .....  $\Omega$ .

**PART B** : TEC & MPT [Refer to Figure 2.7]

Step 7 : Open-Circuit voltage :  $V_{ab}(oc) = V_T =$  ..... Volts

Step 8 : Dial reading when  $V_L = 0.5 V_T$ ,  $N =$  .....  
& the corresponding value of  $R_L =$  ..... Ohms

{ or

Load Voltage  $V_L =$  ..... Volts , with  $R_L =$  ..... Ohms }

TA Signature: .....



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( LAB RECORD Continued )

Maximum Power Transfer Theorem Verification : [Step 9]

Nominal Load Resistor ( $R_L$ ) Values used: [Note:  $R_a < R_b < R_T$  and  $R_d > R_c > R_T$ ]

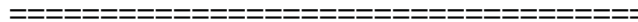
[  $R_L = R_T$  when  $V_L = V_T/2$  ]

$R_a = \dots \Omega$ ,     $R_b = \dots \Omega$ ,

$R_c = \dots \Omega$ ,     $R_d = \dots \Omega$ ,

Load Resistance $R_L \Omega$	Load Voltage $V_L$ volts	$P_L = (V_L)^2/R_L$ W or mW
$R_a =$		
$R_b =$		
<b><math>R_L</math> (for <math>V_T/2</math>)</b>		
$R_c =$		
$R_d =$		

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**LAB REPORT** (Weight: 50%)

**PART (A) : ERROR ANALYSIS:** Calculate the error observed in the experimentally determined  $R_{in}(Expt)$  and in the ohmmeter-measured value  $R_{in}(OM)$  with respect to the theoretical value  $R_{in}(calc)$ . Comment on the results.

Error in  $R_{in}(expt) = 100 [R_{in}(expt) - R_{in}(calc)] / R_{in}(calc) = \dots\dots\dots\%$

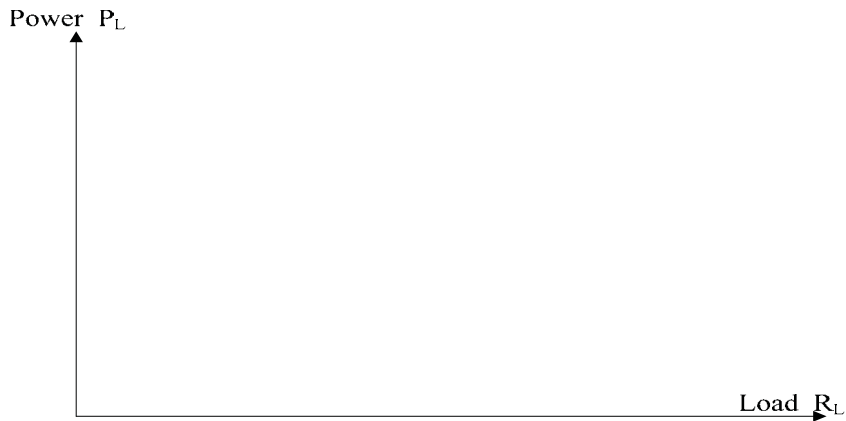
Error in  $R_{in}(OM) = 100 [R_{in}(OM) - R_{in}(calc)] / R_{in}(calc) = \dots\dots\dots\%$

**PART (B) :TEC & MPT :**

(a) Calculate the value of  $V_T$  and  $R_T$  from the data of Steps 7 & 8  
**Draw the TEC in the space provided below.**

(b) The maximum power available from the TEC is  $P_{max} = \dots\dots\dots W$

(c) Plot  $P_L$  against the five selected values of  $R_L$  in the co-ordinate space provided below :



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**DISCUSSION & CONCLUSION:** [Discuss possible reasons for any differences observed between theory and the experimental results. Express, **in your own words**, what you learnt from this experiment. ]

**Please remember to follow all report-format and submission rules given earlier !**

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## EXPERIMENT 3

### AC CIRCUITS : PHASORS and IMPEDANCE DETERMINATION

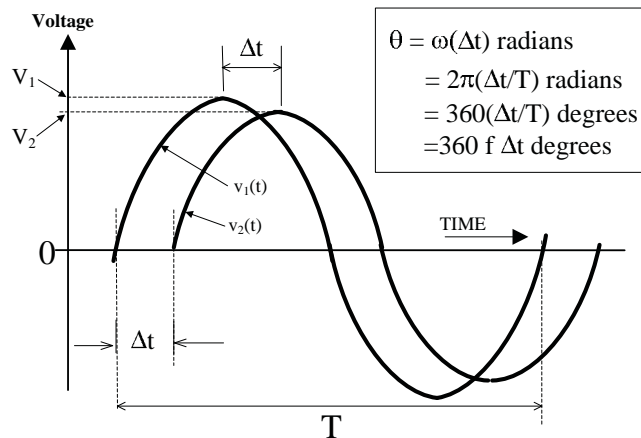
**STUDY OBJECTIVES** : (A) Voltage & Current phasor relationships  
(B) Determination of an impedance Z

**PREREQUISITES**: 1. Complete familiarity with the use of the lab instruments as acquired in Experiment #1 .  
2. Reading & making an attempt to understand the material given in Appendix-B, as well as in the tutorial/descriptive material given below, before coming to the laboratory

#### **TUTORIAL**

**PART [A]**: This experiment is concerned with sinusoidal voltages and currents which are encountered in AC circuits. AC circuit analysis is performed using a phasor-equivalent circuit, which is obtained from the original time-domain circuit by replacing all currents and voltages by their phasor-equivalents and all the passive elements by their impedances. Phasors and impedance are explained with examples in Appendix-B. In this experiment, the oscilloscope is used to observe magnitude and phase relations between sinusoidal waveforms .The experimental data is also used to determine the impedance Z, using various circuit examples.

A phasor simply expresses the magnitude (conventionally, in RMS units)of a voltage or current and its *phase relationship* with respect to a reference waveform. The zero-phase cosine function  $A\cos(\omega t + 0^\circ)$ , is conventionally taken as the reference signal, with its equivalent phasor defined as  $A\angle 0^\circ$ . For example, consider the display of the two waveforms  $v_1(t)$  and  $v_2(t)$  shown in Figure 3.1.



**Figure 3.1:** Phase-shift determination from time-difference  $\Delta t$

If  $v_1(t)$  is taken as the reference, it is seen that  $v_2(t)$  lags (*ie* occurs later)  $v_1(t)$  by the time difference  $\Delta t$ , which is directly related to the phase shift  $\theta$ . The phase lag (in this case) is given by  $\theta = 360f\Delta t$  degrees. Thus, the phasors corresponding to  $v_1(t)$  and  $v_2(t)$  are respectively  $0.707V_1\angle 0^\circ$  and  $0.707V_2\angle -\theta^\circ$ , volts RMS, the negative sign for  $\theta$  indicating that  $v_2(t)$  lags  $v_1(t)$ . A phasor diagram can be drawn showing the above magnitude and phase information.



For example, consider two waveforms as in Figure 3.1, and let  $V_1 = 4$  volts (reference),  $V_2 = 3.8$  volts,  $f = 2$  kHz and  $\Delta t = 115 \mu\text{s}$ . Then the corresponding two RMS voltages are respectively 2.83 and 2.69 volts and the  $V_2$  phasor lags the reference phasor by  $(360)(2000)(115 \times 10^{-6})$  or  $\approx 83^\circ$ . The  $V_2$  phasor is hence written as  $2.69 \angle -83^\circ$ . The corresponding phasor diagram for  $V_1$  and  $V_2$  can now be drawn as shown in Figure 3.2.

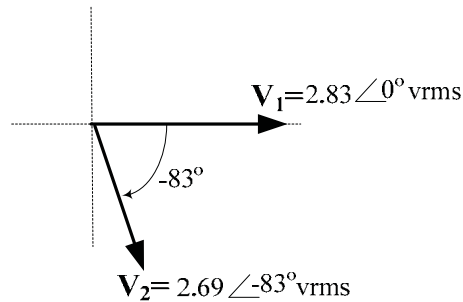


Figure 3.2

**Phase angle observation:**

The ‘series RLC circuit’ (shown in Figure 3.3) is used in this experiment to display ‘lead’ and ‘lag’ phase relations between waveforms. For the circuit, operating at a frequency  $f = \omega/2\pi$  Hz, the equivalent terminal impedance  $Z$  is given by :

$$Z = j\omega L + 1/j\omega C + R = R + j[\omega L - 1/\omega C] = R + jX$$

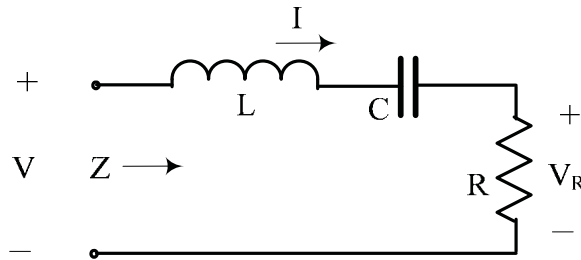


Figure 3.3 : Series RLC circuit

At the resonant frequency  $f = f_0 = \frac{1}{2\pi\sqrt{LC}}$ , the reactance  $X = 0$ , hence  $Z = R$  and the associated voltage and current waveforms (& their phasors) will be in phase with each other. Varying the frequency across  $f_0$  will cause the impedance angle  $\theta$ , given by

$$\theta = \tan^{-1} \frac{(\omega L - \frac{1}{\omega C})}{R},$$

to change from negative values (current  $I$  leads voltage  $V$ ) to positive values (current  $I$  lags voltage  $V$ ). **The above ‘lead’ and ‘lag’ situations can be seen on (and measured from) the DSO display of the  $v(t)$  and  $i(t)$  waveforms.** Since an oscilloscope basically displays voltage inputs, it will be necessary to obtain a voltage signal that is directly proportional to  $i(t)$ . In the above circuit, such a signal is readily available as the voltage drop  $v_R(t)$  across  $R$ . Since  $v_R(t) = R i(t)$ , the  $v_R(t)$  waveform displayed will in fact be a scaled version of  $i(t)$ ,  $R$  being the scaling factor. Thus, a display of both  $v(t)$  and  $i(t)$  can be achieved by using the circuit shown in Figure 3.4, which is

the same as that in Figure 3.3, but with function generator(FG) and oscilloscope (DSO) connections added.

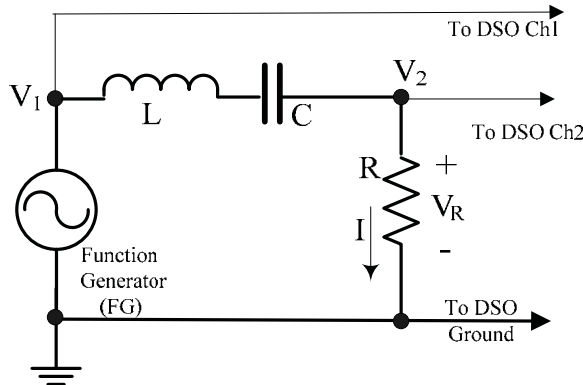


Figure 3.4

Both  $V_1$  and  $V_R(V_2)$  are node voltages referenced to the common ‘ground’ of the FG and DSO. The voltage  $V_1$  on Ch1 is taken as the ‘zero-phase’ reference waveform and it represents the voltage  $V$  across  $Z$  in Figure 3.3. The voltage  $V_2 (=V_R)$  on Ch2 is a scaled version of the current phasor  $I$  as mentioned before. The phase lead or lag can be found at any given frequency by measuring the time difference  $\Delta t$  between two adjacent reference points, such as the peaks or the zero-crossings in Figure 3.2. Recall that  $V$ -bar cursors are available on the DSO to find  $\Delta t$ .

**Impedance determination:**

The circuit of Figure 3.4 also allows the determination of the total impedance  $Z$  connected to the FG. Taking  $V_1 \angle 0^\circ$  as the reference being displayed on Ch1, the signal on Ch2 is  $V_2 \angle \theta^\circ$  where  $\theta^\circ$  is the measured lead or lag magnitude given by  $(360 f \Delta t)$ degrees. Since  $V_2 \angle \theta^\circ = R I \angle \theta^\circ$ , we have

$$Z = \frac{V_1 \angle 0^\circ}{I \angle \theta^\circ} = \frac{V_1 \angle 0^\circ}{\frac{V_2 \angle \theta^\circ}{R}} = R \frac{V_1}{V_2} \angle -\theta^\circ$$

With  $R$  known and the quantities  $V_1$ ,  $V_2$  and  $\theta$  measured on the oscilloscope, the impedance  $Z$  connected to the FG can be determined at any given frequency.

**In the experiment, circuits similar to the one in Figure 3.4 will be used to observe voltage-current phase relations and to measure the impedance of some test circuits. .**

**EXPERIMENTAL**

The experiments are performed using a component box whose photograph is shown in Figure 3.5 together with an outline drawing of the panel. Several components are mounted on the box along with banana-jack terminals, which are used for onboard as well as input-output interconnections. A detailed terminal-reference list is given following the figure. Some internal connections are already made between the terminals as seen in the outline drawing. Banana-plug patchcords of various lengths and colours, which are available in the lab, are used to make all interconnections. The box has 3 resistors of fixed **nominal** values of  $200\Omega$ (or  $240\Omega$ ),  $2.2\text{ k}\Omega$  and a ‘grounded’  $511\Omega$  and one variable resistor [fitted with a 10-turn, turns-counting dial] whose effective terminal value can be varied continuously from  $60\Omega$  to  $10,060\Omega$ . Two ‘grounded’ capacitors having **nominal** standard values of  $50\text{nF}$  and  $100\text{nF}$  are provided along with an ‘ungrounded’  $220\text{nF}$  capacitor. The on-board inductor has a **nominal** value of  $49\text{mH}$  and it has an ‘internal’ series resistance of  $\approx 113\Omega$  which must be taken into account in calculations.

The term ‘grounded’ in the description above only refers to the common connection between the ‘GND’ terminal on the left, the 511Ω resistor and the 50nF and 100nF capacitors. This common connection need not necessarily be used as the ground. Thus, even the 50nF and 100nF capacitors can be used as series (floating) capacitors by using appropriate connections.

**Use the shortest possible patch cord connections between any given pair of terminals.**

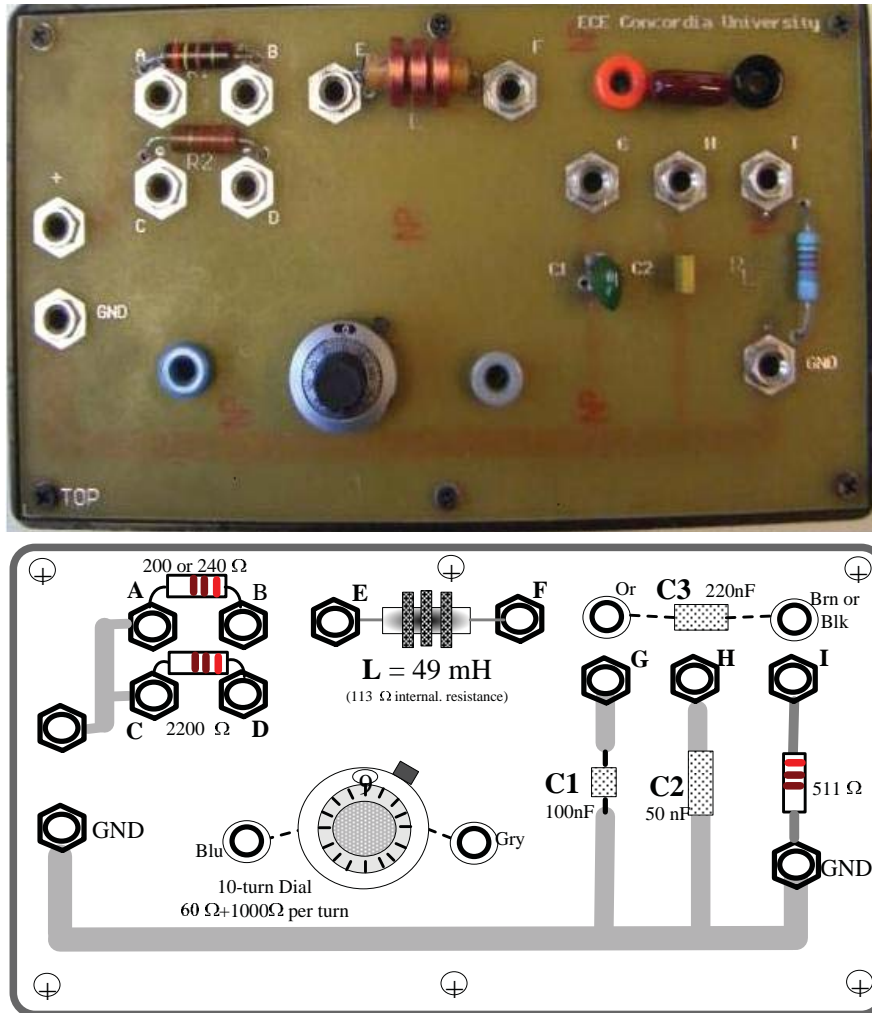


Figure 3.5

**Terminal Connection Reference** (for Figure 3.5)

**TERMINALS**

**CONNECTED COMPONENTS**

**Resistors & busses**

GND	Ground bus ( <u>internally interconnected</u> )
A–B ( $R_1$ )	200Ω <u>or</u> 240Ω , 2W resistor
C–D ( $R_2$ )	2200Ω , 2W resistor
[A - C & top left unmarked terminal are <u>internally connected</u> ]	

I–GND ( $C_2$ )	511Ω ,1 W Resistor (“grounded “)
Blu–Gry	10kΩ ten-turn potentiometer fitted with a 10-turn dial, Connected in series with 60Ω [Total : 0.06 to 10.06 kΩ ]

## Inductor

E-F 49 mH inductor with an internal resistance  $r \approx 113 \Omega$

## Capacitors

Orange–Brown (or Black) 220 nF capacitor “floating”  
G–GND ( $C_1$ ) 100 nF capacitor “grounded”  
H–GND ( $C_2$ ) 50 nF capacitor “grounded”

Although the resistor values are specified in the experimental steps, the student need not use the exact values suggested. Other values can be obtained by combining the onboard resistors and/or using the variable resistor (10-turn potentiometer).

Values given above are for reference. The actual values of all components should be measured in the lab. For resistors and capacitors the bench-top Agilent DMM should be used. For inductors (and capacitors) the RCL-meter (at 1 kHz measurement frequency) located on the printer table may be used.

## PROCEDURE & RESULTS: [A] Phasor relations

- 1 Consider the circuit shown in Figure 3.6. The function generator is shown as a TEC. Make these connections as shown in Figure 3.7 using the Expt#3 box. Where  $C = 220 \text{ nF}$ ,  $R = 511 \Omega$  and  $R_p = 240 \Omega$  (or  $200 \Omega$ ).

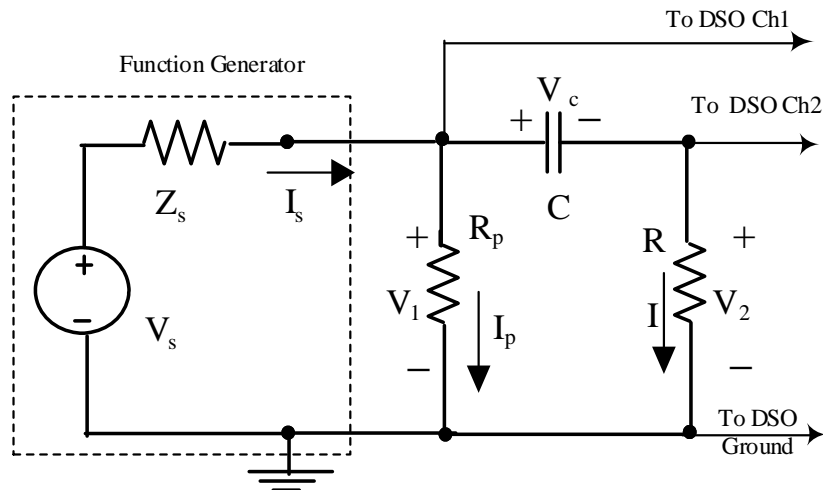


Figure 3.6

2. Set the DSO to measure the RMS amplitudes of both channels. Adjust the channel sensitivities to 1 Volt/div. Turn on the V-bar cursors for  $\Delta t$  measurement. Set the FG to produce a sinewave output of about **2 V<sub>rms</sub>** at **1 kHz**. Show this voltage  $V_1$  as Ch1 on the DSO and display the frequency measurement. (Move the displayed measurements off the graticule by pressing CLEAR MENU.)

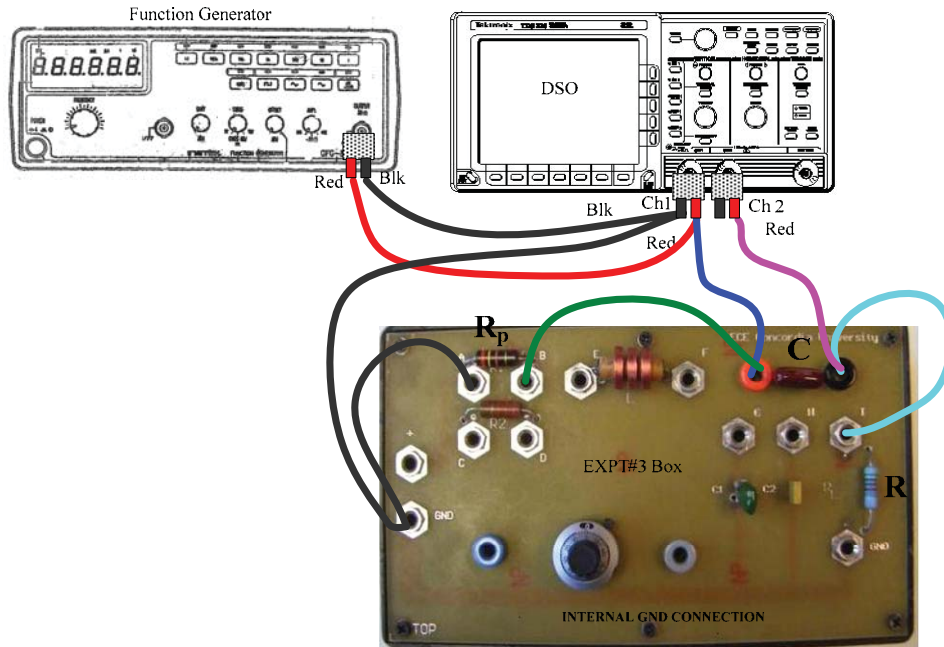


Figure 3.7: Test connections for the circuit of Figure 3.6

- Adjust the Time/Div control until only one or two cycles are displayed. Then position the V-bar cursors to show the time difference  $\Delta t$  between the two waveforms. **Obtain a printout** showing the following information: Ch1 frequency, RMS values of  $V_1$  &  $V_2$  and  $\Delta t$ . A typical display is shown in Figure 3.8. Enter the values shown on **your** printout into the Lab Record.

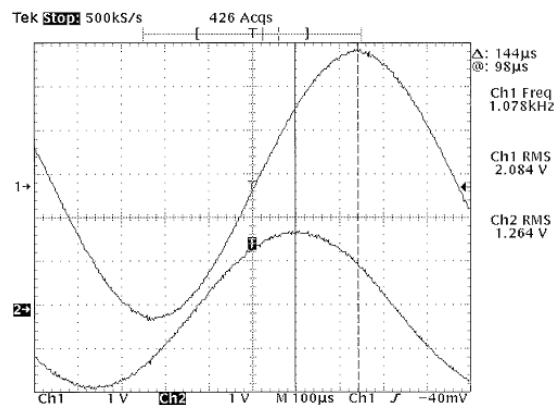


Figure 3.8

- Next, consider the series RLC circuit shown in Figure 3.9. Typical connections are shown in Figure 3.10 with  $C_{eq} = (220+100+50)nF = 370nF$  and  $R = 511\Omega$ . Make the connections shown in Figure 3.10 with the FG and DSO settings retained as in Step 2. **Note that the three C's are in parallel and terminal I is now used as the ground!**

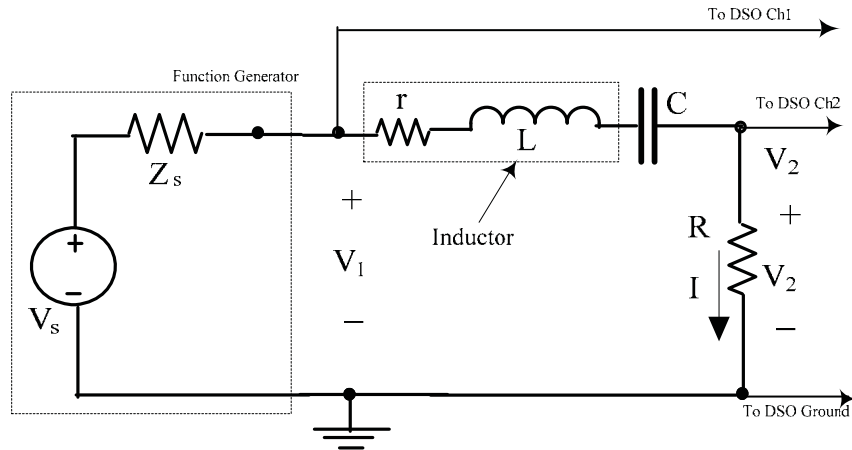


Figure 3.9

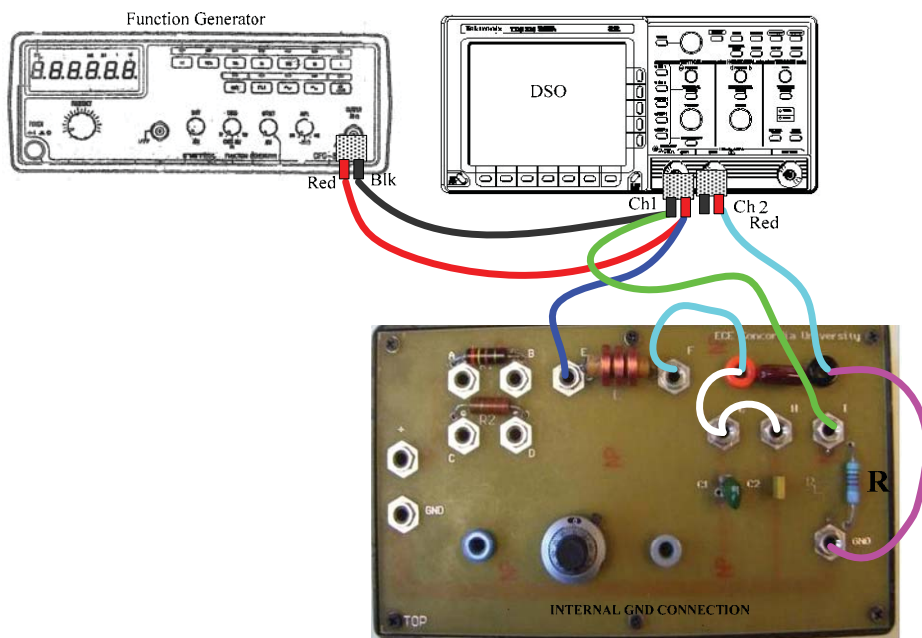
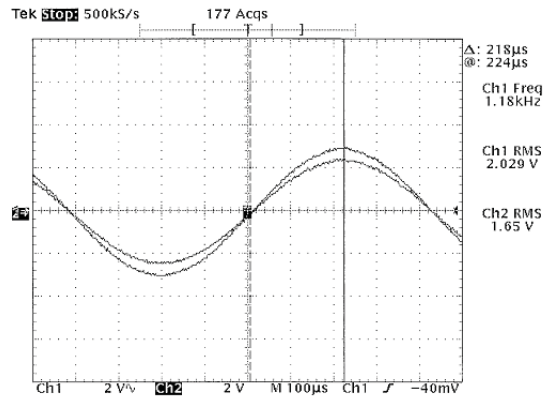
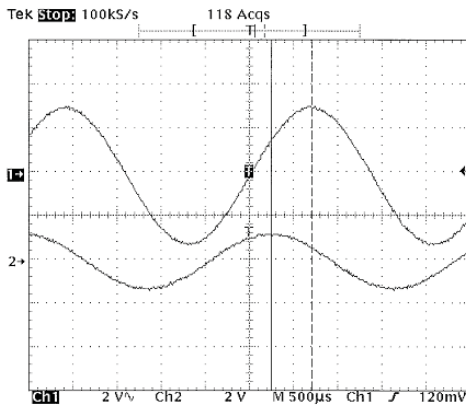


Figure 3.10: Test connections for the circuit of Figure 3.9

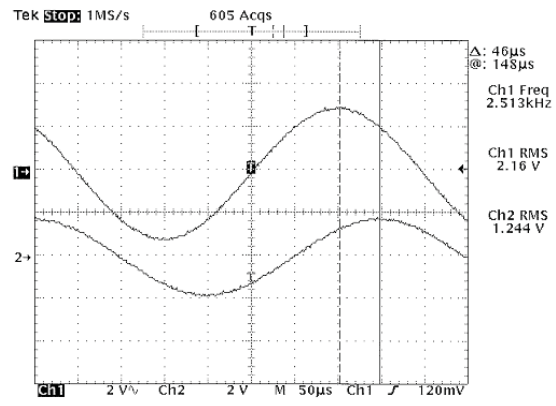
5. Starting at about 500 Hz, slowly increase the frequency while observing the Ch2 waveform amplitude as well as the phase-shift. The voltage  $V_2$  will reach a peak at  $f \approx f_0$  at which point  $V_2$  will be in phase ( $\theta = 0^\circ$ ) with  $V_1$ . For  $L = 49\text{mH}$  and  $C = 370\text{nF}$ , the resonant frequency  $f_0 = \frac{1}{2\pi\sqrt{LC}}$  should be  $\sim 1182$  Hz. Adjust the DSO controls to **obtain a printout** showing the 'resonant' condition. A typical display is shown in Figure 3.11(a).
6. **Obtain printouts showing** Ch1 frequency  $f(\text{Hz})$ , RMS values of  $V_1$  &  $V_2$  and  $\Delta t$  at **two** sample frequencies  $f_1 < f_0$  (where  $V_2$  will **lead**  $V_1$ ) and  $f_2 > f_0$  (where  $V_2$  will **lag**  $V_1$ ). Select  $f_1$  and  $f_2$  such that the phase shift  $\theta$  as seen on the DSO is in the  $30^\circ$  to  $60^\circ$  range. Typical displays are shown in Figures 3.11(b) and (c). Enter the values shown on **your** printouts into the Lab Record.



(a) Resonance condition,  $\theta = 0^\circ$



(b)  $V_2$  leads  $V_1$  by  $59.5^\circ$



(c)  $V_2$  lags  $V_1$  by  $41.6^\circ$

Figure 3.11

### Results [Phasor relations]

(a) From the results of Step 3 draw a phasor diagram, with reference to Figure 3.6, showing the phasors  $V_1$ ,  $V_2$  and  $I$ . Calculate and plot the phasors  $V_c$ ,  $I_p$ , and  $I_s$  on the diagram. The diagram need not be 'to scale', but must show the correct phase relationships.

(b) From the results of Step 6 draw the two phasor diagrams at the frequencies  $f_1$  and  $f_2$ , with reference to Figure 3.9, showing the phasors  $V_1$  and  $I$ .

### PROCEDURE & RESULTS : [B] Impedance determination

From the tutorial material given earlier, it can be seen that the data obtained in Part [A] can also be used to determine the impedance  $Z_{RC} = R + 1/j\omega C$  in the circuit of Figure 3.6 at  $f = 1$  kHz and the impedance  $Z = (R + r) + j[\omega L - 1/\omega C]$  in the circuit of Figure 3.9 at the chosen frequency  $f_1$  or  $f_2$ . We shall obtain these impedances.

In addition, the 'test impedance'  $Z_x$  of a series-parallel element combination will be found to illustrate further the determination of  $Z$ . The circuit for the 'test' impedance, shown in Figure 3.12, is a modification of the one in Figure 3.9: a variable resistance  $R_v$  is added in parallel with the LC combination.  $R_v$  is obtained using the on-board  $10k\Omega$  variable resistor (10-turn



potentiometer). Typical connections for the modified circuit, using the potentiometer for  $R_v$ , are shown in Figure 3.12. [ If desired  $R_v$  can be a fixed value resistor of an appropriate value]

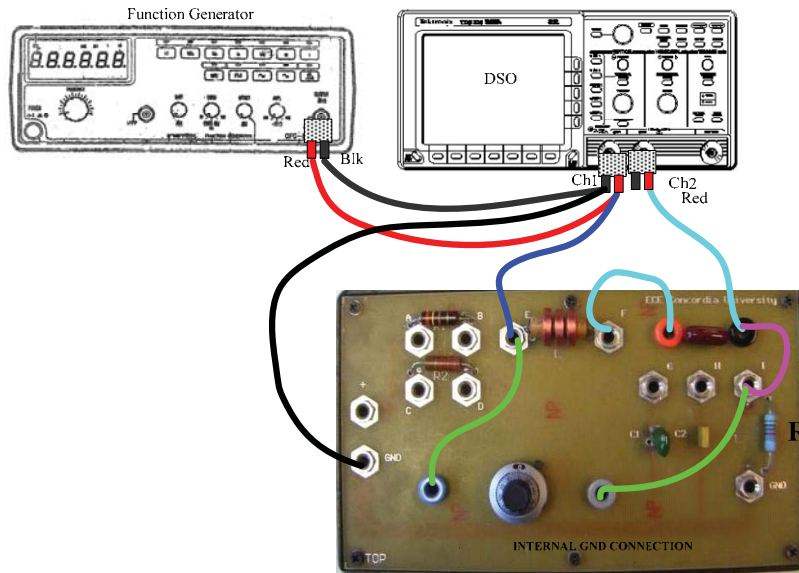


Figure 3.12: Test connections for measuring the impedance  $Z_x$

$Z_x$  can be calculated using the nominal element values .

For example, if the 10-turn pot is set at 1.5 turns from zero, it will yield a resistance of 1.56 k $\Omega$ . The 'test' impedance is then given by

$$Z_x = 511 + R_v P [ r + j\omega L + 1/j\omega C ]$$

( where P = 'in parallel with'). Using the nominal values  $r = 113 \Omega$  ,  $R = 511 \Omega$  ,  $L = 49 \text{mH}$  ,  $C = 220 \text{nF}$  and a frequency  $f = 3 \text{kHz}$  ( $\omega = 18849.56 \text{ rad/s}$ ), we obtain :

$$Z_x = 511 + \frac{1560(113 + j682.49)}{1673 + j682.49} = 823.9 + j 508.74 \approx 968 \angle 32^\circ \text{ Ohms}$$

The determined value of  $Z$  should be compared with the above calculated value.

7. Make the connections shown in Figure 3.12. Set  $f \approx 3 \text{kHz}$  ,  $V_1 \approx 2 \text{V rms}$  and  $R_v = 1560 \Omega$  (1.5 CW dial turns from zero). **Obtain a printout** showing  $V_1$  ,  $V_2$  ,  $f$  and  $\Delta t$  .Enter the values shown on **your** printout into the Lab Record.

### **Results [Impedance determination]**

(a) From the data of Step 3 determine the impedance of  $Z_{RC}$  in polar form and compare the result with the calculated value .

Using the measured value of the reactance  $X_c (= 1/\omega C)$  and the frequency, determine the value of  $C$  and compare it with the value directly measured on the laboratory RLC meter.

(b) From the results of Step 6 determine the effective impedance of the series-RLC circuit

$$Z = R + r + j\omega L + 1/j\omega C$$

at the chosen sample frequencies  $f_1$  and  $f_2$ . Compare the results with the 'theoretical' values using  $r = 113 \Omega$ ,  $L = 49 \text{mH}$  and  $C = 370 \text{nF}$  and the chosen frequencies.

(c) From the results of Step 7 determine the effective 'test' impedance  $Z_x$  and compare the result with the 'theoretical' value  $968 \angle 32^\circ \Omega$ .



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**PRE-LAB** [ To be completed and submitted before performing Lab # 3 ]

**(Weight: 10%)**

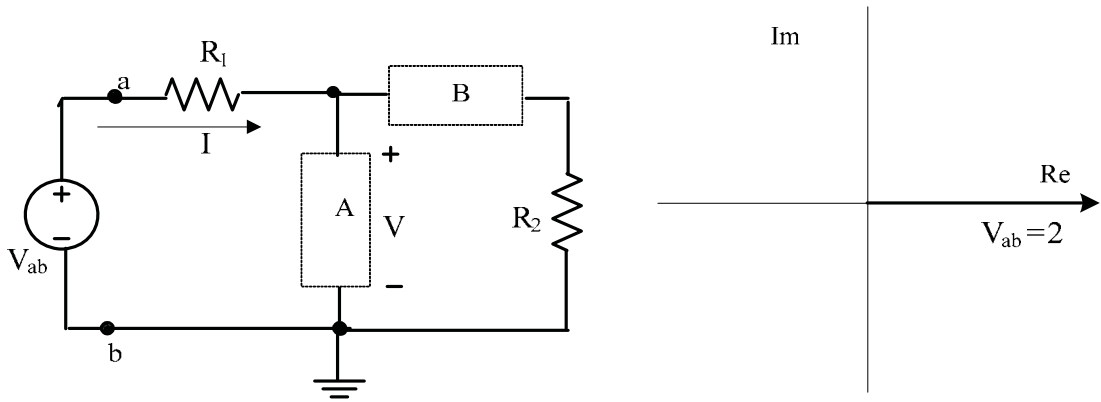
(1) A sinusoidal voltage signal has the peak-to-peak value  $V_{pp}$  and a frequency  $f$  Hz. On an oscilloscope display, the above signal appears to be ‘time-shifted’ by  $\Delta t$  sec with respect to another signal having the same frequency .

$V_{pp} = \dots\dots\dots$  Volts,  $f = \dots\dots\dots$ Hz.,  
 $\Delta t = \dots\dots\dots$ sec

For **your choice** of  $V_{pp}$ ,  $f$  and  $\Delta t$  determine

- (a) the RMS value  $V_{RMS} = \dots\dots\dots$  Volts
- (b) the Period  $T = \dots\dots\dots$ sec
- (c) the radian frequency  $\omega = \dots\dots\dots$ radians/sec
- (d) the ‘phase-shift’ between the two signals is  $\theta = \dots\dots\dots$ degrees

(2): For the circuit shown  $R_1 = 500\Omega$  and  $R_2 = 1000\Omega$  . The components A and B (within the dotted outlines) may be capacitors (C) in the range of 100–300 nF or inductors (L) in the range of 20-50 mH. The frequency of operation is in the range of 2000–5000Hz. and  $V_{ab} = 2$  volts RMS.



Indicate the (L and/or C) component of **your choice** for A & B within the dotted outlines (with values) and the frequency  $f = \dots\dots\dots$ Hz. and determine, by calculation,

- (a) the impedance (in polar form) connected to the source,  $Z_{ab} = \dots \angle \dots$  , Ohms
- (b) the phasor current  $I = \dots\dots\dots$ A/mA
- (c) sketch the phasor diagram showing  $I$  and  $V$  , with  $V_{ab}$  as reference.

[Hint: Obtain  $V$  using KVL:  $V = V_{ab} - IR_1$ ]  
Show all calculations below (neatly!) :

continued overleaf >>>>

(3) Assume that you have constructed the circuit setup of Figure 3.9, with frequency  $f$  adjusted to 4kHz. and that the measurements obtained from the printout (Step 6) were as follows: :

$V_1 = \dots\dots\dots$ volts [ **choose** between 4 & 6 V RMS]

$V_2 = \dots\dots\dots$ volts [ **choose** between 500mV & 800mV RMS] with  $V_2$  lagging  $V_1$ .

and the timeshift between the two waveforms is

$\Delta t = \dots\dots\dots$  $\mu$ s [ **choose** between 20 & 40  $\mu$ s]

**Determine** :

(a) the magnitude of the unknown impedance  $Z = (\dots\dots \dots j \dots\dots\dots) = \dots\dots \angle \dots\dots$  from the hypothetical values assumed above.

(b) the 'nature' of the impedance : Inductive / Capacitive (Circle the answer)

Show all calculations below (neatly!) :

=====

**LAB RECORD** (Weight: 30 % )

**Phasor relation & Z determination : Figure 3.6, Steps 1 to 3**

R = ..... $\Omega$ .,  $R_p$  = .....  $\Omega$ .  
Nominal value of C = 220 nF ,  
**Measured** value of C on RLC-meter = .....nF @ 1kHz

From the printout

Ch1 voltage  $V_1$  = .....Volts RMS

Ch2 voltage  $V_2$  = .....Volts RMS

Ch1 Frequency  $f$  = .....Hz

Time-shift between  $V_1$  &  $V_2$ ,  $\Delta t$  =..... $\mu$ s

**Figures 3.9 , Steps 4 to 6:**

RLC-meter measured values (all @ 1kHz):

r = .....  $\Omega$  L = .....mH, C = .....nF, R=..... $\Omega$

Resonant frequency  $f_0 \approx$  ..... Hz

From the printout at **frequency  $f_1$**  :

Ch1 voltage  $V_1$  = .....Volts RMS

Ch2 voltage  $V_2$  = .....Volts RMS

Ch1 Frequency  $f = f_1 = \dots$  .....Hz

Time-shift between  $V_1$  &  $V_2$ ,  $\Delta t$  =..... $\mu$ s

From the printout at **frequency  $f_2$**  :

Ch1 voltage  $V_1$  = .....Volts RMS

Ch2 voltage  $V_2$  = .....Volts RMS

Ch1 Frequency  $f = f_2 =$  .....Hz

Time-shift between  $V_1$  &  $V_2$ ,  $\Delta t$  =..... $\mu$ s

TA signature:.....

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**Figure 3.12 , Step 7 :**

From the printout at **frequency**  $f = \dots\dots\dots\text{Hz}$

Ch1 voltage  $V_1 = \dots\dots\dots\text{Volts RMS}$

Ch2 voltage  $V_2 = \dots\dots\dots\text{Volts RMS}$

Ch1 Frequency  $f = \dots\dots\dots\text{Hz}$

Time-shift between  $V_1$  &  $V_2$ ,  $\Delta t = \dots\dots\dots\mu\text{s}$

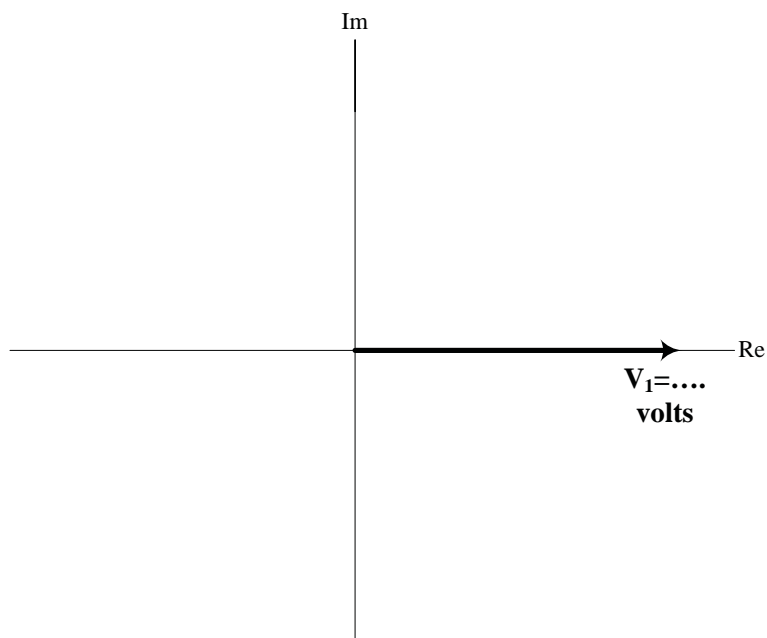
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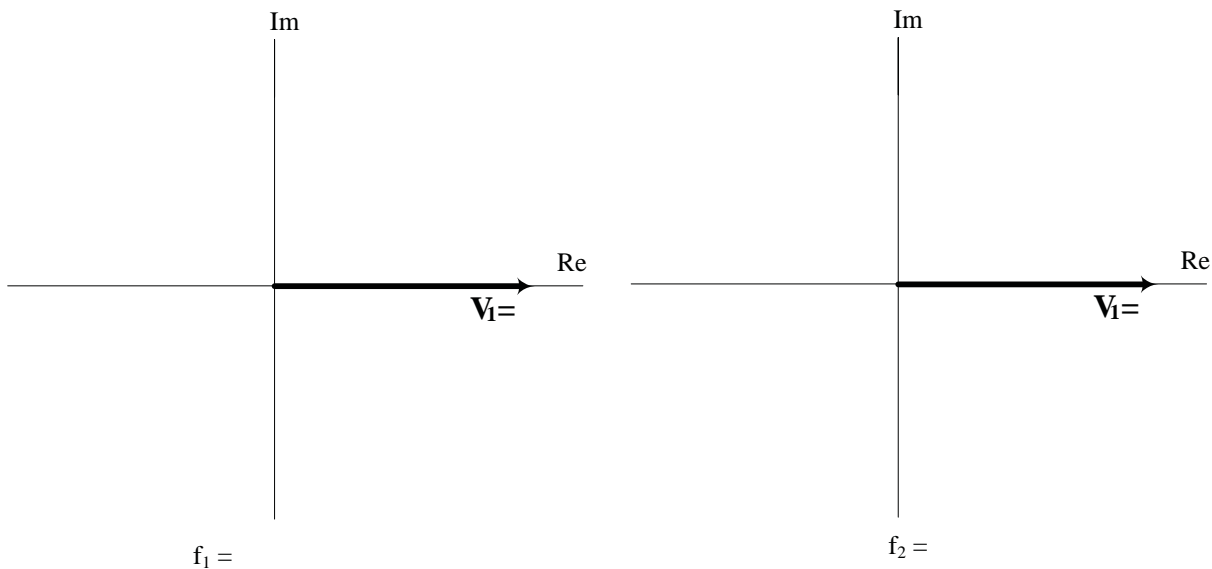
## **LAB REPORT (Weight: 60%)**

### **Phasor relations :**

(a) From the printout data of Step 3, draw the voltage phasors  $V_1$ ,  $V_2$  and the current phasor  $I$  on the complex co-ordinate plane below. Then draw the phasor  $I_p = V_1/R_p$ . Graphically obtain  $V_c$  by using the KVL phasor relation  $V_c = V_1 - V_2$ . [Either draw the diagram to 'scale' or use complex-number algebra\* on the phasors you have drawn. [\* show calculations by the side of the diagram]



(b) From the printout data of Step 6, draw the phasors  $V_1$  and  $I$  on the complex co-ordinate plane below for each of the two frequencies used.





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**Impedance determination: ALL EXPERIMENTAL IMPEDANCE DETERMINATIONS SHOULD USE RMS VOLTAGE AND TIME-SHIFT (cursor0 DATA FROM THE PRINTOUTS)**

(a) From the data of Step 3,

Determined value of  $Z_{RC} = \dots\dots\dots \angle \dots\dots\dots \Omega$

Magnitude Error between determined and nominal values (referred to nominal)  
 =  $\dots\dots\dots$  %

Angle Error between determined and nominal values (referred to nominal)  
 =  $\dots\dots\dots$  %

Comments:

(b) (i) From the data of Step 6,

Sample frequency  $f_1 = \dots\dots\dots$  Hz

Determined value of  $Z(\omega_1) = \dots\dots\dots \angle \dots\dots\dots \Omega$

Magnitude Error between determined and nominal values (referred to nominal)  
 =  $\dots\dots\dots$  %

Angle Error between determined and nominal values (referred to nominal)  
 =  $\dots\dots\dots$  %

(ii) From the data of Step 6,

Sample frequency  $f_2 = \dots\dots\dots$  Hz

Determined value of  $Z(\omega_2) = \dots\dots\dots \angle \dots\dots\dots \Omega$

Magnitude Error between determined and nominal values (referred to nominal)  
 =  $\dots\dots\dots$  %

Angle Error between determined and nominal values (referred to nominal)  
 =  $\dots\dots\dots$  %

Comments:

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(c) From the data of Step 7 :

Frequency  $f = \dots\dots\dots$

Determined value of  $Z(\omega_2) = \dots\dots\dots \angle \dots\dots\dots \Omega$

Magnitude Error between determined and nominal values (referred to nominal)

=  $\dots\dots\dots$  %

Angle Error between determined and nominal values (referred to nominal)

=  $\dots\dots\dots$  %

Comments:

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**DISCUSSION & CONCLUSION:** [Discuss possible reasons for any differences observed between the experimental results and the 'theoretically' predicted ones. Express, in your own words, what you learned from this experiment. ]

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## EXPERIMENT 4

### TRANSFORMERS & THREE-PHASE POWER MEASUREMENTS

- STUDY OBJECTIVES** : (A) To study the operational characteristics of a single-phase transformer  
(B) To measure power in a three-phase circuit using the two-wattmeter method

- PRE-REQUISITES**: 1. Reading and making an attempt to understand the tutorial and other material given below **and in Appendices A and B** before coming to the lab. Familiarity with the use of the DMM and the DSO.
2. **PLEASE CAREFULLY READ AND OBSERVE THE SAFETY PRECAUTIONS GIVEN IN THE ‘PROCEDURE’**

#### **TUTORIAL**

##### **PART (A): Transformers**

A transformer is an inductive device which is extensively used in AC circuits to ‘step-up’ or to ‘step-down’ voltage (or current) magnitudes. The device is based on the phenomenon of ‘mutual inductance’ between two or more magnetically-coupled inductance coil windings. Transformers are also used to provide electrical isolation between circuits or as an ‘impedance matching’ component to ensure maximum transfer of power from one circuit to another or to a load. The basic constructional features of an ideal, single-phase, two-winding transformer and its electrical symbol are shown in Figure 4.1, where the voltages and currents are expressed in RMS values for convenience in power calculations etc.

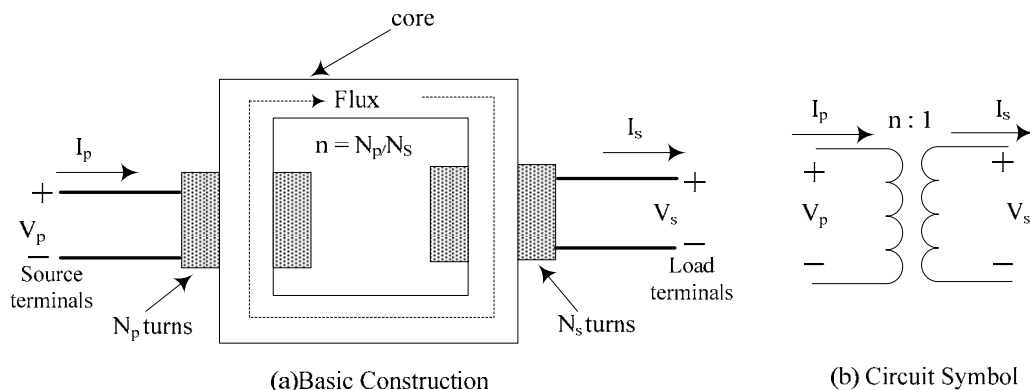


Figure 4.1

The winding with  $N_p$  turns, to which the input voltage  $V_p$  is applied, is called the ‘primary’ and the winding with  $N_s$  turns, which is connected to the load, is called the ‘secondary’. The applied primary voltage  $V_p$  causes a current  $I_p$  to flow in the primary, which produces a magnetic flux  $\phi$  (in the ‘core’) which also *links* the secondary coil. Any change in  $I_p$  will cause a change in  $\phi$  which will *induce* a voltage  $V_s$  in the secondary coil in accordance with Faraday’s law of induction. In an ideal transformer all of the flux generated by the primary winding will link the secondary winding, with no flux leakage .



Since the flux linkage  $\phi$  is common to both primary and secondary coils, Faraday's law of induction gives the result :

$$\frac{d\phi}{dt} = \frac{V_p}{N_p} = \frac{V_s}{N_s}$$

Hence,  $V_p$  and  $V_s$  are inter-related by the ratio  $n$  given by :

$$n = V_p/V_s = N_p/N_s$$

$n$  is called the *transformer ratio* (or *turns ratio*) of the ideal transformer. In an ideal transformer, the power output will be equal to the power input since there are no losses. Hence,  $V_p I_p = V_s I_s$  and consequently,  $V_p/V_s = I_s/I_p$ .

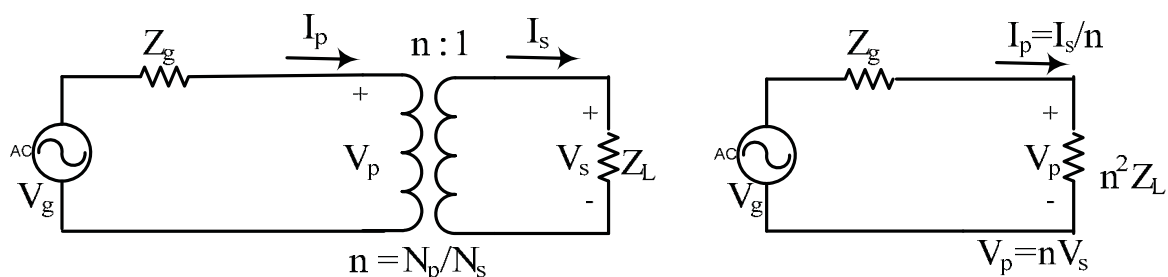
Thus,  $n$  can be expressed in terms of the turns ratio, the voltage ratio or the current ratio as:

$$n = N_p/N_s = V_p/V_s = I_s/I_p.$$

**{ A note regarding the 'transformer ratio':** The transformer ratio ('turns ratio')  $N_p/N_s$  is expressed in various textbooks in two different forms as either " $n:1$ " where  $n = N_p/N_s$  or as " $1:N$ " where  $N = N_s/N_p$ , which could be a source of confusion to some students. Each form has its advantages. The student is advised to consistently use one form or the other and to state the form used when presenting the problem solution. **In this manual, the form " $n:1$ " where  $n = N_p/N_s$  is used.**}

AC voltages or currents may be 'stepped-up' or 'stepped-down' between the defined 'primary' and 'secondary' windings, depending upon the value of  $n$ . This property of the transformer makes it extremely useful in the area of electrical power delivery. The device is also capable of 'transforming' impedances as shown by the following brief analysis of Figure 4.2(a), which shows an ideal transformer connected to a real source (internal impedance  $Z_g$ ) and to a load  $Z_L$ . Let the impedances 'seen' by a source connected to the primary terminals and by a load connected to the secondary be  $Z_p$  and  $Z_s$  respectively. Thus ,

$$Z_p = V_p/I_p = nV_s/(I_s/n) = n^2(V_s/I_s) = n^2Z_s = n^2Z_L.$$



(a) Transformer connected to a real source and load

(b) "Primary-referred Equivalent Circuit

Figure 4.2

Hence, the load impedance  $Z_L$  appears to the real source ( $V_g, Z_g$ ) as the impedance  $Z_p = n^2 Z_L$ . Such a transformation is extremely useful in 'impedance matching' procedures required for maximum power transfer between an AC source and a specified load. The circuit of Figure 4.2(a) can hence be replaced by the 'primary-referred' equivalent of the circuit of Figure 4.2(b),

which is a virtual circuit that does not contain the transformer symbol. Such transformations are very useful in the analysis of transformer-coupled circuits and also in the derivation of the ‘equivalent circuit of a real (non-ideal) transformer’ [A real transformer can be represented by a circuit containing an ideal transformer connected to other elements which reflect the non-ideal qualities such as resistive and magnetic losses]

**Power Efficiency**  $\eta$  : Due to conductive(‘ohmic’) losses as well as magnetic-circuit losses(‘iron losses’), a real transformer has a finite ‘power efficiency’  $\eta$ , which is the ratio of the load power  $P_L$  to the input power  $P_{in}$  expressed as a percentage.

In Figure 4.2(b), the input power  $P_{in}$  is given by (see Appendix-B) :

$$P_{in} = V_g I \cos \theta_{total} = I^2 \operatorname{Re}(Z_g + n^2 Z_L)$$

where “ $\cos \theta_{total}$ ” is the power-factor ‘seen’ by  $V_g$  and  $I$  is the RMS value of the current in the ‘primary referred’ equivalent circuit .

Similarly, the load power  $P_L$  is given by:

$$P_L = V_p I \cos \theta_{Z_L} = I^2 \operatorname{Re}(n^2 Z_L)$$

where “ $\cos \theta_{Z_L}$ ” is the load power-factor.

The efficiency can now be written as

$$\eta = 100 P_L / P_{in} \% = 100 \{ \operatorname{Re}(n^2 Z_L) / \operatorname{Re}(Z_g + n^2 Z_L) \} \%$$

In real transformers,  $\eta$  is reduced due to loss components inherent in  $Z_g$

**Voltage Regulation** (VR or %Reg): The ‘load regulation’ or ‘voltage regulation’ is another performance specification which is an indicator of the sensitivity of the output voltage of the transformer to variations in the load. The ‘percentage regulation’ (% Reg) is expressed as

$$100 [V_{NL} - V_{FL}] / V_{FL} \%$$

where  $V$  is the secondary voltage and the subscripts NL and FL refer to ‘No-Load’ and ‘Full-Load’ respectively. To experimentally determine the % regulation, the transformer is usually operated at its rated full-load current .

Power efficiency  $\eta$  and the “% Reg” are both found from measurements of input and output voltages, currents and powers.

**PART (B): 3-Phase Power Measurement by the Two-Wattmeter Method:**

The total power in a 3- $\phi$  system can be measured by inserting three single-phase wattmeters in the three lines, with the wattmeter ‘ground’ terminals being connected to either the ‘neutral’(if present) or to any other arbitrary reference. The ‘two-wattmeter’ method, shown in Figure 4.3, is possible because if the wattmeter ‘grounds’ are connected to one of the three lines as reference, then the wattmeter connected in that line will read zero and may be removed.

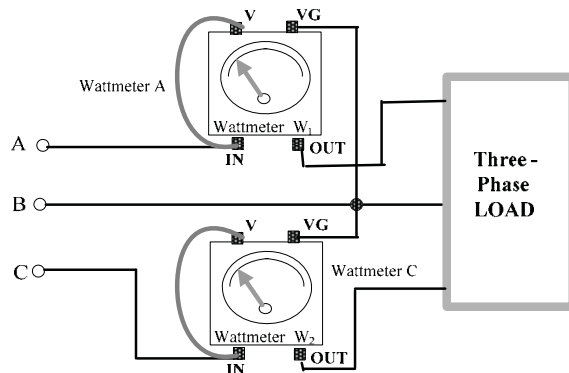


Figure 4.3: Power measurement using the 2-Wattmeter method

If  $\theta$  is the load impedance angle, it can be shown that for the phase sequence ABC, the angle between  $V_{AB}$  and  $I_A$  is  $(30^\circ + \theta)$  and the angle between  $V_{CB}$  and  $I_C$  is  $(30^\circ - \theta)$ . Thus, the two wattmeter readings are:

$$W_A = V_L I_L \cos(30^\circ + \theta) \quad \text{and} \quad W_C = V_L I_L \cos(30^\circ - \theta)$$

The sum of the two readings is

$$W_C + W_A = [2 \cos 30^\circ] V_L I_L \cos \theta = \sqrt{3} V_L I_L \cos \theta = P$$

The difference of the two readings is

$$W_C - W_A = [2 \sin 30^\circ] V_L I_L \sin \theta = V_L I_L \sin \theta = Q / \sqrt{3}$$

Taking the ratio of the above two expressions, we obtain

$$\tan \theta = \sqrt{3} \frac{[W_C - W_A]}{[W_C + W_A]}$$

from which the load impedance angle  $\theta$  and the power factor  $\text{pf} = \cos \theta$  may be found.

For unity pf loads, the readings  $W_A$  and  $W_C$  will be identical and their sum is the total average power  $P$ . For purely reactive or zero pf loads,  $P = 0$ . Hence both wattmeters will read the same wattage but with opposite signs (the reversing switch will have to be used on the 'negative reading' meter to obtain a positive pointer deflection). For intermediate-pf loads, interpretation of the readings is required, as follows: As the pf is reduced from unity, one of the meters will read lower, but the sum of the two readings will give  $P$ . However, when the pf reaches 0.5 [ $\theta = \pm 60^\circ$ ], leading or lagging, one of the two meters will read zero although power is being supplied to the load. For a  $\text{pf} < 0.5$ , one of the meters will attempt to read a negative value and the reversing switch must be used to obtain a positive deflection, but the reading must be interpreted as being negative.

## **EXPERIMENTAL**

### **SAFETY PRECAUTIONS : PLEASE CAREFULLY READ AND FOLLOW THESE PRECAUTIONS !!**

1. **NO WATER BOTTLES OR LIQUID CONTAINERS ARE PERMITTED IN THE LAB , AND THIS RULE IS PARTICULARLY IMPORTANT IN POWER EXPERIMENTS !**
2. **Always return the variac control knob to zero before making circuit changes.**  
**Always return the R knob on the RL-load to its mid-position after use.**
3. **Never 'daisy-chain' patchcords. Use appropriate cord lengths & colours.**
4. **Never disconnect a lead in a circuit which is 'powered'.**
5. **DO NOT MOVE the 3-phase transformer box, the 3-phase load box, and the Capacitance Box, the RL-load Box and the Agilent 344405A DMM (& preferably even the Wattmeters & the Fluke DMM) from their assigned positions (see photo below). If moved, the Wattmeters and Fluke DMM should be returned to their original places shown in the photograph after use)**
6. **The CT & VT connections above the 3-phase transformer box are not to be disconnected or re-wired !**
7. **Always double-check your circuit before applying power.**

**FOR THIS EXPERIMENT, IT IS MANDATORY TO USE THE PROVIDED SHIELDED BANANA CABLES !!!**

**Before you start the experiment, it is time-saving to check the fuses on the 3-phase variac, on the two wattmeters and on the R-L load unit.**

To check the variac fuses: The variac is fitted with the ‘fuse-status indicator’(FSI) box, described in the appendix. **With no connections made to the variac, turn the variac knob fully clockwise.** The three amber-coloured indicator lamps on the FSI box should glow if all three fuses are good. If an indicator does not glow, the corresponding fuse behind the terminal-box must be replaced. [The variac fuses can also be checked using a DMM: With the DMM set to 200 volts AC, check the outputs of the variac for a small voltage setting, say 20 volts. If the fuses are not blown, all three outputs should give an indication with approximately equal values].

To check the other fuses: Set the DMM to the  $200\Omega$  ‘ohmmeter’ range and check for continuity between the current terminals of the wattmeter (the front terminals) and then between the R terminals of the load unit. A continuity or resistance value indication should be obtained if the fuse is good.

The CT & VT connections can also be checked , if necessary, as follows:

To check the CT & VT connections: Set the DMM to the  $200\Omega$  ‘ohmmeter’ range. Check the resistance at the VT/CT terminal box (above the DSO): The resistances at the VT and CT outputs should be  $\sim 1\Omega$  and  $\sim 14\Omega$  respectively. If they are not, then the CT/VT connections above the 3-phase transformer box have probably been disconnected or incorrectly wired.

**Ask your lab instructor to check your circuit before turning on power .**



## Procedure & Results

PART [A]: Characteristics of a single-phase transformer (Determination of transformer ratio, power efficiency, %-Regulation and observation of Z-transformation.)

1. The test circuit is shown schematically in Figure 4.4 and a detailed wiring diagram is given in Figure 4.5. Wattmeter  $W_1$  and Wattmeter  $W_2$  measure the input power and load power, respectively. CT & VT are special-purpose ‘instrument-transformers’ which provide voltages proportional to their input current and voltage respectively, for displaying these parameters on the DSO, mainly for phaseshift measurements. [Nominal VT and CT sensitivities are **50mV/volt** and **105mV/Amp.**]

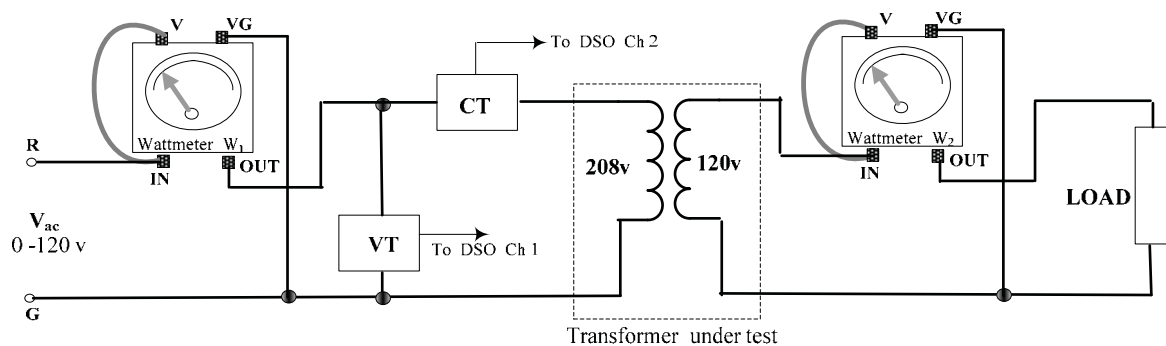


Figure 4.4: Basic single-phase transformer test circuit  
[DMMs & DSO are not shown]

Connect the circuit shown in Figure 4.5, using the shortest available patchcord lengths to make connections between the various units. Set up the DSO to display the RMS values of the VT and CT outputs. Set the DSO bandwidth to 20 MHz to remove high-frequency ‘noise’ in the VT and CT signals as much as possible. Also turn on the V-Bar cursors on the DSO, for use in phase-shift measurements. **The transformer is used in the “step-down” mode for all the tests,** the nominal ratio being 208:120 or  $\sqrt{3}$  (=1.73).

- 2 Disconnect the load temporarily at the wattmeter end. Slowly turn the variac control to the fully clockwise position. With the Agilent 34405A DMM set in the ACV-Auto Mode (autoranging AC voltmeter), measure the **no-load** voltages across input terminals 1 & 2 and across output terminals 3 & 4 of the transformer box [see Figure 4.5] and enter them in the Lab Record. Leave the DMM connected to measure the secondary voltage, before proceeding to the next step.

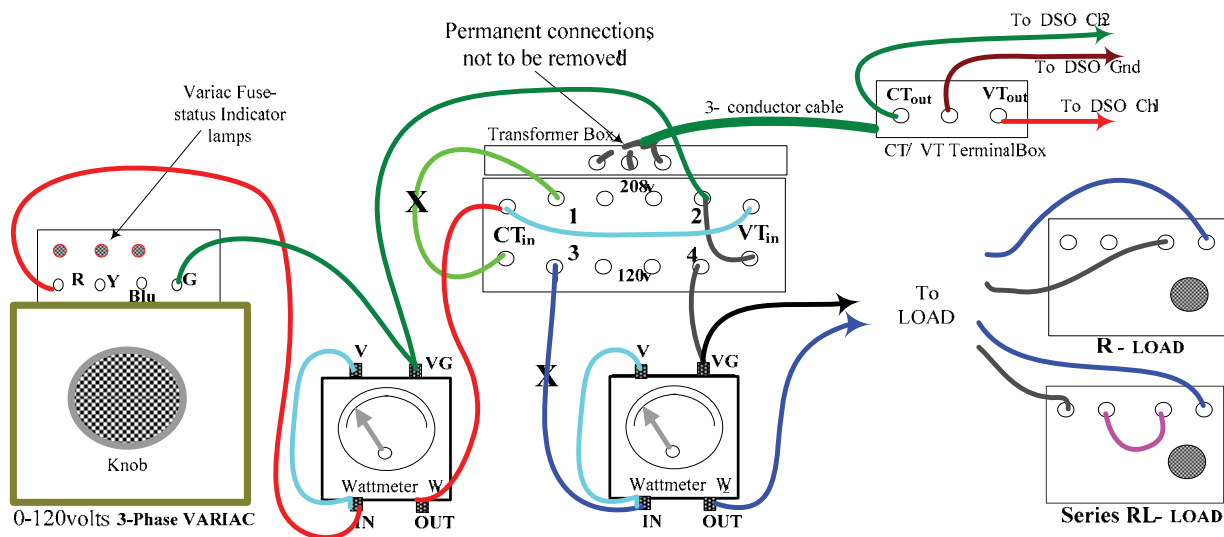


Figure 4.5: Detailed connections corresponding to the test circuit of Figure 4.4  
 [ DMMs & DSO are **not** shown]

3. **Connect the R load** with the control knob turned fully clockwise ( $R = 100\Omega$ ) and repeat the above input and output voltage measurements as well as the primary and secondary power indicated by the wattmeters. Enter all readings into the Lab Record.
4. Next, set the Fluke 8010A DMM as a 2000mA AC ammeter and use it to measure the primary-side and secondary-side currents by successively inserting it at the two points marked **X** in Figure 4.5 (see leads connected to points 1 & 3) (**The variac control should be reduced to zero every time before making changes such as insertion of the ammeter etc . The secondary voltage indicated by the Agilent DMM (see end of Step 2) can be used as a reference to return to the same variac setting.**)
5. Adjust the displays on the DSO and use the DSO V-Bar cursors to measure and record the time-shift  $\Delta t$  between the VT and CT traces.
6. Repeat Steps 3, 4 and 5 above with a series-RL load connected (see load connection in the figure). Set  $R$  to a value calculated to yield a theoretical power factor of 0.5 : Since the power-factor  $PF = \cos(\tan^{-1}\omega L/R)$ , a  $PF = 0.5$  requires  $R = \omega L / \tan 60^\circ = (377)(0.2) / 1.732 \approx 43.5 \Omega$  }.



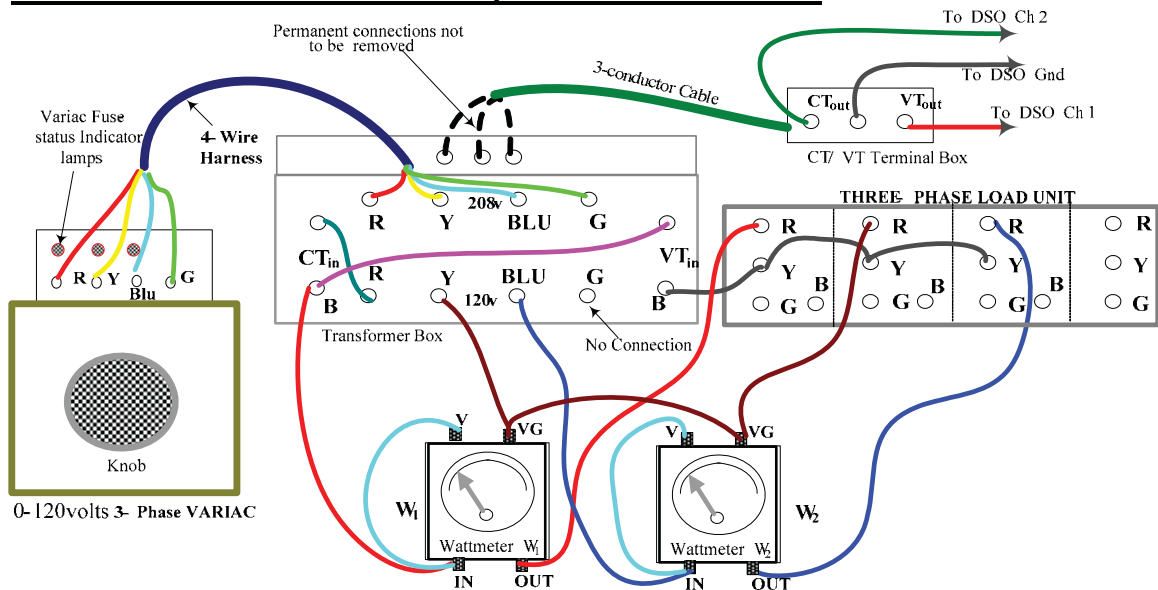
**PART [B]: 3-Phase Power Measurement** (using the two-wattmeter method )

The two-wattmeter method of Figure 4.3 is implemented in the detailed diagram shown in Figure 4.6. [ In this figure Red-Yellow-Blue-Green is used to designate the phases instead of ABCN in order to correspond to the colours of the variac , transformer box and 3-phase load box terminals]. Total average-power is measured for five different balanced, Y-connected, loads : R, L, C, a series-RL and a (series-RL) // C load. In each case the phase shift between the load voltage and current is also measured using the CT/VT signals. Use the same DSO settings as in PART[A]. Note that the CT & VT are connected to display/measure the phase current and phase voltage of the ‘R-phase’ only.

**Resistive Load**

{ **CAUTION : PERFORM THIS TEST AS QUICKLY AS POSSIBLE SINCE THE RESISTORS IN THE LOAD BOX TEND TO OVERHEAT OTHERWISE** }

7. Connect the circuit shown in Figure 4.6 , which shows the load unit configured as a **76Ω** , Y-connected resistive load. Use the **4-wire harness to connect the variac to the 208v primary side of the 3-phase transformer, using proper colour codes.** Note that Yellow is used as the ‘common’.
  
8. Slowly turn the variac control CW until the VT output [on Ch1] is about  $3 V_{RMS}$  .With the 50mV/volt VT sensitivity, this indicates that the phase voltage is ~ 60 Volts rms. Quickly read the power  $W_1$  &  $W_2$  , indicated by the wattmeters on the R & BLU phase lines (ie A & C phases). If one of the wattmeters is trying to indicate negative, use the toggle switch to obtain a positive reading. Enter the two wattmeter readings into the Lab Record. **Note the switch positions (usually to the right) on the wattmeters as these will be the ‘reference’ switch-positions for the R-load.**



**Figure 4.6 :** Detailed connections for 3-phase power measurements. [Load Unit connected for Resistive load]

- 9 Adjust the displays on the DSO and use the V-Bar cursors to measure and record the time-shift  $\Delta t$  between the VT and CT traces. Obtain a printout of the VT & CT waveforms showing all required measurements, ie frequency, RMS values and the cursor  $\Delta t$  value corresponding to the phase shift between the two waveforms. Enter the data into the Lab Record .
10. Repeat Steps 8 & 9 above, for the other four loads\* . **The other four loads are obtained by successively changing the connections on the 3-phase load unit, as described below.**

**\*THE PROCEDURE FOR THE OTHER LOADS IS EXACTLY THE SAME AS FOR THE RESISTIVE CASE, EXCEPT THAT THE WIRE CONNECTIONS ON THE THREE-PHASE LOAD UNIT MUST BE CHANGED FOR EACH CASE.**

Front panel details and a photograph of the 3-phase load unit are shown in Figure 4.7 [same as Figure A11 Of Appendix-A]

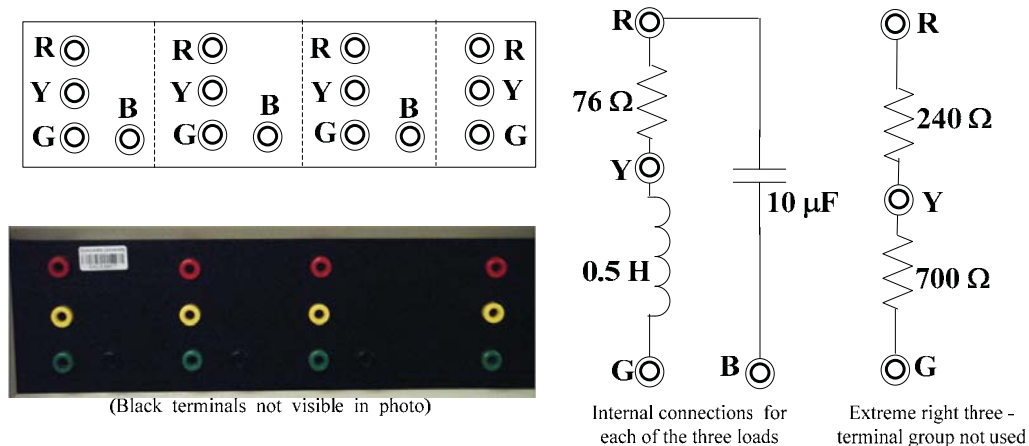


Figure 4.7: Three Phase Load Details

**The 240Ω and 700Ω resistors (rightmost RYG terminals) are not used.** The 3-phase loads are obtained in succession by changing connections on the three sets of remaining terminals.

**THE SEQUENTIAL WIRING CHANGES REQUIRED TO OBTAIN THE VARIOUS LOADS ARE GIVEN BELOW:**

**The student should make a short sketch in each of the above cases to verify that the wiring changes do result in the specified load configuration.**

**Pure inductive load** : Starting from the pure-R case, change ALL connections originally going to the Red terminals on the Load Unit to the Green terminals.

**Pure capacitive load** : Starting from the pure-R case, change ALL connections originally going to the Yellow terminals on the Load Unit to the Black terminals.

**Series RL load** : Starting from the pure-R case, change ALL connections originally going to the Yellow terminals on the Load Unit to the Green terminals.

**Series RL // C load** : Starting from the R-L case, short-circuit the Green and Black terminals with a short patchcord. This connects C across the series combination of R & L.



**Wattmeter reading interpretation** : The steps to be followed in each case above are exactly the same as for the resistive load with the caution that the polarity of  $W_1$  and  $W_2$  must be interpreted correctly before calculating the power. For pure-R, both  $W_1$  and  $W_2$  will be positive and their sum gives the total power. The reference positions of the wattmeter switches must be carefully noted for the pure-R case, so that 'negative' power values may be correctly interpreted for non-R loads. For a load with a pf of exactly 0.5, one of the wattmeters will read zero. For a pf less than 0.5, one of the wattmeter readings must be interpreted as being negative (so that P is the difference between  $W_1$  and  $W_2$ ) to give the correct power.

-----

The calculated nominal load values, at 60 Hz, are as follows;

R – Load  $Z_R = 76\Omega$

Purely L load  $L = 500\text{mH}$  ,  $Z_L = j 188.5 \Omega = 188.5 \angle 90^\circ \Omega$

Purely C load  $C = 10 \mu\text{F}$  ,  $Z_C = -j 265.25 \Omega = 265.25 \angle -90^\circ \Omega$

Series-RL Load  $Z_{RL} = R + j\omega L = 76 + j 188.5 = 203.24 \angle 68^\circ \Omega$  , [PF = 0.375 lagging]

Series RL//C Load  $Z_{RLC} = \frac{(R + j\omega L)(\frac{1}{j\omega C})}{R + j\omega L + \frac{1}{j\omega C}} = (76 + j 188.5)(-j 265.25)/(76 - j 76.75)$

$Z_{RLC} = 458.33 + j 197.6 \Omega = 499.1 \angle 23.3^\circ \Omega$  , [PF = 0.918 lagging]

=====

**PRE-LAB (Weight: 20 %) SHOW RELEVANT CALCULATIONS ON A SEPARATE PAGE IF NECESSARY**

**PART (A):**

- (1) The circuit of an 'ideal' transformer with primary turns  $N_p = \dots\dots\dots$  and secondary turns  $N_s = \dots\dots\dots$  is connected on the secondary side to a load impedance  $Z_L = (\dots\dots + j \dots\dots)$  ohms.  
 For values of  $N_p, N_s$  and  $Z_L = Z_s$  **selected by you**, (choose  $n$  between 1.5 and 2.5) determine:
- a) The transformation ratio  $n = \dots\dots\dots$
  - b) The impedance 'seen' on the primary side  $Z_p = \dots\dots\dots + \dots\dots\dots$
- (2) The above transformer and load are connected to a 60Hz voltage source whose no-load terminal voltage is  $V_g = 120$  voltsRMS, and 'internal' impedance  $Z_g$  is  $3\Omega$ . Determine
- a) The Average load power  $P = \dots\dots\dots$  Watts
  - b) The Reactive load Power  $Q = \dots\dots\dots$  VARs
  - c) The PF 'seen' by the source,  $PF = \dots\dots\dots$
  - d) The RMS load voltage  $V_L = \dots\dots\dots$  volts
  - e) The Power efficiency  $\eta = \dots\dots\dots$  %
  - f) The % Voltage Regulation =  $\dots\dots\dots = \dots\dots\dots$  %

**PART (B):**

- (1) A balanced 60 Hz three-phase Y-Y, 3-wire system is connected to measure power using the two-wattmeter method of Figure 4.6. The line-to-line voltage is 208 voltsRMS. The positive (non-zero) readings of the wattmeters are  
 $W_A = \dots\dots\dots$  Watts and  $W_C = \dots\dots\dots$  Watts.  
 The line-current magnitude is  $I = \dots\dots\dots$  Amps.

For values of  $I, W_A$  and  $W_C$  **selected by you**, determine

- a) The total average power  $P = \dots\dots\dots$  Watts
  - b) The power-factor of the load  $PF = \dots\dots\dots$
  - c) The load impedance  $Z = \dots\dots \angle \dots^\circ$  Ohms
- (2) A  $\Delta$ -connected balanced load has the value  $Z_\Delta = \dots\dots\dots + j \dots\dots\dots$  Ohms. is connected to a balanced Y-connected source and the line-current magnitude is  $I = \dots\dots\dots$  Amps. For values of  $Z_\Delta$  and  $I$  **selected by you**, determine :
- a) The impedance of an equivalent Y-connected load  
 $Z_Y = \dots\dots\dots + j \dots\dots\dots$  ohms
  - b) The Phase-voltage magnitude of the source  
 $V_{ph} = \dots\dots\dots$  Volts RMS

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**LAB RECORD: (Weight: 30 %)**

**PART (A): TRANSFORMER TEST DATA :** Frequency  $f \approx 60$  Hz.[Steps 1 & 2] :

No Load Primary voltage  $V_p = \dots\dots\dots$  Volts

No Load Secondary voltage  $V_s = \dots\dots\dots$  Volts

(a) Load  $Z_L = R = 100\Omega$  [Steps 3 , 4 & 5 ]

Primary voltage  $V_p = \dots\dots\dots$ Volts ; Secondary voltage  $V_s = \dots\dots\dots$  Volts

Primary current  $I_p = \dots\dots\dots$ Amp ; Secondary current  $I_s = \dots\dots\dots$ Amp

Wattmeter readings :  $P_{in} = \dots\dots\dots$ Watts ;  $P_{out} = \dots\dots\dots$  Watts

$\Delta t$  (from cursor data on CT/VT waveforms) =  $\dots\dots\dots$ sec.

(b) Load  $Z_L = R + j\omega L \approx 43.5 + j75.4 \Omega$  [ie R set at  $43.5 \Omega$  &  $L \approx 0.2H$  ,  $f \approx 60$  Hz]  
[Step 6]

Primary voltage  $V_p = \dots\dots\dots$ Volts ; Secondary voltage  $V_s = \dots\dots\dots$  Volts

Primary current  $I_p = \dots\dots\dots$ Amp ; Secondary current  $I_s = \dots\dots\dots$ Amp

Wattmeter readings :  $P_{in} = \dots\dots\dots$ Watts ;  $P_{out} = \dots\dots\dots$  Watts

$\Delta t$  (from cursor data on CT/VT waveforms) =  $\dots\dots\dots$ sec.

**PART (B) : THREE-PHASE POWER TEST DATA :** Frequency =  $\sim 60$ .Hz.

Readings for  $V_{ph} \approx 60$  VoltsRMS ( ie VT output on CH1  $\approx 3$  VoltsRMS)  
[Steps 7 to 10]

LOAD	VT Output Volts RMS	CT Output Volts RMS	Cursor $\Delta t$ for Phase shift sec or msec	W <sub>1</sub> Watts	W <sub>2</sub> Watts
<b>R</b>					
<b>L</b>					
<b>C</b>					
<b>Series RL</b>					
<b>Series RL//C</b>					

TA Signature  $\dot{\quad}$  .....

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**LAB REPORT: Weight: 50 %)**

**PART (A):** (a) Turns Ratio

Specified transformer ratio  $n = 208/120 = 1.733$

Experimental value(from voltage measurements)  $n = \dots\dots\dots$

Error :  $\dots\dots\dots\%$

(b) For the load  $Z_L (= Z_s) = R + j\omega L \approx 43.5 + j75.4 \Omega$ ,  
 Secondary impedance magnitude  $Z_s$  (from voltage & current measurements)

$Z_s = \dots\dots\dots$

Impedance angle (from cursor  $\Delta t$ )  $\theta = \dots\dots\dots$ degrees

Primary impedance magnitude  $Z_p$  (from voltage & current measurements)

$Z_p = \dots\dots\dots$

Verify that  $Z_p = n^2 Z_s$  :

$\dots\dots\dots$

(c) Voltage Regulation: % Reg ( R load ) =  $\dots\dots\dots$

% Reg ( RL load ) =  $\dots\dots\dots$

(d) Power Efficiency (from Wattmeter data):  $\eta$  ( R load ) =  $\dots\dots\dots$

$\eta$  ( RL load ) =  $\dots\dots\dots$

**PART (B): Average Power P & Power Factor PF (RL and RL//C Loads)**

LOAD	$P_{theory}$ Watts	$P_{expt}$ Watts	% Error in P	$PF_{theory}$	$PF_{expt}$	% Error in PF
Series RL						
Series RL//C						

1 :  $P_{theory} = 3 I^2 ReZ$  and  $PF = \cos[\tan^{-1}(ImZ/ReZ)]$

2 :  $P_{expt} = W1 \pm W2$  and  $PF_{expt} = \cos(360f\Delta t)^\circ$

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**DISCUSSION & CONCLUSION:** [Discuss possible reasons for any differences observed between theory and the experimental results. Express, in your own words, what you learned from this experiment. ]



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## EXPERIMENT 5

### DC MOTOR CHARACTERISTICS

**STUDY OBJECTIVES** : To become familiar with the characteristics of a Permanent-Magnet DC Motor

**PRE-REQUISITES**: Reading and making an attempt to understand the tutorial material given below , **Appendix A , Section(5) and Appendix- B** .

DC motors are extremely useful devices which are widely used in industrial applications such as robotic control systems. DC motors are made in a wide variety of sizes and configurations. In this experiment, the motor constants and the torque-speed characteristics of a small permanent-magnet DC (PMDC) motor will be determined .

#### **Introduction.**

The basic features of electromechanical energy conversion and DC motors are discussed in Appendix-C. The PMDC motor basically consists of a permanent magnet stator and a wound-rotor connected to a commutator. The DC motor is an electromechanical device, with an electrical input (voltage, current) and a mechanical output (speed, torque). The essential components of the mechanical load are the rotational inertia  $J$  and the viscous friction  $B$  as shown at left in Figure 5.1. The characteristics of the motor in the steady state may be analyzed with respect to the equivalent circuit on the right of the above figure (reproduced from Appendix-C, after omitting the field circuit)

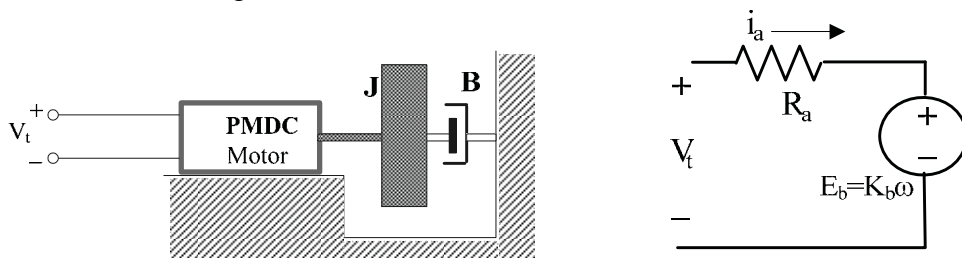


Figure 5.1: DC motor with load and its DCSS electrical equivalent circuit.

Referring to the equivalent circuit , the armature current  $I_a$  is given by:

$$I_a = \frac{V_t - K_b \omega}{R_a}$$

where  $V_t$  is the terminal voltage,  $R_a$  is the armature circuit resistance ,  $\omega$  is the rotational speed in radians/sec and  $K_b$  is the Back-emf Constant which relates the back-emf  $E_b$  to  $\omega$  through the 'Blu' law, i.e  $E_b = K_b \omega$ .

The torque developed  $T$  is related to the armature current through the 'Bli' law :  $T = K_T I_a$

Solving for  $T$  , we obtain (see Appendix-C ) :

$$T = \frac{K V_t}{R_a} - \frac{K^2 \omega}{R_a} = k_1 - k_2 \omega$$

where  $K$  is a constant which has the same numerical value (in the SI system of units) as both  $K_T$  and  $K_b$  (see Appendix-C) .

The first equation shows that the ‘back emf’  $E_b$  provides a ‘built-in negative feedback’ which tends to ‘stabilize’ the motor with respect to changes in output speed. For example, if  $\omega$  decreases *due to an increase in the load*,  $E_b$  will decrease proportionately, which in turn will increase the current  $I_a$  thereby causing an increase in torque  $T$ , and consequently, the speed  $\omega$ .

In this experiment, two identical motors A and B connected to a common shaft, as shown schematically in Figure 5.2, are used. *The two motors are assumed to have the same nominal characteristics since they are of the same type.* The coupler between the motors is a slotted disc which serves as a shaft speed sensor. The slot position is sensed by an optoelectronic sensor which produces a train of pulses having a period  $T_p$ . [See Appendix A, Pages 118/119 for details]. The rotational speed  $\omega$  (in radians/sec) =  $\frac{\pi}{T_p(\text{sec})}$ , which is equivalent to  $(30/T_p)$  RPM, ie  $N(\text{RPM}) = 30/T_p(\text{sec})$ .

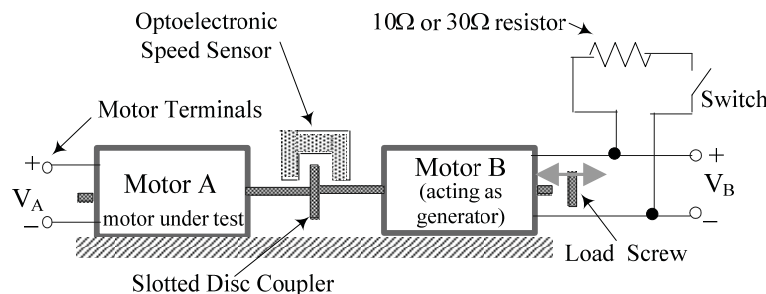


Figure 5.2

In the experiment, an input voltage  $V_A$  applied to the driving motor A is varied (by first decreasing & then increasing it) over a certain range and the corresponding values of the input current  $I$ , the open-circuit voltage  $V_B$  of the driven motor B and the speed are measured. [A higher starting value of  $V_A$  is used in order to overcome possible ‘stiction’ effects]. The output voltage  $V_B$  of the driven motor (now acting as a generator) is measured at various speeds. Since  $V_B = K_b \omega$ , a plot of  $V_B$  against  $\omega$  is used to determine the value of  $K_b$  (in Volt-sec/radian units) [=  $K_T$  (in N-m/amp) =  $K$ ]. With  $K_T$  known, the torque developed corresponding to an input current  $I$ , can be found from the equation  $T = K_T I$ .

The torque-speed characteristic for a given input voltage is obtained by mechanically loading the system using a small friction-brake (‘load screw’) available on the rig. Additional loading through an equivalent ‘electrical’ load will also be demonstrated by connecting a resistive load to the driven motor B which functions as a generator.

Effective Viscous Friction B of the load: In steady state operation, the inertial element  $J$  (see Figure 5.1) has no effect and the steady state torque is given by  $T = B\omega$ . from which  $B$  may be determined at any given loading condition. It should be noted that the value of  $B$  determined in the experiment will correspond to the total viscous friction ‘seen’ by motor A.

Effective Armature circuit resistance  $R_a$ : Assuming that the back-emf of motor A has the value of  $V_B$  at any given speed  $\omega$ , the effective armature circuit resistance is given by the equation

$$R_a = \frac{V_t - E_b}{I} = \frac{V_A - V_B}{I}$$

An average value of  $R_a$  will be found using several readings.

## Procedure

1. Connect the circuit exactly as shown in the detailed diagram of Figure 5.3. Make sure that both power supplies are switched off. Set the Fluke 8010A DMM to read DC, 2000mA and set the Agilent 34405A DMM to DCV-Auto. Set up the DSO to trigger on Ch1 input. Turn the ‘current’ control on the Anatek power supply to its fully CW position. On the experimental rig: **Make sure that loading screw FL is unscrewed so that it is not in contact with the motor axle** and **make sure that the switch EL is in its centre position.**

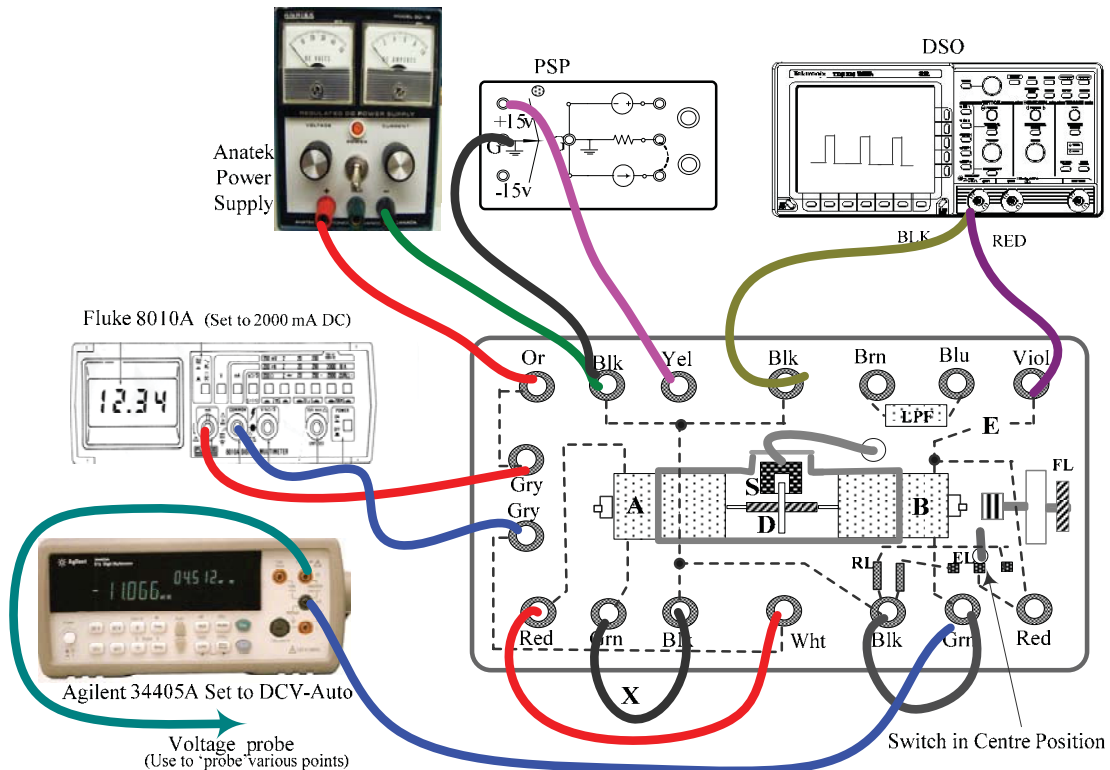


Figure 5.3 : Experimental Setup

2. Connect ‘voltage lead’ from the Agilent 34405A DMM to the Wht(White) terminal on the rig and temporarily disconnect the lead X at either the Grn or the Blk terminal to the left of the Wht terminal. This disconnects drive motor while allowing the drive voltage  $V_A$  to be set. **Turn on the Anatek PS and the master supply to the PS Panel** . Adjust the voltage control on the Anatek supply until the indicated voltage is about 7 volts. Now, re-connect the lead X to the terminal from which it was disconnected. The motor should start and the Fluke 8010A DMM should indicate the current being drawn. The DSO should display a pulse train. Adjust the DSO trigger controls if necessary to obtain a stationary display of the pulses. Gradually reduce the voltage  $V_A$  using the voltage control on the Anatek supply and then increase it back to 7 volts while carefully observing the current indication on the Fluke 8010A DMM . Observe the variation of motor speed and current. **[CAUTION: WHEN REDUCING THE VOLTAGE, DO NOT ALLOW THE MOTOR TO STALL, SINCE THIS WILL RESULT IN EXCESSIVE MOTOR CURRENT AND POSSIBLE ‘BURNOUT’ !]**

3. **Basic Measurements** : Starting from the value  $V_A = 7$  volts, reduce  $V_A$  in steps of 1 volt until a voltage of 3 volts is reached. Then increase  $V_A$  to 3.5 volts, in steps of 1 volts, until  $V_A = 6.5$  volts is reached . At each of the **nine** settings, record the following variables and enter them into Table A of the Lab Record :
  - (a) the voltage  $V_A$ , by probing the Wht (White) terminal
  - (b) the voltage  $V_B$  of the driven motor **B**, by probing the rightside Red terminal  
 [Note that a **negative** value will be obtained for  $V_B$  because of the manner in which the motor is connected. **Ignore the negative sign and record only the magnitude** ]
  - (c) the current  $I$  displayed by the Fluke 8010A DMM
  - (d) the period of the pulse train  $T_p$  seen on the DSO, by measurement using the V-Bar cursors
  
4. **Mechanical Loading: [This step must be done with care!!]** With  $V_A$  set at a nominal value of 6 volts, record the current  $I$  and the period  $T_p$  . **VERY GENTLY** , screw-in the friction load screw FL until the felt pad at its end makes contact with the axle of motor B. Continue to gently advance FL until a small speed reduction is heard and can also be observed as an increase in  $T_p$  on the DSO. Obtain readings (a), (b), (c) and (d) listed above in Step 3, for three different load-screw (FL) settings in addition to the “No Load” setting .[Representative current values around 400, 450 & 500 mA may be used ] Enter the values into the first four rows of Table B of the Lab Record :  
**Reset** the load screw to the “No Load” setting ( not making contact with the axle) after taking the data. [**CAUTION: DO NOT ADVANCE THE LOAD SCREW TO AN EXTENT THAT WILL CAUSE THE MOTOR CURRENT TO EXCEED 550 mA !** ]
  
5. **Electrical Loading** : With  $V_A$  set at a nominal value of 6 volts and the load screw in the “No Load” position, turn the switch EL to its right side position. This loads motor electrically with a  $30\Omega$  resistor ( ie motor B now functions as a generator supplying the  $30\Omega$  load ).The power dissipated in the resistor appears as an additional load to the drive motor A and the speed will be reduced. Obtain the same readings (a), (b), (c) and (d) listed before for this switch position and then for the left side switch position, which connects a  $10\Omega$  resistor as the load . Enter the values into the last two rows of Table B of the Lab Record .  
 Finally, reset the switch to its centre position.

**Results:** Obtain the various results as instructed in the **Lab Report** section.

**PRE-LAB (Weight: 20 %)**

SHOW ALL RELEVANT CALCULATIONS ON A SEPARATE SHEET

(1) A DC motor has the following parameter specifications :

Armature resistance  $R = \dots\dots\dots\Omega$  ( range : 1.5 to 6  $\Omega$  )

Back-emf Constant  $K_b = \dots\dots\dots$  Volt-sec/rad (range 0.002 to 0.008 V-s/rad)

“No Load” speed  $\omega_{nl} = \dots\dots\dots$ RPM (range 5000 to 7000 RPM)  
[convert to radians/sec!]

Input Voltage  $V_{in} = \dots\dots\dots$ Volts (range 2-10 volts )  
[Choose  $V_{in} > E_b$  by 1-3 volts]

“Full Load” speed  $\omega_{fl} = \dots\dots\dots$ RPM (range 2000 to 6000 RPM)  
 ( $\omega_{fl} < \omega_{nl}$  )

For values of the above parameters **selected by you** (within the ranges shown) determine (under steadystate conditions, L  $\rightarrow$  SC , J  $\rightarrow$  OC ) :

(a) The No-load and Full load armature currents  $I$  (no load) =  $\dots\dots\dots$  A  
 &  $I$  (full load) =  $\dots\dots\dots$  A

(b) The corresponding torque  $T = \dots\dots\dots$  Nm

(c) The effective ‘NoLoad’ Viscous Friction  $B = \dots\dots\dots$ Nms/rad

(d) The speed regulation  $S = \dots\dots\dots$ %

Comments re. your calculations:

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**LAB RECORD (Weight: 20 %)**

Step 3: **TABLE A :**

Decrease the input  $V_A$  from 7 Volts and then increase it in the steps given and enter the corresponding values of the other variables.

**Table A**

	$V_A$ Volts	$V_B$ Volts	I mA	$T_p$ sec
D e c r e a s i n g ↓ ↑ I n c r e a s i n g	7			
	6			
	5			
	4			
	3			
	3.5			
	4.5			
	5.5			
	6.5			

Steps 4 & 5 : **MECHANICAL & ELECTRICAL LOADING**

**Table B**

	FL Position	$V_A$ Volts	$V_B$ Volts	I mA	$T_p$ sec
MECHANICAL LOADING	Fully Released	6			
	FL Setting#1	6			
	FL Setting #2	6			
	FL Setting #3	6			
ELECTRICAL LOADING	Switch EL to Right, 30 $\Omega$ Load	6			
	Switch EL to Left, 10 $\Omega$ Load	6			

TA Signature : .....



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## **LAB REPORT (Weight: 60 %)**

Determination of motor constant  $K$  ( $=K_b=K_T$ ).

From the data of Table A , calculate and enter  $\omega$  values in the table below:

$V_B$ Volts	Speed $\omega$ radians/s

Plot the voltage  $V_B$  (magnitude only) against  $\omega$ (radians/sec) using all the values recorded in the above table. Determine the slope of the ‘best fit’ straight line through the points [ Linear regression software such as that available in Excel<sup>TM</sup> etc may be used].This gives the nominal value of the ‘Back- Emf’ constant  $K_b$  in Volt-second /radian. Obtain  $K_b$  from the ‘best fit’ line. The numerical value also corresponds to the torque-constant  $K_T$  in Newton-metre / ampere.

$$K_b = \dots\dots\dots\text{Volt-sec/radian} \quad (= K_T , \text{ in N-m/amp})$$

### Determination of the Torque-Speed characteristic [ ‘Loading curve’ ]

From the data of TABLE B (Mechanical & Electrical loading)and the value of  $K_T$ , calculate and enter values for the torque  $T$  against the  $\omega$  values in the table below:

	MECHANICAL LOADING			ELECTRICAL LOADING		
	RELEASED	FL#1	FL#2	FL#3	EL>Right	EL>Left
Torque $T$ mN-m						
Speed $\omega$ radians/s						

Plot the torque  $T$  against  $\omega$ (radians/sec) using all the values recorded in the above table. Determine the slope of the ‘best fit’ straight line through the points [ Linear regression software such as that available in Excel<sup>TM</sup> etc may be used].This will yield the nominal values of the constants  $k_1$  and  $k_2$  given earlier.

Continued>>>>

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(LAB REPORT Continued)

[Note that if  $T$  and  $\omega$  are in units of mN-m and radians/sec, respectively, when plotting in Excel™,  $k_1$  and  $k_2$  will also be expressed in mN-m and mN-m-sed/radian.]

**Effective Viscous Friction in the unloaded condition :** From the table used to plot the loading characteristic, determine the approximate viscous friction ‘seen’ by the driving motor A when it is not additionally loaded (use the data in the first column of the table):

$$B = T/\omega = \dots\dots\dots \text{ Nm-sec/radian}$$

**Effective Armature circuit Resistance  $R_a$ :** From the data of Table A , determine the values of  $R_a$  corresponding to the nine data values , using

$$R_a = \frac{V_t - E_b}{I} = \frac{V_A - V_B}{I}$$

and hence obtain an average value:

$$\text{Average } R_a = \dots\dots\dots \Omega$$

**Speed regulation:**

From the data of TABLE B , let the ‘no load’ condition be defined by FL being fully released and switch EL in its center position. Choose any one of the loaded condition as ‘full load’ and calculate the Speed Regulation  $S$  :

$$\text{No-Load Speed } \omega_{\text{no load}} = \dots\dots\dots$$

$$\text{Full-Load Speed } \omega_{\text{full load}} = \dots\dots\dots \text{ [State chosen load condition]}$$

$$\text{Speed Regulation } S = 100 [ \dots\dots - \dots\dots ] / (\dots\dots) = \dots\dots\dots\%$$

**Efficiency:** With the same reference values used for calculating  $S$  above, determine the efficiency  $\eta$  :

$$V_A = 6 \text{ volts , } I = \dots\dots\dots\text{mA}$$

and  $\omega = \dots\dots\dots\text{rad/sec}$

$$P_{\text{out}} = T\omega = K_T I \omega = \dots\dots\dots\text{Watts}$$

$$P_{\text{in}} = V_A I = \dots\dots\dots\text{Watts}$$

Hence ,

$$\text{Efficiency } \eta = 100 P_{\text{out}} / P_{\text{in}} = \dots\dots\dots \%$$

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**DISCUSSION & CONCLUSION:** [Discuss possible reasons for any differences observed between theory and the experimental results. Express, in your own words, what you learnt upon doing this experiment.]

[An attempt may be made to correlate the experimentally obtained values of the constants  $k_1$  and  $k_2$  with the constants of the Torque-Speed equation  $\frac{KV_t}{R_a}$  and  $\frac{K^2}{R_a}$  derived in the tutorial section]

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## APPENDIX – A

### EQUIPMENT DESCRIPTIONS

#### ( 1 ) MULTIMETERS

##### The Fluke 8010A Digital Multimeter (DMM)

A *multimeter* is an instrument which can be configured to measure circuit variables such as current and voltage, as well as other parameters such as resistance. *Ideal* meters are fictitious instruments which will not disturb or change the circuit in which they are being used to measure a given quantity. Thus , an ideal ammeter must behave like a *short-circuit* and an ideal voltmeter must behave like an *open-circuit*. The characteristics of a DMM closely approach those of an *ideal* meter, thereby improving the accuracy of measurements. Although DMMs are available with very advanced measurement capabilities, the basic DMM is usually designed to measure only current, voltage and resistance. A typical meter of the latter kind, the **Fluke Model 8010A**, is used in the lab. A short description of the front panel items of this DMM follows.

Front panel features of the Fluke 8010A DMM: The front panel of the Model 8010A used in the lab is shown in Figure A1. Descriptions of the various controls are given below Figure A1.

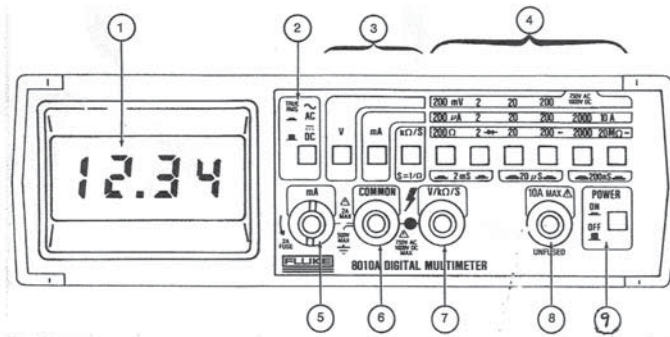


Figure A1 : Front panel of the DMM

Description of front panel items (according to the indicated item number in Figure A4)

1. Numerical LCD Display
2. DC/AC Switch : Push to 'out' position for DC measurements, 'in' for AC )
3. MODE buttons : Push 'in' : 'V' for voltmeter mode, 'mA' for ammeter mode, 'kΩ/S' for resistance or ohmmeter mode (For Conductance S, push in 'kΩ/S' **and pairs** of range buttons as indicated, eg 200Ω & 2kΩ pressed together gives the 2mS range)
4. RANGE buttons : Push 'in' to select the range indicated above the button
5. **Fused Current Input Terminal** : DC current flowing into this terminal and out of the COMMON terminal(6), will produce a 'positive' indication on the display. The positive indication has no '+' sign displayed. If the current enters the COMMON terminal and leaves terminal (5), then a negative sign will precede the displayed value of current. **There is a 2A fuseholder built into this terminal.** It can be accessed by turning the terminal by 90° counterclockwise and then lifting out the terminal. The fuse in the terminal fuseholder must only be replaced with a 2A (AGX-2) fuse if the ammeter mode is not working. Replacement of the fused-terminal is in the reverse order of the removal steps. **Please note: The Current Input Terminal is a special part ! It is important to make sure that this part is always re-inserted in the DMM whenever it is taken out as it is not a replaceable component !]**



**To avoid possible damage to itself as well as to other circuits, a DMM should never be left in the ammeter-mode, after use.**

6. COMMON (or Reference Ground ) terminal (for ALL modes )
7. **Voltage** (and **Ohmmeter**) Terminal : A positive voltage (with respect to the COMMON terminal) applied to this terminal will produce a ‘positive’ indication on the display. The positive indication has no ‘+’ sign displayed. If the voltage applied to this terminal is negative with respect to the COMMON terminal , then a negative sign precedes the value displayed .  
If an **isolated resistance** R is connected between this terminal and the COMMON terminal, and the appropriate resistance range is selected, the value of R is displayed.
8. Special **10A (high current)** current input terminal, for currents > 2A. The ‘mA’ and ‘10A’ buttons must both be pressed. **THIS TERMINAL IS NOT FUSED AND CURRENTS FLOWING INTO IT MUST NOT EXCEED 10A !!**
9. ON/OFF or POWER button : Push ‘in’ to turn ON , push ‘out’ to turn OFF.

### **SPECIFICATIONS of the Fluke 8010A DMM**

Voltmeter Mode: [ DC or effective-value(RMS-value) on AC ]

Input Impedance\* : DC :10 M $\Omega$  ; AC : 10 M $\Omega$  in parallel with < 100pF, all ranges

Accuracy :  $\pm$  1 % or better, DC to 20 kHz (max . frequency 200kHz)

Response time : < 1 sec

Ammeter Mode: [ DC or effective-value(RMS-value) on AC ]

Accuracy :  $\pm$  2 % or better, DC to 20 kHz (max . frequency 200kHz)

Maximum Burden Voltage \* : 0.3v upto 200mA range, 0.9v on 2000mA range

Response time : < 2 sec

Ohmmeter Mode : Accuracy :  $\pm$  0.5 % or better, all ranges.

\* These specifications are indicative of the closeness of the DMM to the “ideal meter” conditions.

**CAUTION : . The proper mode must be selected on the DMM, to make it function as an ammeter, voltmeter or ohm-meter. Always set the DMM in the required mode BEFORE connecting it! In particular never connect the ammeter terminals directly to a voltage output. For safety, the DMM should be configured as a voltmeter when no being used.**

**The Agilent 34405A Digital Multimeter (DMM)** is a more recent DMM model, which has advanced capabilities which include Frequency, Capacitance and Temperature measurement. This DMM has **auto-ranging** capability as well.

The front panel features of the Agilent 34405A together with identification of the various controls are given in Figure A2.

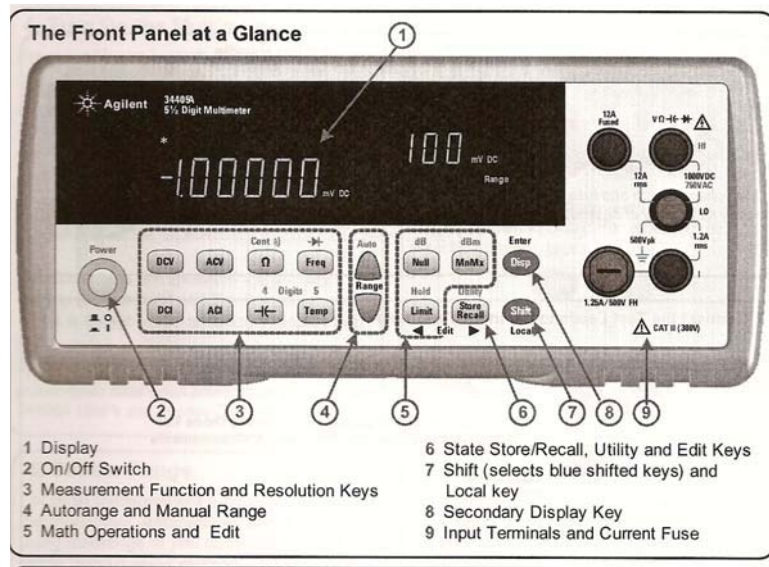


Figure A2

The detail of the input terminals and the basic setup steps are given in Figures A3(a) & A3(b)

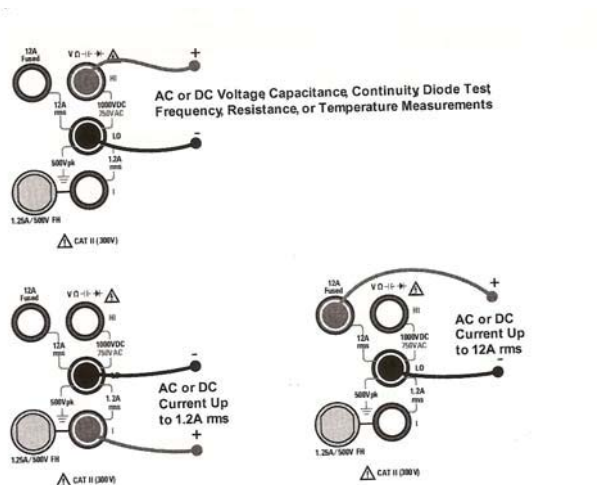


Figure A3(a)

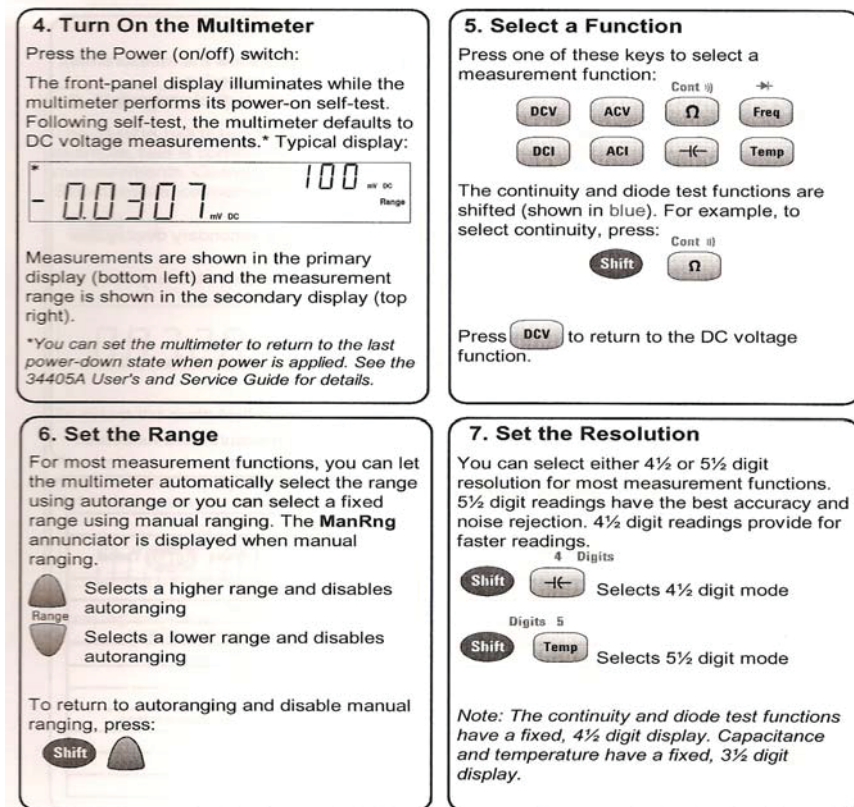


Figure A3(b)

## SPECIFICATIONS of the Agilent 34405A DMM

Voltmeter Mode: [ DC or effective-value(true RMS-value) on AC ]

AUTORANGING DCV/ACV – 5 ranges:100mV,1V,10V,100V ,1000V/750V

Input Impedance\* : DC :10 MΩ± 2 % ; AC : 1 MΩ± 2 % in parallel with < 100pF, all ranges

Accuracy : ± 1 % or better, DC to 30 kHz (max . frequency 100kHz)

Response time : < 1 sec

Ammeter Mode: [ DC or effective-value(true RMS-value) on AC ]

Accuracy : ± 2 % or better, DC to 20 kHz (max . frequency 200kHz)

Shunt Resistance \* : 0.1 to 10Ω (10mA to 1A range), 0.01Ω for 12A

Ohmmeter Mode : 7 Auto Ranges:100Ohm, 1kΩ, 10kΩ,100kΩ,1MΩ,10MΩ,100MΩ,

Accuracy : ± 0.5 % or better, all ranges.

\* These specifications are indicative of the closeness of the DMM to the “ideal meter” conditions.

Frequency : 300 kHz Autoranging , dependant on input voltage level

Capacitance : 1 nF to 10,000μF Autoranging , 6 ranges, 5.5 digit

Temperature: -80°C to +150°C ±0.2° with 5kΩ thermistor probe

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( 2 ) **FUNCTION GENERATORS** are used to provide various input (or excitation) signals for testing electrical circuits. The output(s) of the circuit are displayed and measured using a variety of instruments, the most common one being the **oscilloscope**. In the lab, the **Instek GFG-8216A Function Generator**(abbreviated **FG**) and the **Tektronix TDS320 Oscilloscope** (a **Digital Storage Oscilloscope**, abbreviated **DSO**) are used . Repetitive signals (also called ‘periodic’ signals) such as sinusoidal-, square-wave- and triangular-wave signals are an important class of outputs commonly available from FGs.

Periodic signals are characterized by a constant repetition period T, shown on the left in Figure A4 for an arbitrary periodic waveform. Single cycles of squarewave, triangular-wave and sinusoidal voltage signal waveforms of different frequencies are also shown on the right in the figure. The inverse of the period ( $1/T$ ) called the frequency f, is measured in Hertz (Hz), 1 Hz being equivalent to 1 Cycle per second (‘cps’ or ‘c/s’). Well defined reference-points such as the zero-crossings or the peaks can be used for defining the period T as indicated in the figure.

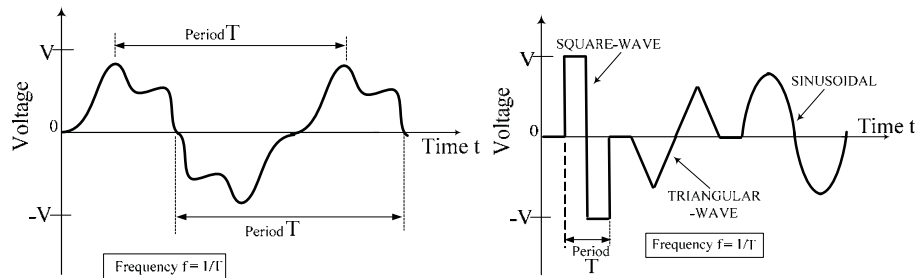


Figure A4

In the ELEC275 lab, the sinusoidal output of a function generator is extensively used .The basic terminology used for sinusoidal signals is given in Appendix B

**The Instek GFG-8216A Function Generator:** The front panel of the GFG8216A FG is shown in Figure A5, followed by brief descriptions of various controls. The FG also has two other input connectors on the rear panel, which are not used for this lab. [The front panel button labelled ‘Gate’ operates only when the ‘counter’ input on the rear panel is used, and is not described in the explanation of terms following Figure A5]

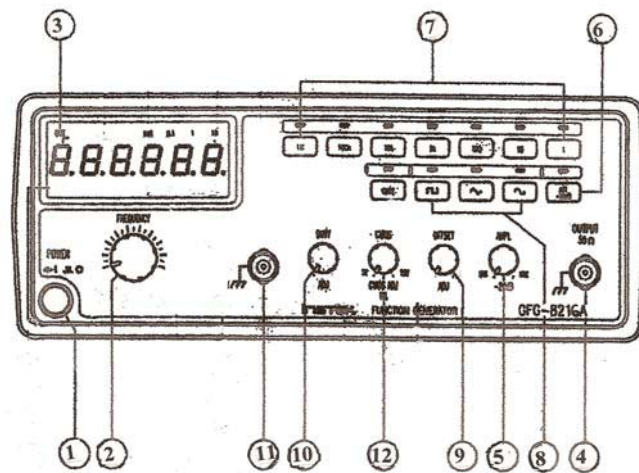


Figure A5: Front panel of Function Generator

### Description of front panel controls

1. Power Switch : Push 'in' to turn on and to 'out' to turn off.
  2. Frequency Control knob: Turn clockwise to increase the frequency (~10:1ratio) Adjusting this control in conjunction with the 'Frequency-Range' control buttons(7), changes the output frequency. A small 'prefix'(m, k or M , standing for milli-,kilo and mega-) appears at the bottom of the display(3), as an indicator of the frequency
  3. Six-digit LED Display of the frequency (Hz, kHz or MHz)
  4. Output Connector('BNC'): A BNC-to-Banana Jack Adapter is permanently affixed to this connector. The output impedance is 50  $\Omega$ , resistive.
  5. Output Amplitude Control knob : Adjusts voltage output to a maximum of 10V<sub>pp</sub> [Pull 'out' for variable attenuation upto -20dB]
  6. Attenuator Button : Provides an additional - 20 dB attenuation.
  - 7 Frequency Range Buttons : Labelled 1, 10,100,1k, 10k, 100k, 1M , these buttons allow the selection of the frequency-range controlled by the frequency-control knob (2) [Total **Range is 0.3Hz to 3 MHz**]
  8. Waveform Selector Buttons: Square, Triangular or Sine-wave output.
  9. DC Offset Control knob: If pulled 'out', this knob can be adjusted to center the AC output over a DC 'bias' voltage ( $\pm 10$  volts ,variable)Push the knob 'in' for **zero offset** , which is the normal position.
  10. Duty Cycle/Symmetry Control: Adjusts the duty-cycle (or 'symmetry') of theOutput waveform , when pulled 'out'.
- [11 & 12: TTL/CMOS output control and Output Connector: These are digital logic outputs and associated controls, not used in these labs]

Note: The BNC-to-Banana Jack adapter fixed to the FG output connector allows the standard banana-plug ended patchcords available in the lab to be used for making input and output connections.

**( 3 ) OSCILLOSCOPE BASICS :** The oscilloscope is an instrument which allows the display and measurement of time-varying voltage waveforms. Early oscilloscopes used the cathode-ray-tubes (CRTs) which were similar to television picture-tubes and utilized the deflection of an electron beam by the voltage of the signal to be displayed. The beam was controlled by X- deflection and Y-deflection circuits (which deflected the beam in the horizontal and vertical directions) and made to strike a phosphor-coated glass screen to produce a visible trace. The visible line-traces are seen on the screen due to the effect of phosphor coating as well as 'vision persistence' effects of the human eye. The basic 'mechanics' of waveform display may be simplistically explained as follows: In the absence of the applied voltage-input (applied to the Y-deflection ), the electron beam is *repeatedly swept* (deflected) horizontally across the screen by a *sawtooth-shaped* voltage applied to the X-deflection circuit. This 'sweep voltage' ensures that the beam-spot (on the screen) traverses the screen, from left to right, in a *precise time period* but returns to the starting point on the screen in a negligibly short time. The precise and repeated X-deflections of the beam allow the *calibration* of the horizontal screen-trace in terms of a specific time, known as the time-base (or 'Time per Division') of the instrument. With the X-sweep operating, if the time-varying voltage signal to be displayed is simultaneously applied to the Y-deflection circuits, then the resulting trace on the screen will be that of the Y-signal, *scaled in accordance with both the operating time-base and the deflection-characteristics of the Y-deflection circuit*. If the voltage to be displayed is a repetitive signal (such as a sine-wave), a 'stable' (stationary) display can be produced by 'synchronizing' the start of the time-base(X-sweep) with the signal, a process known as '*triggering*'. With proper horizontal and vertical *calibrations* and *triggering* of the trace, the signal under consideration can be clearly

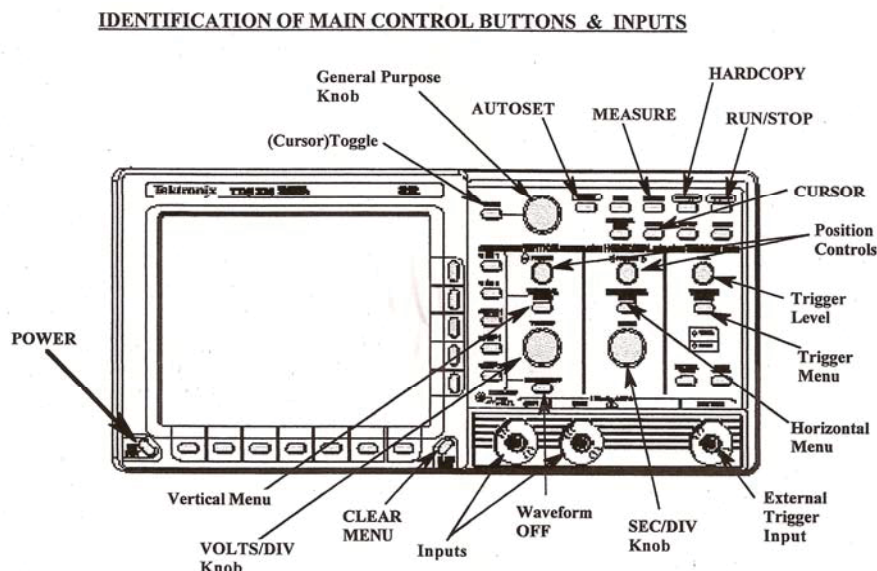


displayed. Waveform measurements could be then made either using the directly-viewed trace or from photographs of it. The term ‘storage oscilloscope’ originally referred to a ‘scope in which a ‘long-persistent phosphor’ was used for the screen coating, enabling a rapid event on the trace to be viewed for a relatively long time. With the development of digital circuits this ‘storage’ capability has been more comprehensively achieved. The oscilloscope is an instrument which has undergone tremendous development since its invention. Modern oscilloscopes use liquid-crystal display (LCD) panels and are almost exclusively digital machines which have extensive automated measurement capabilities. The Tektronix TDS 320 DSO used in the present lab is such an instrument.

**The Tektronix TDS 320 Digital Storage Oscilloscope (DSO)** : This oscilloscope is a 2- Channel, 100 Mhz waveform display and measuring instrument which is highly automated. The DSO is menu-driven and all settings are made by pushing the front panel buttons and turning a few rotary knobs. Many common electrical signal measurements such as peak-to-peak and RMS amplitudes, frequency and period can be automatically measured and displayed along with the observed waveforms. A very useful feature is the availability of vertical(‘V-Bar’), horizontal (‘H-Bar’) and ‘paired’ cursors, which when positioned on waveforms using a control knob, allows horizontal intercepts (time-differences), vertical intercepts(voltage-differences) or both (‘paired’ cursors) to be measured and displayed. Another useful feature is the availability of a ‘Math’ function which displays the result of performing mathematical operations on the Channel 1(Ch1) and Channel 2(Ch2) voltage signals, such as addition, subtraction and multiplication. The cursors and the ‘Math’ function are used frequently in the laboratory procedures.

In the laboratory, records of test waveforms are obtained by printing the displayed (and stored) waveform on a laser printer. The DSOs at all the lab stations are connected through a digital switch to a common laser printer. Pushing the ‘Hardcopy’ button on the DSO results in the displayed screen [which must first be ‘frozen’(stored) by using the Run/Stop button] being printed with the proper station identification. The printer is programmed to produce two copies (for use by the two students at each station) when ‘Hardcopy’ is pressed.

The front panel of the TDS320 is shown in Figure A6

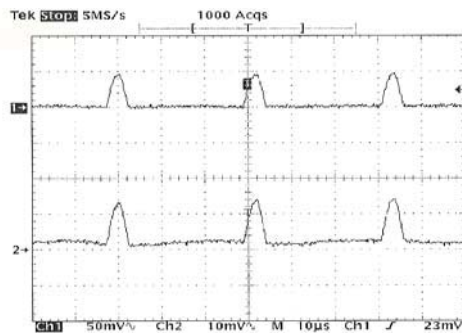


**Figure A6:** Front panel of the TDS 320 DSO

Operation of the TDS 320 is mostly menu-driven as mentioned earlier. Three primary menu-buttons: VERTICAL MENU, HORIZONTAL MENU and TRIGGER MENU are located in the right half of the front panel. Pressing any of these, as well as the other buttons in the upper part of the panel, activates the 7 “Main Menu” buttons located at the bottom of the screen, and the 5 “Side Menu” buttons located immediately to the right of the screen. These two button-groups are then used for setting the DSO parameters.

**INITIAL SET UP using AUTOSET:**

1. Press ON/STDBY on the left of the screen. The DSO turns on and performs a self check. and displays a message Then press CLEAR MENU on the bottom-right corner of the screen. The graticule will now be displayed.
2. Press AUTOSET located at the top part of the panel. Pressing this button automatically selects the proper settings required for an optimum display of the signals applied to the input terminals. Pressing AUTOSET with no applied input, for example, displays the typical screen shown in Figure A7 which shows ‘noise’ voltages appearing across the BNC-to-Banana Jack adapter input terminals



**Figure A7:** Typical screen display with no inputs applied

3. If AUTOSET is pressed with a repetitive signal input (such as sinusoidal input) an optimum and stationary display consisting of several cycles of the waveform will result. The Channel 1(Ch1) and Channel 2(Ch2) sensitivities and the time- base (SEC/DIV) can then be changed using the rotary control knobs to satisfactorily display the input signal.  
Note: The BNC-to-Banana Jack adapters fixed to the DSO input connectors (Ch1 & Ch2) allows the standard banana-plug-ended patchcords available in the lab to be used for making input output connections.

Brief descriptions of the front panel controls of the TDS320 digital storage oscilloscope follow.

**FREQUENTLY USED OPERATIONAL BUTTONS & CONTROLS:**

**CLEAR MENU :** Clears the menu from the screen when pressed. If used after selecting MEASUREMENT variables, pressing this button clears the menu but the measured values are moved to the right of the graticule

**Ch1,Ch2, Math, Ref1,Ref2 :** Pressing these buttons creates the appropriate trace on the screen. Ch1 & Ch2 are normally pressed to obtain the two channels. MATH creates a trace labelled ‘M’ which can be then configured as Ch1+Ch2, Ch1-Ch2 ,Ch2-Ch1 or Ch1\*Ch2 etc. The two Ref channels are intended for use in waveform comparisons

**A small arrow indicator along the left edge of the graticule indicates the ZERO voltage position of each trace**

**WAVEFORM OFF :** Pressing this button removes the currently selected waveform

**POSITION (Vertical & Horizontal) :** These controls located above the VOLT/DIV and SEC/DIV knobs respectively, are used to position the relevant traces.

VOLTS/DIV : Sets the vertical sensitivity of the selected channel (indicated at the bottom of the screen.)

SEC/DIV : Sets the timebase ( time per division)of the horizontal axis.

VERTICAL MENU : Pressing this button enables the setting of Input Coupling ( DC, AC or Gnd), Bandwidth ( Full or 20MHz), Channel Inversion, zero- ing of vertical position and vertical offset [ The last named setting allows the *internal* addition of a variable DC signal to the input and is useful when observing small signals *with a large DC offset* (known as a “DC bias”)].  
For signals below 20 MHz, selecting the ‘20 MHz BW’ can yield a cleaner display in many cases since it ‘filters’ out ‘noise’ signals. ‘Fine Scale’ allows the vertical sensitivity to be set between standard pre-fixed values.

**General Purpose (GP) Knob & Toggle Button** : This knob, located at the top left side and the associated TOGGLE button, is used to control many of the variable ‘side menu’ items. Together with the TOGGLE button it is also used for positioning the cursors for various voltage and time readouts [See ‘CURSOR’ next]

CURSOR : Pressing this button allows access to cursors, which are lines (or bars) which may be positioned using the abovementioned GP Knob and the TOGGLE button .The ‘active’ cursor is the ‘solid’ bar whose position can be set using the GP knob. The ‘dotted’ bar becomes the active cursor when the TOGGLE button is pressed. There are three types of cursors available : ‘H-Bars’, ‘V-Bars’ and ‘Paired’.

The V-bars are used to measure the time-interval ( $\Delta t$ ) between cursors , while the H-bars are used for voltage-interval( $\Delta V$ ) measurements. These two cursors can be used independent of the display. Paired cursors consist of both V and H cursors, acting simultaneously, with small H bars riding on the waveform. Thus, paired cursors are used to find the voltage-difference and the time-difference between any two points on a single waveform.

The general measurement procedure using cursors is as follows: Set the position of the active cursor using the GP knob, then press TOGGLE to activate the second cursor and then set its position. The intervals between the cursor positions appear on screen as small  $\Delta$  values. Press the CLEAR button to move these readings to the right side of the graticule.

[Note: Cursor measurements can be visually recorded in the event of a Printer-system malfunction]

MEASURE : Pressing this button activates the main and side menus which are then used to make automated measurements such as Period, Frequency, Peak and RMS magnitudes, overshoots , etc. Measurements can be removed by using REMOVE MEASUREMENT from the main menu bottom row.



**Buttons used for printout:**

RUN/STOP & HARDCOPY : Pressing this button starts and stops signal acquisition .  
**The R/S button must always be pressed to ‘freeze’ the waveform before pressing the HARDCOPY button to obtain a printout.**

**OTHER BUTTONS ( less frequently or not used normally ) and their functions :**

HORIZONTAL MENU : Pressing this button subsequently allows setting of the timebase parameters ( normally set to ‘Main Only’) and the Trigger position (normally set to 50% ,as can also be done by pressing the ‘SET LEVEL TO 50% under the TRIGGER MENU button)

TRIGGER MENU : Pressing this button subsequently allows sweep or trigger parameters to be set. Normally, after pressing this button, the leftmost main-menu button is repeatedly pressed to get ‘Type Edge’ triggering [‘Video’ is not used in the lab].Under ‘Edge’ triggering, other parameters such as Trigger Source (Ch1,Ch2,EXT,AC line), Trigger Coupling (DC,AC ), Slope and Level can be set.

DISPLAY : Pressing this button subsequently allows screen such as screen Intensity, Graticule style (Full/Frame), Format (YT or XY) to be set

ACQUIRE : Pressing this button allows setting of the signal acquisition mode ( ie sample, peak-detect, single-sequence etc. Normally set to Mode >>Sample Stop after >>Run/Stop button only). To activate the Single Sequence mode, press ‘Stop after’ >> ‘Single Acquisition Sequence’. The DSO then acquires a single sequence and displays it until the Run/Stop button is pressed. The R/S button then acts as a “single shot” button. The acquisition parameters (press ACQUIRE and set) must be set to Mode>> Sample, Stop after >> Run/Stop button only.

SAVE/RECALL SETUP : Pressing this button activates the Save/Recall setup menu under which , upto 10 front-panel stored setups (including Factory Setup) can be stored and recalled.

UTILITY : THIS BUTTON IS TO BE USED FOR SYSTEM CONFIGURATION ONLY. Pressing this button brings up four pop-up menus: Config ,I/O, Cal and Diag., of which only I/O is of interest in normal operation, the others being used only for service procedures(Calibration & Diagnostics).Under I/O , the proper output port being used must be selected. (Serial,RS232 in the lab)

**Proper settings for hardcopy in the lab should be as follows:**

<b>Hcp Port</b>	set to >>> <b>RS232C</b>
<b>Hcp Layout</b>	set to >>> <b>Landscape</b>
<b>Hcp Format</b>	set to >>> <b>Laserjet/Laser printer</b>
<b> GPIB</b>	set to >>> <b>Hardcopy(Talk only)</b>
<b>RS232C config.</b>	set to >>> <b>Baud Rate to 19200</b>
<b>Hard Flagging</b>	set to <b>"ON"</b>
<b>Soft Flagging</b>	set to <b>'OFF'</b>
<b>EOL</b>	set to <b>LF</b>
<b>Parity</b>	set to <b>'None'</b>
<b>Stop Bits</b>	set to <b>'1'</b>
<b>Delay</b>	set to <b>0 sec</b> , using the GP knob.

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#### (4) DESCRIPTIONS OF POWER EXPERIMENT (Expt#4) EQUIPMENT

The equipment used in the 'Power' experiment consists of the following units :

1. A 3-phase Variac ( 0 to 120 volt Variable AC Power source)
2. A 3-phase transformer module
3. A single-phase RL-load unit .
4. A three-phase R-L-C load unit.
5. Two Analog Wattmeters.[ Simpson Model 1379]
6. The Fluke 8010A & the Agilent 34405A DMMs (described in Appendix A, Section 1)
7. The TDS 320 DSO/Printout system (described in Appendix A, Section 3)

Descriptions of items #5 & #6 were given in earlier sections. This section of the appendix describes the items #1 to #5 in the list above.

**The 3-phase Variac** [Gray metallic unit with a large knob, sitting on top of the the left end of the hutch at each workstation.] consists of three single-phase variable-transformers (called **variacs**), internally connected in a Y-configuration and mechanically coupled so that the wiper positions are the same on all three units for any given control-knob position. The variac is plugged into the 3-phase, 120 volt AC supply available in the lab.

The variac is protected by three 3A time-delay fuses which are not the standard AGX fuses used in the other lab modules. The variac is fitted with a Fuse-Status-Indicator (FSI) box which allows the fuses to be checked quickly: With nothing connected to the terminals and with the control knob turned fully clockwise, all three amber lamps on the FSI should glow when the three fuses are good . Photographs of the variac without and with the FSI box are shown in Figure A8.



VARIAC ,SHOWING  
FUSES [WITHOUT FUSE-  
STATUS INDICATOR BOX]



VARIAC ,[WITH FUSE-STATUS  
INDICATOR BOX MOUNTED]

Figure A8: The 3-Phase Variac

The colour codes for the output terminals on the FSI box are as follows:

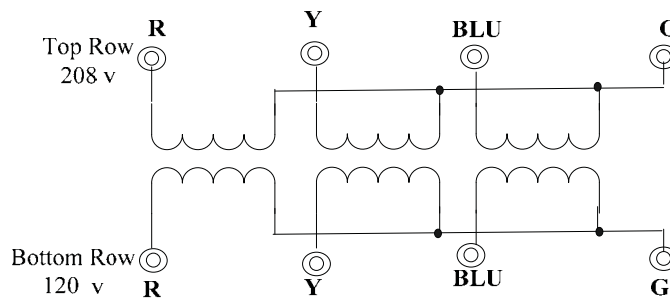
**Red = Phase 1 ( $0^\circ$ ), Yellow = Phase 2 ( $-120^\circ$ ), Blue = Phase 3 ( $-240^\circ$ )**  
**Green = Common, Neutral, Ground**

[ie: the ABC sequence corresponds to Red-Yellow-Blue]

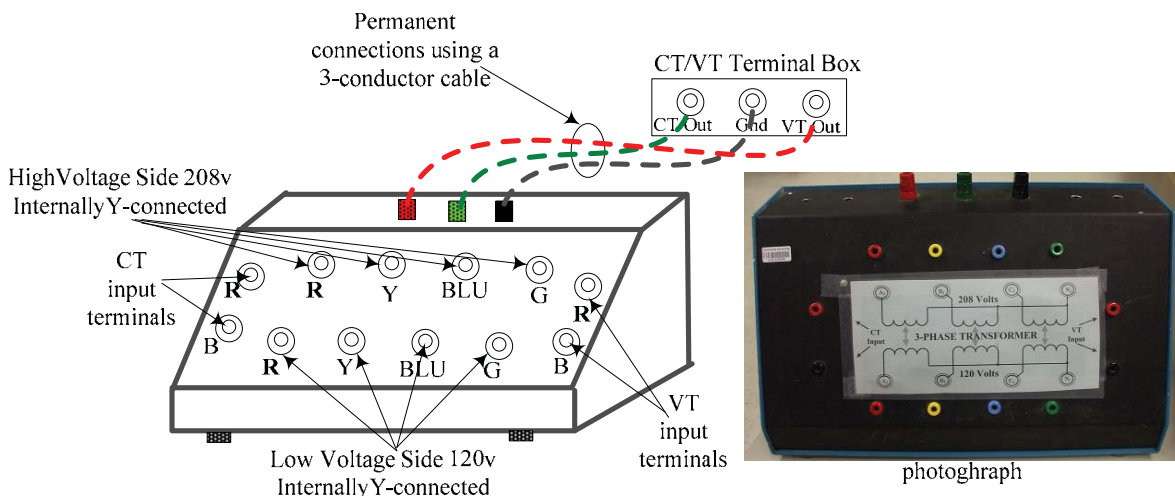
The maximum line-to-line voltage at the output terminals is nominally 208 Volts RMS (reached when the variac control knob is turned clockwise to its maximum), and the corresponding line-to-ground voltage is nominally 120v. In Part A of Experiment # 4, the variac is used a single-phase source and the output is taken from the Red (or Yellow or Blue) terminal and the ground (Green) terminal. In Part B of Experiment # 4, all three phases are used..

[ **Important Note: The variac has no ON/OFF switch and its control knob must always be returned to the zero position for safety .**

**The Transformer Unit** is located under the hutch at left end of the bench. The transformer unit, shown in Figure A9, contains three 208/120 volt single-phase transformers internally connected in a Y–Y configuration, shown in Figure A9(a), to serve as a 3-phase transformer. The top and bottom rows are the “208v” and “120v” sides of the transformer, respectively.



**Figure A9(a):** Three-phase transformer box internal connections  
 [ VT & CT connections are not shown ]



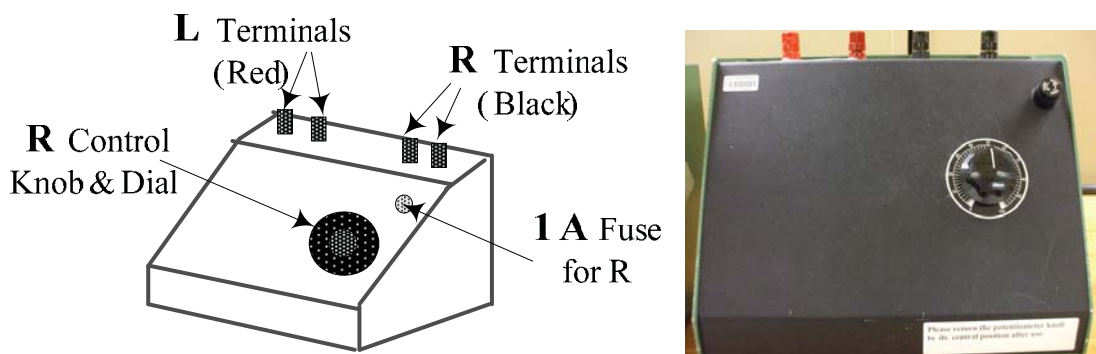
**Figure A9(b):** The 3-Phase Transformer [also contains a VT & a CT]

**The VT & CT units:** The ‘transformer unit’ also contains a “Voltage-Transformer” VT (also called a ‘Potential Transformer’) and a “Current-Transformer” CT which are used as transducers to provide voltage signals proportional to their input voltage and current, respectively, in order to display the latter on the DSO. The outputs of the VT and CT **are already connected**, using a 3-conductor cable with a common ground, to a small terminal box located on the hutch above the DSO. The terminals on both the transformer box and the CT/VT terminal box are colour-coded as follows: GREEN for CT-Output, BROWN or BLACK for Ground or Common, RED for VT-Output. The terminal box jacks should be connected to the DSO using short banana-plug patchcords. A sketch of the transformer box and a photograph of it are shown in Figure A9(b).

**The permanent CT/VT connections that are already made at the top of the transformer box are not to be removed! Because of these connections, as well as for safety the transformer box should not be moved from its location in the workstation.**

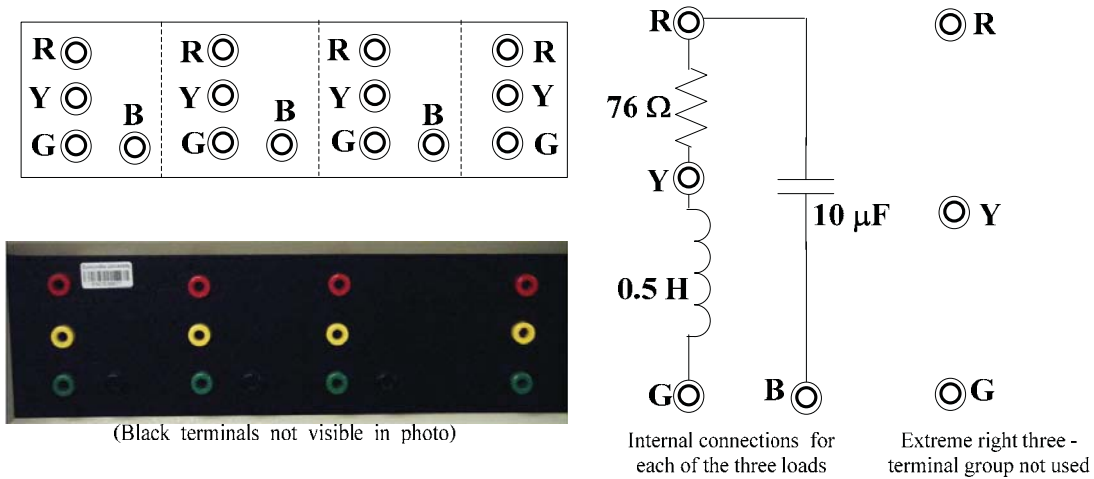
**VT & CT sensitivities :** The average calibration sensitivities of the VT and CT are nominally **50mV/Volt** and **105 mV/Amp** respectively. For example, if the DSO Ch1 connected to the VT output indicates a value of 3 VRMS, then the voltage at the VT input (primary) is  $(3)/(0.05)$  or  $\sim 60$  Volts RMS. Similarly, if the CT signal on Ch2 reads 38 mV RMS, then the actual current in the CT primary is  $(38)/(105)A$  or  $\sim 0.36$  Amps RMS. [Note: The Red and Black input terminals of the VT and CT are their positive and negative references, respectively. The Black terminal of the VT must be connected to a ‘common’ or ground for proper phase relations]

**The single-phase RL-load unit**, shown in Figure A10, contains a power inductor of nominal value 0.2 H and a variable power resistor (rheostat) of nominal value  $100\Omega$ , 150W mounted in a metal cabinet. The R element is provided with a control knob and graduated scale. The resistance value increases as the knob is turned clockwise. The rheostat is protected by a 1A fuse which is accessible from the front of the unit. When set at its minimum and maximum, the wiper of the rheostat sometimes makes intermittent contact; hence it is advisable to check the resistance using an ohmmeter in such cases. For safety reasons, the R control knob should always be set to its midpoint when not in use. **The R control knob should never be left at its minimum position.**



**Figure A10:** The single-phase load unit

**The 3-phase load unit** contains three sets of fixed-value R, L and C elements mounted within a metal cabinet and connected internally. A photograph of the front panel of the unit , together with circuit diagrams of the internal elements is shown in Figure A11.



**Figure A11:** The three-phase load unit

Three identical element groups, which may be connected in the desired load configurations, are available. The various load configurations required may be obtained by appropriate patching between the terminals [These are given in the Experiment # 4 procedures]. The three terminal group at the extreme right are unconnected internally and are not used.

**The Wattmeter** is a moving-coil meter which has two coils, a low resistance ‘current coil’ and a high resistance ‘voltage coil’ [see Figure A12]. Each coil is connected to a pair of terminals. To measure the average power P delivered to a load, the ‘current coil’ is connected in series with the load so that the load current I flows through it and the ‘voltage coil’ terminals are connected across the load so that the load voltage V appears across it. The meter produces a pointer-deflection which is calibrated in terms of average power  $P (= VI \cos\theta)$ . Note that the ‘live’ end of the ‘voltage coil’(Red terminal) may be connected either to the load-side of the ‘current coil’ or to the line-side (as in Figure A12). Either of these connections may be used assuming that the impedance of the current coil is negligible. In the experimental circuits, the ‘line-side’ connection is used as seen in Figure A12. Depending upon the phase relationship between V and I, it is possible that the meter will attempt to give a downscale (or negative)reading. Such a downscale swing will result in the pointer straining against the zero-stop, which if allowed to continue, will damage the meter. For this reason, the terminals connected to the ‘voltage coil’ are internally reversible by means of a ‘reversing switch’ in order to allow wattmeter readings which tend to become negative.

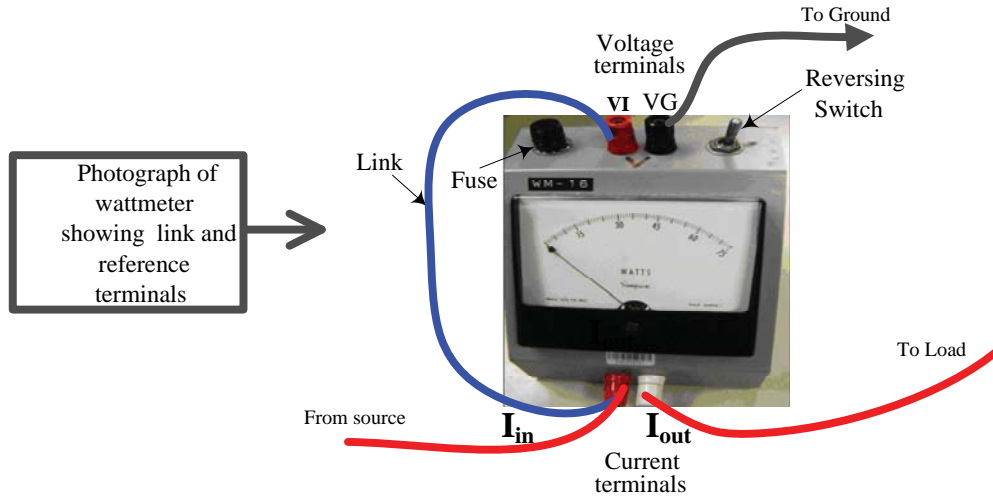
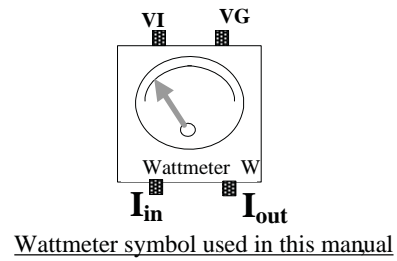
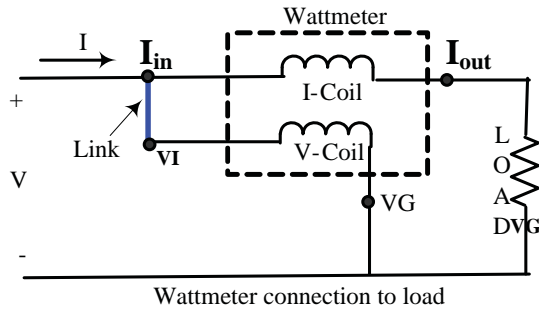


Figure A12: The Wattmeter and its connections

Ideally, the ‘current coil’ should have zero-impedance and no voltage across it and the ‘voltage coil’ should draw no current and hence the wattmeter itself should not draw any power. The accuracy of wattmeters is usually specified. The wattmeter has a protective fuse which must be replaced if necessary. The Full Scale (FS) range of the of the Simpson Model 1379 Wattmeter used in the lab is 75 Watts (max. current 1 Amp) and its accuracy is  $\pm 2\%$  of FS.

**Simplified Wattmeter connections :**

The connections to a wattmeter can be simplified by first ‘linking’ the Red terminal of the current coil to the Red terminal of the voltage coil and label the Red current-coil terminal as the “current in” terminal ( $I_{in}$ ). With the link connected, only three connections:  $I_{in}$ ,  $I_{out}$  and Ground need to be made to the circuit

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#### (5) DESCRIPTIONS DC MOTOR EXPERIMENT (Expt#5) EQUIPMENT

The equipment used in DC Motor experiment consists of the following units :

1. A DC Motor experimental rig
2. The Anatek Model 50-1S DC power supply
3. The Fluke 8010A & Agilent 34405A DMMs (described in Appendix A)
4. The TDS 320 DSO/Printout system (described in Appendix A)

Descriptions of items # 3 & # 4 were given in earlier sections. This section of the appendix describes the items #1 and #2 in the list above.

The DC Motor experimental rig consists of two small PMDC motors [ Mabuchi Model RS-365SH ] mechanically-coupled 'back-to-back'. The motors are mounted in a PVC holder which in turn is bolted to a plastic case, the top view of which is shown in Figure A13.



Figure A13: Top view of the DC Motor rig.

Various electrical connections are brought out to colour-coded banana plug jacks mounted on the case.

The various component and the internal connections are shown in Figure A14. Motor **A** is used as the 'driving' motor and motor **B** is used as the 'driven' unit, which functions as a generator. Certain direct internal electrical connections are shown as dotted lines. Some other internal connections and electronic components related to the opto-switch and the low-pass filter are only shown as blocks. External connections to the power supplies and other instruments are made using the standard banana-plug patch cords.



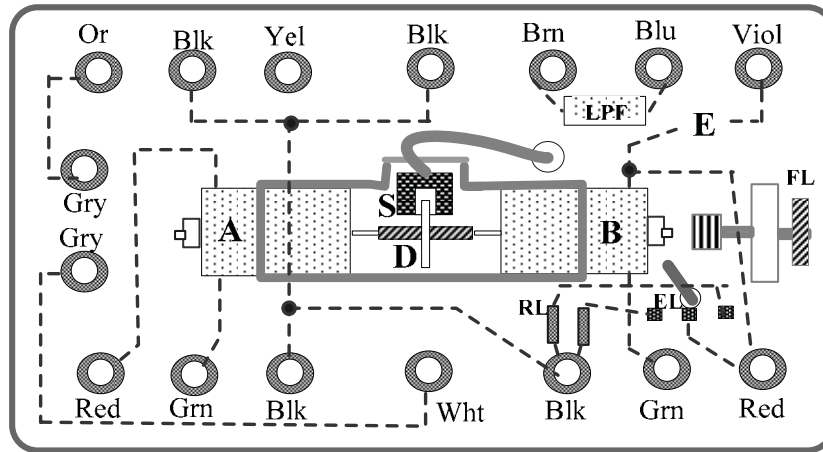


Figure A14 : Physical layout of experimental rig , showing internal connections

A friction load screw (**FL**) , mounted at one end [the right hand end of Figure A14] allows the application of an external mechanical friction load by moving the screw such that a felt pad located at the end of the screw makes contact with the axle end of the driven motor **B**. **The friction load screw should be used very gently and never such that it stalls the motor!** A three-position toggle switch (**EL**) allows the terminals of the driven motor **B** to be isolated (in the centre position) or to be connected to one of two load resistors (**RL**) [ $10\Omega$  &  $30\Omega$ ] so that the system may be electrically loaded .

Speed measuring system: The mechanical-coupler assembly linking the two motors has a slotted disc **D** which, together with an optoelectronic switch (**S**) and associated electronics, (**E**) provides a pulse-train which can be observed on the oscilloscope. The disc **D** has **two** diametrically-opposed peripheral slots which, together with the optical-interrupter switch (**S**) and associated circuitry, produces two pulses per revolution as an indicator of the angular velocity. The system must be connected to 15 volts DC between the Yel(+) & Blk(-) terminals on the top row of Figure A14, with the output obtained from the Viol (Violet coloured) terminal. When the output is observed on an oscilloscope a pulse train, whose idealized and actual forms are shown in Figure A15, will be obtained..

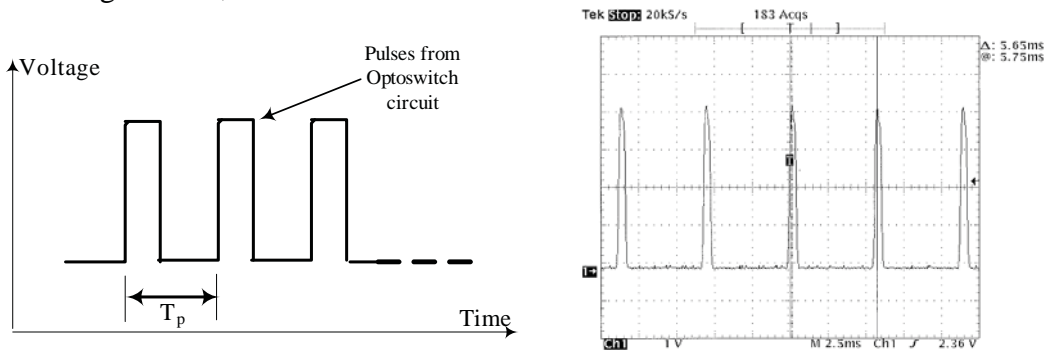


Figure A15

Since one-half of a revolution ( $\pi$  radians) is covered during the period  $T_p$  (seconds), the angular velocity  $\omega$  (radians/sec) is given by  $\omega = \pi/T_p$ .

[Also, since  $1\text{RPM} = 2\pi/60$  radians/sec, we have  $1$  radian/sec =  $(60/2\pi)$  RPM.

Hence  $(\pi/T_p)$  radians/sec is equivalent to  $(\pi/T_p)(60/2\pi)$  RPM, or  $(30/T_p)$  RPM. That is, the rotational speed  $N(\text{RPM}) = 30/T_p(\text{sec})$ . For example, according to the actual pulse train shown in Figure A15,  $\omega = \pi/0.00565 = 556$  radians/s or  $N = 30/0.00565 \approx 5310$  RPM.

**The Anatek Model 50-1S power supply** is located between the DSO and the centre post of the hutch. It is used as the input power source for the DC motor A. In order to avoid possible damage to the motor, **the supply has been modified internally such that the maximum output voltage available is about 9 volts.** A photograph of the front panel of the supply is shown in Figure A16.



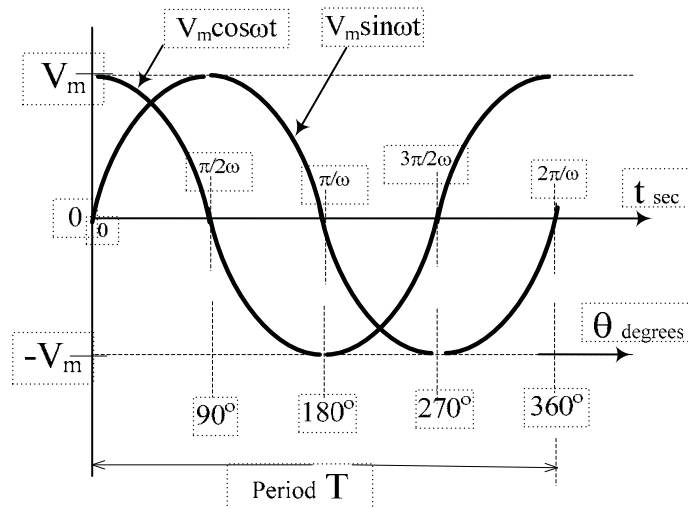
Figure A16 : Front panel of Anatek 50-1S DC Power Supply

The supply has multi-turn ‘voltage control’ knob and ‘current control’ knobs. **The ‘current control’ knob should be turned clockwise to its maximum position , so that adequate current can be delivered.** The multi-turn ‘voltage control’ allows fine adjustment of the output voltage, which is available from the red and black terminals (the centre green terminal is a ‘chassis’ ground). Small analog meters indicating the output voltage and current are located above the two control knobs. **The ammeter should be frequently monitored, in particular, to check that the motor current never exceeds 0.5 A.**

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**APPENDIX – B**  
**SINUSOIDAL SIGNALS, COMPLEX NUMBERS,**  
**PHASORS and IMPEDANCE**  
**and 1- $\phi$  and 3- $\phi$  POWER DEFINITIONS**

1. **Sinusoidal signals (& AC circuit analysis)** : Sinusoidal signals such as  $V_m \sin \omega t$  and  $V_m \cos \omega t$  (commonly called ‘AC’ signals), shown in Figure B1, are the operating signals in “AC circuits”. In the laboratory such voltage signals are provided by a function generator (FG) described in Appendix-A. These signals are repetitive with a fixed *period* of repetition  $T$ . Their magnitude alternates cyclically between equal positive and negative peak (maximum) values  $V_m$ , with respect to some reference value (usually zero, as shown). Each complete alternation is called a cycle and the number of alternating cycles per second (cps) is called the *frequency*  $f$  (Hz), which is equivalent to  $1/T$ . Mathematically, the sine and cosine functions are generated by a vector rotating in the *complex-plane* with constant angular velocity  $\omega$  as will be seen in Section 2 of this appendix.



**Figure B1:** A single cycle of the sine and cosine waveforms

The maximum value  $V_m$  (also called  $V_p$ ) is called the *peak amplitude*. The parameter  $\omega = 2\pi f = 2\pi/T$  is called the ‘circular frequency’ or more commonly, the ‘radian frequency’. It is directly related to the frequency  $f$  (Hz) :  $\omega = 2\pi f \approx 6.283 f$ , radians/sec. Two other commonly used magnitude measures are the ‘*peak-to-peak*’ amplitude  $V_{pp}(= 2V_m)$  and the ‘*root-mean-square*’ (RMS) value  $V$  or  $V_{RMS}(= V_m/\sqrt{2}$  or  $0.707 V_m$ .)

The RMS value (which is also called the ‘effective value’) of a sinusoidal signal  $V_m \sin \omega t$  is calculated from the definition

$$V = V_{RMS} = \sqrt{\frac{1}{T} \int_0^T (V_m \sin \omega t)^2 dt} = \frac{V_m}{\sqrt{2}}$$

RMS values are used in the calculation of AC power.

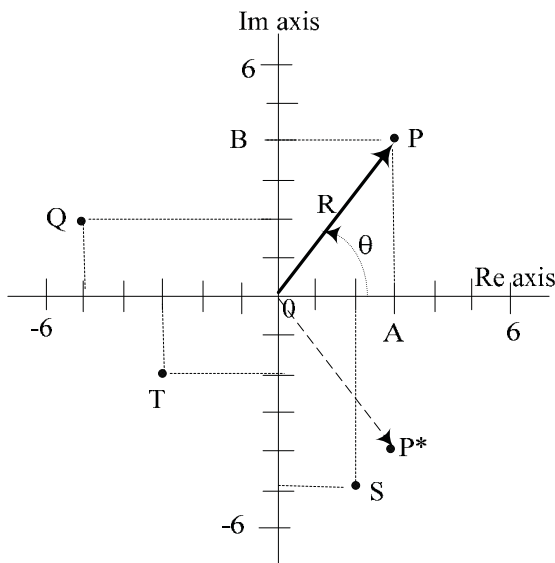
An arbitrary sinusoidal signal,  $v(t) = V_m \cos(\omega t \pm \theta)$  is completely specified by the quantities  $\omega (= 2\pi f)$ , the peak value  $V_m$  (or the corresponding RMS value) and its ‘phase-shift’  $\theta$  with respect to a reference signal. A ‘zero-phase’ cosine signal  $V_{Ref} \cos(\omega t \pm 0^\circ)$  or,

simply  $V_{\text{Ref}} \cos \omega t$  is conventionally taken as the reference, where  $V_{\text{Ref}}$  is the magnitude reference value which can be specified in either ‘peak’ or ‘RMS’ units. Thus, in an AC circuit operating at a given frequency  $f (= \omega/2\pi)$ , every signal (voltage or current) can be represented by a **phasor**, which specifies its magnitude (usually in RMS units) and its phase-angle (usually in degrees) relative to the reference. In mathematical terms, a phasor is a **complex number** which is defined by a magnitude and a relative phase.

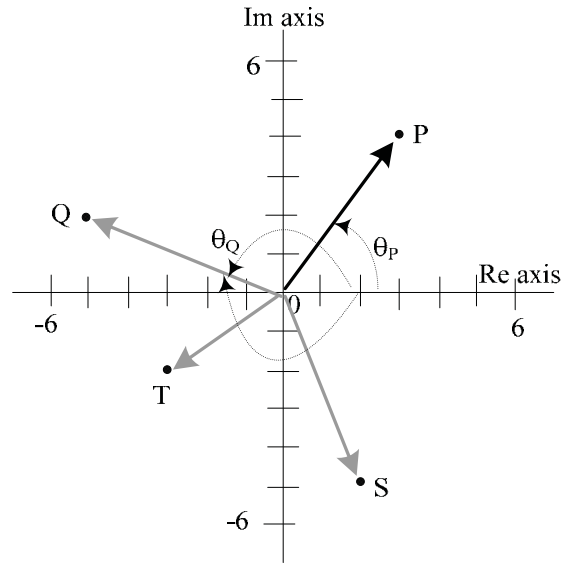
**AC circuit analysis** is performed on **phasor circuits**, in which all voltages and currents are represented by phasors and all circuit elements are replaced by their **impedances** ( $Z$ ), which are phasor-analogues of DC resistance. The impedance  $Z$  of an element is defined as the ratio of the phasor-voltage to phasor-current associated with the element. Since the latter quantities are complex numbers,  $Z$  is also a complex number. Also, since  $Z$  is defined by an equivalent of Ohm’s Law (*ie* a V-to-I ratio), all the analysis methods used for DC circuits can be applied to AC circuits as well, the only difference being that all variables are now complex quantities and all mathematical operations (such as the summations involved in KCL, KVL etc) must now follow the rules of vector algebra. Tutorials on impedance and phasor circuits are given in later sections of this appendix.

**2. Complex Numbers:** Complex numbers were introduced in mathematics to facilitate the solution of algebraic equations in which the square-root of a negative number occurs, for example,  $x^2 + 9 = 0$ . The solution  $x = \sqrt{-9}$  has no representation in the field of real numbers, but can be expressed as  $\sqrt{-1(9)} = j\sqrt{9} = \pm j3$ , where  $j = \sqrt{-1}$ . Numbers such as  $\pm j3$  are called ‘imaginary’ numbers. Complex numbers are quantities of the form  $[A + jB]$ , where  $A$  and  $B$  are real numbers.  $A$  and  $jB$  are called the ‘real’ (Re) and ‘imaginary’ (Im) parts of the complex number. Complex numbers can be plotted as points on the **complex plane**, composed of ‘Re’ and ‘Im’ axes as shown in Figure B2.

The complex numbers  $P = 3 + j4$ ,  $Q = -5 + j2$ ,  $T = -3 - j2$  and  $S = 2 - j5$  are shown plotted in Figure B2(a). The  $(A + jB)$  form used in this figure is called the ‘**rectangular**’ form of a complex number.



**Figure B2(a)**



**Figure B2(b)**

The number  $A + jB$  can alternatively be expressed using polar co-ordinates as  $R \angle \theta^\circ$  [as shown in Figure B2(b)] which is called the ‘**polar**’ form. A third form (closely related to the

polar form) is  $Re^{\pm j\theta}$  which is called the ‘complex exponential’ form. By virtue of a theorem known as Euler’s Theorem, we have the inter-relation :

$$Re^{\pm j\theta} = R \cos\theta \pm j R \sin\theta = A \pm jB.$$

The complex exponential function can also be used to express the sinusoidal functions  $\cos\theta$  and  $\sin\theta$  :  $\cos\theta = [e^{j\theta} + e^{-j\theta}] / 2$  and  $\sin\theta = [e^{j\theta} - e^{-j\theta}] / 2j$

The ‘magnitude’  $R$  of a complex number is equal to the length of the vector drawn from the origin to the point  $P$  and it is given by  $R = \sqrt{A^2 + B^2}$ . The ‘angle’  $\theta$  is measured counterclockwise (CCW) from the direction of the positive real-axis, and it is correctly given by  $\theta = \tan^{-1}(B/A)$  only for numbers in the right-half of the complex plane. For numbers in the left-half of the plane,  $180^\circ$  must be added to  $\tan^{-1}(B/A)$  to obtain the correct angle. For example, in Figure B2,  $\tan^{-1}(4/3) = \theta_P = 53.1^\circ$  is the correct angle for  $P$ , but for the number  $Q$ ,  $\tan^{-1}(2/-5) = -21.8^\circ$  is not the correct angle  $\theta_Q$ .  $180^\circ$  must be added to  $-21.8^\circ$  to give the correct value of  $158.2^\circ$ . Note that  $158.2^\circ$  is also expressible as  $-201.8^\circ$ , obtained by adding  $\pm 360^\circ$ .

It must be noted that equivalent impedances made up of the ‘passive’ elements  $R, L$  and  $C$  must necessarily have positive  $Re$  components and their impedance vectors will be located in the right-half of the complex plane. Equivalent impedances with negative real parts can result from circuits containing ‘active’ elements such as ‘operational amplifiers’.

**Complex number manipulations:** Knowledge of complex number manipulations is important in AC circuit analysis using ‘phasors’ and impedances. Many ‘scientific’ calculators are capable of performing “P to R” and “R to P” conversions in the ‘complex mode’. Some calculators are even capable of doing ‘chain calculations’ involving sequential multiplications and divisions of complex numbers, which are frequently encountered in AC circuit analysis.

Complex numbers follow all algebraic rules such as addition, subtraction, multiplication, division etc. It is useful to remember the following facts :

- (a) Multiplication/division by  $j$  : Since  $j = \sqrt{-1}$ , we have  $j^2 = -1$ ,  $j^3 = jj^2 = -j$ ,  $j^4 = j^2j^2 = +1$  etc. If a (real) number  $A$  is multiplied by  $j$ , the result is  $jA$  indicating that multiplication by  $j$  is equivalent to a CCW rotation of the vector  $A$  by  $90^\circ$ . Similarly multiplication by  $-j$  is equivalent to a CW rotation of the vector  $A$  by  $90^\circ$ . Expressed in polar form, using unit vectors, we have

$$j = 1 \angle 90^\circ, \quad j^2 = 1 \angle \pm 180^\circ, \quad j^3 = -j = 1 \angle 270^\circ = 1 \angle -90^\circ, \quad \text{etc}$$

*ie* Each multiplication by ‘ $j$ ’ is equivalent to advancing (CCW rotation) the vector by  $90^\circ$  and each division by ‘ $j$ ’ ( $1/j = -j$ ) is equivalent to retarding the vector by  $90^\circ$ . Thus a positive real number  $N$ , when successively multiplied four times by  $j$  becomes  $jN$ ,  $-N$ ,  $-jN$  and  $N$  again.

The above effect of  $\pm 90^\circ$  rotation when multiplied by  $\pm j$  is applicable to any vector in the complex plane.

- (b) Additions & Subtractions are easily done with the numbers in rectangular form, rather than in the other forms.

Eg:  $(6+j8) + (9+j3) + (-4-j15) = (6+9-4) + j(8+3-15) = 11-j4.$

(c) Multiplications & Divisions are easily done with the numbers in polar form. This result can be shown by considering the following equivalence sequences :

$$R_1 \angle \theta_1 \cdot R_2 \angle \theta_2 = R_1 e^{j\theta_1} R_2 e^{j\theta_2} = R_1 R_2 e^{j(\theta_1+\theta_2)} = R_1 R_2 \angle (\theta_1+\theta_2) \text{ and similarly}$$

$$R_1 \angle \theta_1 / R_2 \angle \theta_2 = R_1 e^{j\theta_1} / R_2 e^{j\theta_2} = (R_1 / R_2) e^{j(\theta_1-\theta_2)} = (R_1 / R_2) \angle (\theta_1 - \theta_2) .$$

Eg:  $[20 \angle 42^\circ] [7 \angle 30^\circ] / [35 \angle 24^\circ] = [(20)(7)/35] \angle (42+30-24)^\circ = 4 \angle 48^\circ$

(d) 'Normalization': A complex number in 'reciprocal' form  $1/(A+jB)$  can be converted to a non-reciprocal number  $C + jD$  by multiplying and dividing by the complex-conjugate of the denominator, ie  $\{1/(A+jB)\}[(A-jB)/(A-jB)] = (A-jB) / [A^2 + B^2]$  since  $(A+jB)(A-jB) = [A^2 + B^2]$  .

The result can be written as  $C + jD$  where  $C = A / [A^2 + B^2]$  and  $D = -B / [A^2 + B^2]$

Eg:  $1/(2-j3) = (2+j3)/(4+9) = (2/13) + j(3/13) \approx 0.154 + j 0.231$

(e) Complex conjugate operations: If  $P = A+jB = R \angle \theta^\circ$  is a complex number , then the 'mirror image' of  $P$  across the Re axis,  $P^* = A-jB = R \angle -\theta^\circ$  is called the 'complex conjugate' of  $P$ . Some useful relations involving conjugates are:

	$P+P^* = 2A$	$P-P^* = 2jB .$
and	$PP^* = R^2$	$P/P^* = \angle 2\theta^\circ$

Generation of the sinusoidal functions by a vector rotating in the complex plane:

The complex-exponential function  $Fe^{j\omega t}$  [ or  $Fe^{j\theta}$  where  $\theta = \omega t$  ] may be considered to be a vector of magnitude  $F$  rotating CCW in the complex plane with a constant angular velocity  $\omega = \theta/t$  as shown in Figure B3. The angle  $\theta$  is the angle subtended by the vector with respect to the positive real axis. The 'sinusoidal' functions  $F\cos\theta$  and  $F\sin\theta$  shown on the right-hand-side of the figure are both generated by projections of the rotating vector  $Fe^{j\omega t}$  on the Re and Im axes, respectively, of the complex plane. Note that the cosine and sine functions can be expressed either in terms of  $\theta$  or in terms of time  $t = \theta/\omega$ .

Also note that the sine function lags the cosine function by  $90^\circ$ , ie  $\sin\theta = \cos(\theta - 90^\circ)$ , or  $\sin\omega t = \cos(\omega t - 90^\circ)$ ,

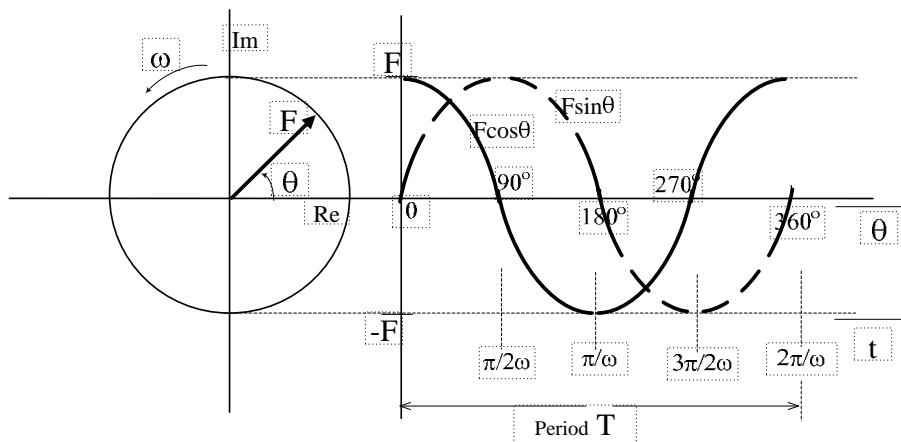


Figure B3: Sine and Cosine function generation from the complex exponential  $Fe^{j\omega t}$

In an AC circuit, all voltages and currents may be considered to be vectors such as  $Fe^{j\omega t}$  all rotating CCW together at the angular velocity  $\omega$ . If the rotation is suppressed, the various vectors form the equivalent of the phasor diagram, showing the magnitudes and phase inter-relationships between the various voltages and currents. **The phasor diagram shows the magnitudes and relative phaseshifts of the the various voltages and currents in the sinusoidal steadystate**

2. **Phasor conventions:** As indicated earlier, phasor voltages and currents are conventionally expressed in RMS units, because it is convenient for power calculations. Also, the zero-phase cosine function is taken as a phase-reference. It is also standard convention to write the phasors in capitalized letters. Some examples are given below to illustrate these conventions:

<u>Time-domain variable</u>	<u>Phasor circuit equivalent</u>
$v_1(t) = 15 \cos 3000 t$ , Volts pk	$V_1 = 10.6 \angle 0^\circ$ Volts rms
$v_2(t) = 6 \sin (3000 t + 34^\circ)$ , Volts rms	$V_2 = 6 \angle -56^\circ$ , Volts rms
$i_a(t) = 10 \cos (3000 t + 155^\circ)$ , A pk	$I_a = 7.07 \angle 155^\circ$ A rms
$i_b(t) = 8.5 \sin (3000 t - 40^\circ)$ , A pk	$I_b = 6 \angle -130^\circ$ A rms

The various corresponding phasors are shown sketched in Figure B4. Note that the radian frequency of 3000 radians/sec [ $f \approx 3000/6.283 = 477.5$  Hz] is not evident from the phasor diagram and must be specified.

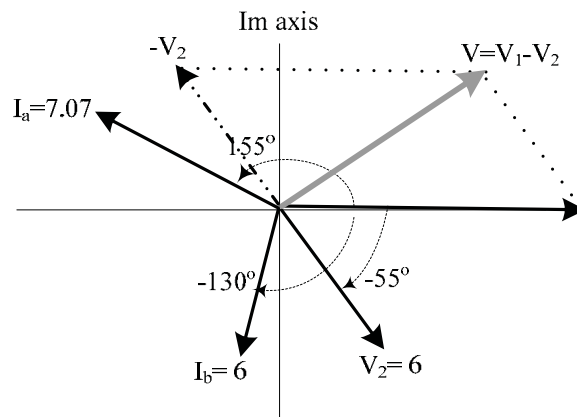


Figure B4 : A phasor diagram

Phasor voltages obey KVL and phasor currents obey KCL, but since phasors are basically vectors, the additions and/or subtractions involved must be performed vectorially. For example, the construction for voltage  $V = V_1 - V_2$  is shown in the above figure, without calculation.

**Impedance Z (& Admittance Y) :** Impedance Z is defined by the Ohm's Law equivalent in the complex domain : If the voltage and current associated with a passive element are given by the complex exponentials  $v(t) = Ve^{j(\omega t + \theta_v)}$  and  $i(t) = Ie^{j(\omega t + \theta_i)}$  then

$$Z = v(t) / i(t) = Ve^{j\theta_v} / Ie^{j\theta_i} = V \angle \theta_v / I \angle \theta_i = (V/I) \angle (\theta_v - \theta_i)$$

(note the cancellation of the common  $e^{j\omega t}$  term in the ratio, which is the equivalent of suppressing the common rotation mentioned before). From the above defining equation, it can be seen that the impedance Z of an element is the ratio of the voltage and current phasors associated with that element :  $V \angle \theta_v / I \angle \theta_i$  and  $Z = |Z| \angle \theta$ , where the magnitude  $|Z|$  is the phasor-magnitude

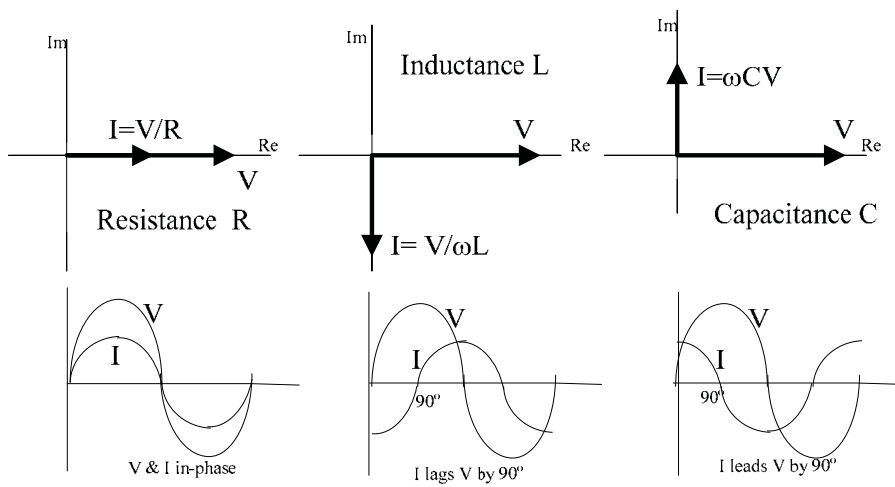


ratio  $V/I$ , and the impedance angle  $\theta = (\theta_v - \theta_i)$ , is the angle by which the voltage-phasor  $V$  leads the current-phasor  $I$ . The unit of  $Z$  is the Ohm and the symbol used for  $Z$  is the same as that used for  $R$ . The reciprocal of impedance  $1/Z$  is called the Admittance  $Y$ , and it is the phasor analogue of Conductance just as  $Z$  is the phasor analogue of Resistance.

We shall now consider the impedance of the three basic passive elements  $R$ ,  $L$  and  $C$ . Application of the complex exponential form to their respective current-voltage relations, namely,  $v(t) = Ri(t)$ ,  $v(t) = L di(t)/dt$  and  $i(t) = Cdv(t)/dt$ , leads to expressions for the corresponding impedances of these elements, respectively given by

$$Z_R = R \qquad Z_L = j\omega L = jX_L \qquad Z_C = 1/j\omega C = -j/\omega C = jX_C$$

It is seen that while  $Z_R$  is a real number,  $Z_L$  and  $Z_C$  are both frequency-dependent imaginary numbers, which are composed of reactances  $X_L$  and  $X_C$ . The impedances  $Z_L = j\omega L$  and  $Z_C = 1/j\omega C$  are also expressible in their polar forms as  $\omega L \angle 90^\circ$  and  $(1/\omega C) \angle -90^\circ$  respectively. The phasor diagrams corresponding to the three basic elements are shown in the top half of Figure B5 and the corresponding waveforms are shown in the bottom half of the figure.



**Figure B5 :** Phasor diagrams (& waveform) for  $R$ ,  $L$  and  $C$  elements.

It can be seen that the voltage and current phasors are ‘in-phase’ with each other for the  $R$  element, whereas for  $L$ ,  $I$  lags  $V$  by  $90^\circ$  and for the  $C$  element,  $I$  leads  $V$  by  $90^\circ$ .

Since impedances are complex quantities, they can be also shown in ‘impedance diagrams’ which are similar to phasor diagrams, but which illustrate the vector-relations between various impedances. [see Example 1 later]

### **Phasor Circuits & Impedance Calculations:**

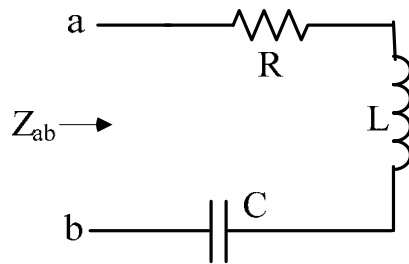
Impedance calculations follow the same rules used for resistive networks, except that all quantities are now complex numbers. Impedance, in general, is expressed as  $Z = R + jX$ , where  $R$  and  $X$  are its resistive- and reactive-parts, respectively. Reactance can be either inductive  $X_L = \omega L$  or capacitive  $X_C = -1/\omega C$ . Since the impedance angle  $\theta = (\theta_v - \theta_i)$  is the angle by which the voltage leads the current, a value of  $\theta$  between  $0^\circ$  and  $+90^\circ$  indicates an inductive impedance whereas a value between  $0^\circ$  and  $-90^\circ$  indicates a capacitive impedance.

Because of the possibility of positive and negative elemental reactances, a combination of  $L$  and  $C$  elements may result in an inductive, capacitive or even a zero reactance at a given frequency. A ‘resonance’ condition is said to occur when the reactive part of an impedance

becomes zero [ie  $\text{Im } Z = 0$ ] due to reactance cancellation and the associated frequency is called a 'resonant frequency'.

Some examples of impedance and phasor circuit calculations are given below .

Example 1: Consider the series combination of a resistance  $R=3000\Omega$ , an inductance  $L= 210 \text{ mH}$  and a capacitance  $C = 47\text{nF}$  shown below.



- Find the equivalent impedance  $Z_{ab}$  of the series combination at the frequencies 600 Hz and 4 kHz.,
- Determine the frequency  $f_o$  at which  $Z_{ab}$  is purely resistive, ie the resonant frequency  $f_o$ .
- Sketch the 'impedance diagram' at 600 Hz.

Solution: The equivalent impedance given by  $Z_{ab} = R + j\omega L + 1/j\omega C = R + j[\omega L - 1/\omega C]$ .

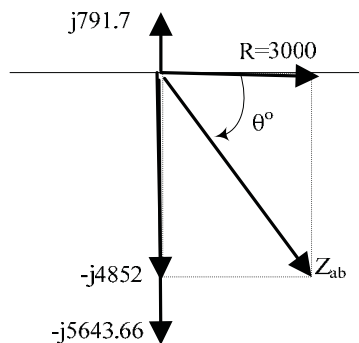
(a) At  $f = 600 \text{ Hz}$  ( $\omega \approx 3770 \text{ rad/s}$ ),  $Z_{ab} = 3000 + j(791.7 - 5643.66) \approx (3000 - j4852) \Omega = 5704.6 \angle -58.3^\circ \Omega$ , which is a 'capacitive' impedance .

At 4 kHz ( $\omega \approx 25132 \text{ rad/s}$ ) the impedance is  $Z_{ab} = 3000 + j(5277.72 - 846.59) \approx (3000 + j4431.13) \Omega = 5351.16 \angle 55.9^\circ \Omega$ , which is an 'inductive' impedance.

(b) The impedance  $Z_{ab} = R$  at the frequency  $\omega_o$  which results in  $\text{Im } Z_{ab} = [\omega L - 1/\omega C] = 0$

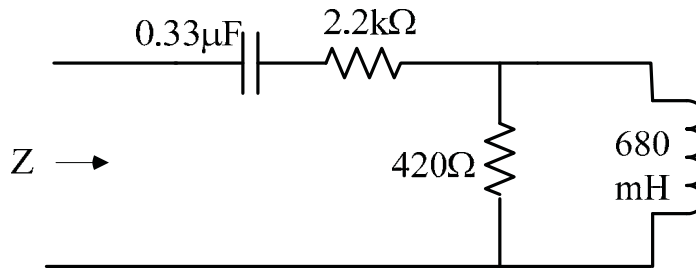
ie  $\omega_o = \sqrt{\frac{1}{LC}} = 10065.6 \text{ rad/s}$  or  $f_o \approx 10065.6/6.283 \approx \underline{1602 \text{ Hz}}$  .

(c) Since  $Z_{ab} = R + j\omega L + 1/j\omega C = 3000 + j791.7 - j5643.66$ , the three components can be successively drawn as vectors and the addition performed geometrically. Alternatively, the two components of the simplified result ,  $3000 - j4852$  , may be plotted as shown below :

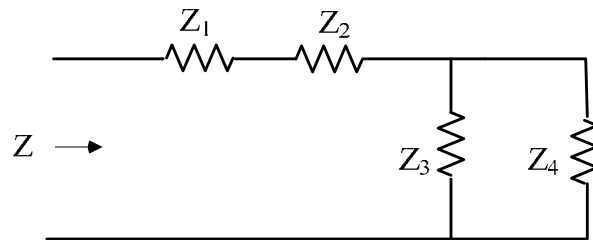


If plotted to scale, the result  $Z \angle \theta = 5704.6 \angle -58.3^\circ$  can be obtained geometrically from the impedance diagram

Example2 : For the circuit shown , find the impedance  $Z$  at a frequency  $f = 440$  Hz.



Solution: The circuit can be re-drawn with the equivalent impedances  $Z_1, Z_2, Z_3, Z_4$  whose values are calculated using  $\omega = 2\pi f \approx (6.283)(440) = 2764.52$  rad/s



where  $Z_1 = 1/j\omega (0.33\mu\text{F}) = -j 1096.14$  ohms

$Z_2 = 2200$  ohms

$Z_3 = 420$  ohms

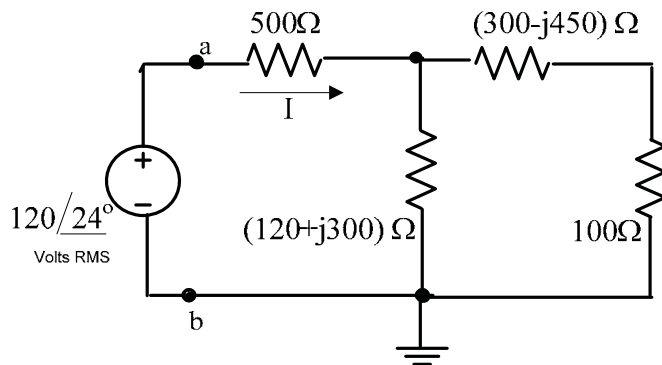
and  $Z_4 = j\omega (0.68) = j 1879.87$  ohms

$Z = Z_1 \text{ S } Z_2 \text{ S } [Z_3 \text{ P } Z_4]$  ,where S = Series, P = Parallel

$$\begin{aligned} Z &= Z_1 + Z_2 + Z_3 Z_4 / (Z_3 + Z_4) = -j 1096.14 + 2200 + (420) (j 1879.87) / [420 + j1879.87] \\ &= -j 1096.14 + 2200 + j 789545.4 / [420 + j1879.87] \\ &= -j 1096.14 + 2200 + 789545.4 \angle 90^\circ / 1926.22 \angle 77.4^\circ \\ &= -j 1096.14 + 2200 + 40.99 \angle 12.6^\circ \\ &= -j 1096.14 + 2200 + 40 + j 8.94 \\ &= \underline{2240 - j1087.2} \text{ ohms} \approx \underline{2489.9} \angle -26^\circ \text{ ohms} \end{aligned}$$

The impedance  $Z$  is capacitive since its angle is negative (ie V lags I or I leads V).  
 {The entire network is equivalent to a resistance of  $2240 \Omega$  in series with an ‘effective’ Capacitance  $C = 1/\omega(1087.2) = 1/3005586.144 = \underline{0.3327} \mu\text{F}$ .}

Example3 : For the phasor circuit shown , determine the impedance  $Z_{ab}$  ‘seen’ by the source and hence find the phasor current I



Solution: The two rightmost impedances are in series , giving an equivalent of  
 $300 - j450 + 100 = 400 - j450$

$$Z_{ab} = 500 \text{ S } [(120 + j 300) \text{ P } (400 - j450)]$$

$$Z_{ab} = 500 + (120 + j 300) (400 - j450) / [120+j300+400-j450]$$

$$= 500 + (120 + j 300) (400 - j450) / (520 - j150)$$

[There are two ways of proceeding with the second term above :

- (1) straight multiplication, term by term, and then normalization, or
- (2) converting the numerator & denominator terms to polar form, then reducing and reversion to rectangular form. The second procedure is used below.]

$$Z_{ab} = 500 + (323.1 \angle 68.2^\circ) (602.1 \angle -48.4^\circ) / (541.2 \angle -16.1^\circ)$$

$$Z_{ab} = 500 + [(323.1)(602.1)/541.2] \angle (68.2^\circ - 48.4^\circ + 16.1^\circ)$$

$$Z_{ab} = 500 + 359.5 \angle 35.9^\circ = 500 + 291.2 + j 210.8$$

$$= \underline{791.2 + j210.8} \text{ Ohms} = \underline{818.8 \angle 14.9^\circ} \text{ Ohms}$$

The impedance  $Z_{ab}$  is inductive since its angle is positive (ie V leads I or I lags V).

The phasor current  $I = 120 \angle 24^\circ / Z_{ab} = 120 \angle 24^\circ / 818.8 \angle 14.9^\circ = \underline{14.7 \angle 9.1^\circ} \text{ mA}$

=====

### Single-phase Power Terms & Definitions :

(a) **The instantaneous power**  $p(t)$  in any element having a terminal voltage and current given by  $v(t) = V_m \cos(\omega t + \theta_v)$  and  $i(t) = I_m \cos(\omega t + \theta_I)$  respectively, is given by their product:

$$p(t) = v(t) i(t) = V_m I_m \cos(\omega t + \theta_v) \cos(\omega t + \theta_I)$$

The angle  $\theta = (\theta_v - \theta_I)$ , by which  $v(t)$  leads  $i(t)$  is actually the impedance angle of the impedance  $Z$  defining the element. For convenience, we will assume  $i(t)$  as a reference and set  $\theta_I = 0$ , so that  $\theta = \theta_v$  and

$$\begin{aligned} p(t) &= v(t) i(t) = V_m I_m \cos(\omega t + \theta) \cos \omega t \\ &= V_m I_m [(1/2) \cos \theta + (1/2) \cos (2\omega t + \theta)] \\ &= VI \cos \theta + VI \cos (2\omega t + \theta) \end{aligned}$$

where  $V$  and  $I$  are RMS values. Note that  $p(t)$  contains an average component  $P = VI \cos \theta$  and a sinusoidal component whose frequency is twice the base frequency  $\omega$ .

(b) **Average power** (also called Real power), **Power Factor & Apparent power** : The average power  $P$  is the non-sinusoidal, average component in the above expression for  $p(t)$ ,

$$P = VI \cos \theta .$$

The term  $\cos \theta$  is called the **Power Factor** (pf or PF) and the product  $VI$  is called the **Apparent Power**  $P_{app}$  (or RMS Power).  $P$  represents actual energy consumption such as in heating or in doing mechanical work,  $P$  (and  $P_{app}$ ) is expressed in Watts. Since  $\theta = 0^\circ$  for purely resistive impedances, the PF for such impedance loads is unity. For inductive impedances,  $0^\circ < \theta < 90^\circ$  and the  $0 < PF < 1$ . Since the  $\cos$  function is symmetrical about zero, capacitive impedance, for which  $0^\circ < \theta < -90^\circ$  yield the same PF range. Therefore, for non-resistive loads the PF must be stated as either a 'lagging PF' or a 'leading PF' for inductive and capacitive loads respectively.

(c) **Reactive power**: Using trigonometric relations, the last equation for  $p(t)$  above can be rewritten as:

$$p(t) = P + VI \cos \theta \cos 2\omega t - VI \sin \theta \sin 2\omega t$$

or 
$$p(t) = P (1 + \cos 2\omega t) - Q \sin 2\omega t$$

The term  $Q = VI \sin \theta$  is called the Reactive Power.  $Q$  represents purely electrical energy interchanges in the reactive elements of  $Z$ .  $Q$  is expressed in units of 'Volt-Amperes-Reactive' or VARs ('var's).

Alternative equations for P & Q: Rather than using the original equations for these quantities, it is often more convenient to use the current through the element and the elemental values: It can be shown that  $P$  and  $Q$  are respectively given by

$$P = I^2 \operatorname{Re} Z \quad \text{and} \quad Q = I^2 \operatorname{Im} Z ,$$

where  $I$  is the RMS magnitude of the current in  $Z$  and  $\operatorname{Re}$  and  $\operatorname{Im}$  refer to the real and imaginary parts of  $Z$ .

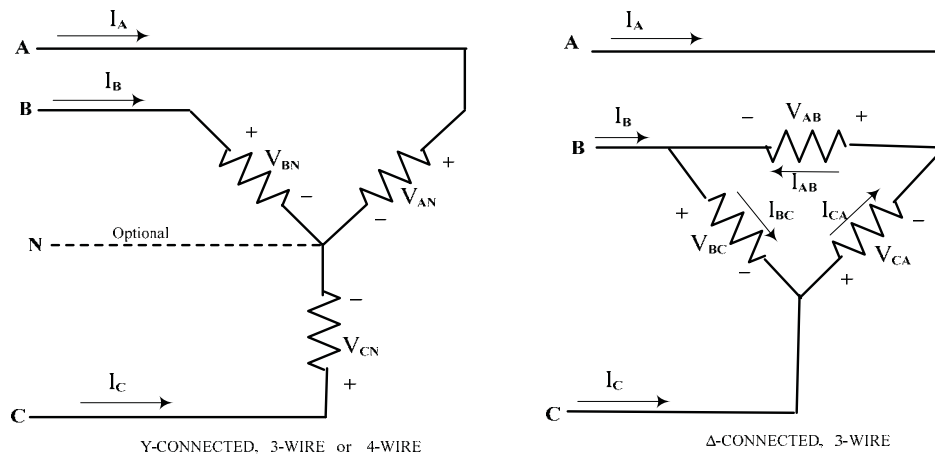
(d) **Complex Power**  $S$  is defined as  $S = P + jQ$ , Watts. Complex power is also calculated from the voltage phasor  $V = V \angle \theta_v$  and the conjugate of the current phasor  $I^* = I \angle -\theta_I$  :

ie 
$$S = VI^* \quad \text{Watts}$$

The conjugate of  $I$  is required in order to obtain the proper angle  $\theta = \theta_v - \theta_I$ . Complex power calculated in this manner directly yields  $P$  and  $Q$  as well, since  $S = P + jQ$ .

**(e) Three-phase Power :**

Residential power circuits are basically two-conductor (or ‘two wire’) systems, known as ‘single-phase circuits’, which consist of a ‘live’ conductor and a ‘neutral’ conductor. Single-phase power (at 120 volts, 60 Hz) is delivered to customers through ‘distribution stations’, which receive the power from the generating stations over great distances. Transformers play an important role in power transmission because of their ability to ‘convey’ power at relatively ‘low’ currents which will minimize resistance losses in the long transmission lines. However, power transmission between the generating station and the industrial/residential users is mostly handled using “three-phase” systems ( 3-Ø systems), which have both economical and technical advantages. In 3-Ø systems power is carried by three ‘live’ conductors, and a fourth ‘neutral’ conductor (which may be absent in some cases). Three-phase power is standard in industrial systems, where devices such as the 3-Ø induction motors are extensively used. Domestic single-phase power circuits are derived from three-phase distribution circuits. In a “balanced 3 phase system”, the voltages present on the three ‘live’ wires (phases) are equal in magnitude but are displaced sequentially by 120° phase angles. The three phases are labelled as A, B and C , with N for the Neutral. An alternative convention is to label these phases as R, Y and B (standing for Red, Yellow & Blue), and G (for Green or ‘ground’). Conventionally, the ‘ABC’ (or ‘RYB’) designation also denotes the sequence in which the respective voltages or currents occur. In the ABC-sequence, also called a “positive sequence”, A leads B which leads C [or C lags B which lags A]. This sequence is the ‘standard’ in North America. Balanced Y-connected, 4-wire systems are commonly used because they can be treated as three identical systems, whose current–voltage values differ only by a phase of 120°. Three-phase generators (sources) are always assumed to be perfectly balanced, whereas three-phase loads can become unbalanced. Three-phase loads consist of three impedances which are either Y-connected [called a “3-Ø, 4-wire system or a “3-Ø, 3-wire” system] or Δ-connected [“3-Ø , 3-wire system”,only], as illustrated in Figure B6. The system is called a ‘balanced’ system when the three impedances are identical to one another and the three applied line-to-line voltages have voltage and phase symmetry. Only balanced 3-Ø ,Y-connected systems are considered in this experiment. However, the student should become familiar with the current-voltage relations in both types of connection.



**Figure B6:** The basic three-phase load configurations Y and Δ.

In Figure B6, the terminals of the three phases are labeled, as explained earlier, as A, B and C , with N for the Neutral. The RYB colour-coding is used in the lab equipment.

Voltage & Current Definitions : The following definitions are applicable to both Y- and  $\Delta$ -connected loads (as indicated) :

Line-to-Line Voltages  $V_{LL}$  ,or simply, Line Voltages  $V_L$  : are voltages between each line-pair,  
eg:  $V_{AB} = V_{AN} - V_{BN}$  in the Y-connection

Phase Voltages  $V_P$  or  $V_{ph}$  : are voltages across each of the 3 impedance elements involved:

eg:  $V_{ph} = V_{AB}$  in the  $\Delta$ -connection  
 or  $V_{ph} = V_{AN}$  in the Y-connection

Line-to-Neutral Voltages : Voltages between each line and the neutral in 4-wire, Y-connected systems, eg:  $V_{AN}, V_{BN}$  or  $V_{CN}$ . This is also the ‘phase voltage’ in a Y-connected 3-wire system although there is no neutral line.

Line Currents : Currents in each of the 3 lines ,eg:  $I_A$  in either connection  
 or  $I_A = I_{AB} - I_{CA}$  in the  $\Delta$ -connection

Phase Currents : Currents in each of the 3 elements involved; also written as  $I_P$  or  $I$

eg:  $I_A$  in the Y-connection or  $I_{AB}$  in the  $\Delta$ -connection.

In the Y-connection, the phase current is identical with the line current whereas in the  $\Delta$ -connection, the phase voltage is identical with the line-to-line voltage. Further, in the Y-connection, each line-to-line voltage is the vector sum of two phase voltages, whereas in the  $\Delta$ -connection, each line current is the vector sum of two phase currents. These phasor relations between the voltages in a balanced Y-connected 4-wire system and the phasor relations between the currents in a balanced  $\Delta$ -connected system are graphically shown in Figures B7(a) and B7(b), respectively.

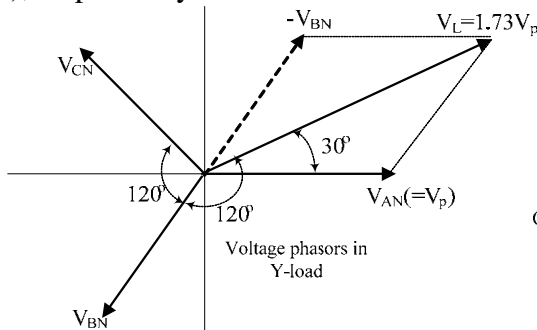


Figure B7(a) : Voltage relations in a Y-connected load

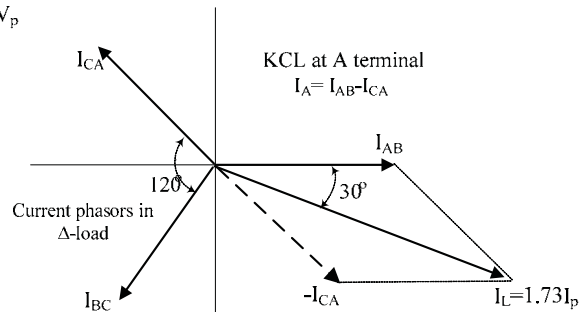


Figure B7(b): Current relations in a  $\Delta$ -connected load

It can be seen from the above figures that in a Y-connected system, the line voltage (ie line-to-line voltage) is  $\sqrt{3}$  times the phase-voltage and that in a  $\Delta$ -connected system, the line current is  $\sqrt{3}$  times the phase current. Also, though not shown in the above figures, the line-to-line voltages in a balanced Y-connected system are symmetrically separated by phase shifts of  $120^\circ$ , as are the line currents in the  $\Delta$ -connected system. These relations allow the ‘equivalences’ to be derived between Y-connected and  $\Delta$ -connected loads : An impedance in the balanced  $\Delta$ -connected load  $Z_\Delta = V_{AB}/I_{AB} = \sqrt{3} V_{AN} (I_A / \sqrt{3}) = 3 Z_Y$ . Thus, for example, three  $100\Omega$  resistances connected as a Y load may be replaced by a balanced  $300\Omega$   $\Delta$ -load..

Note also, that in a balanced Y-connected 4-wire system , application of Kirchoff's current law at the neutral node N will show that the current in the neutral wire is zero because the vector sum of any two adjacent current phasors will be equal and opposite to the third current phasor. Hence, in a perfectly balanced 4-wire system, the neutral wire need not be used.

The power in a balanced 3- $\emptyset$  system is the sum of the powers in the three constituent phases. Thus, we obtain, for the instantaneous power :

$$\begin{aligned} p(t) = & V_{ph}I_{ph} \cos \theta + V_{ph}I_{ph} \cos (2 \omega t + \theta) \\ & + V_{ph}I_{ph} \cos \theta + V_{ph}I_{ph} \cos (2 \omega t + \theta + 120^\circ) \\ & + V_{ph}I_{ph} \cos \theta + V_{ph}I_{ph} \cos (2 \omega t + \theta + 240^\circ) \end{aligned}$$

where  $V_{ph}$  and  $I_{ph}$  are the RMS values of the phase voltage and phase current respectively.

Upon simplification, the above equation yields  $p(t) = 3 V_{ph}I_{ph} \cos \theta$ , which is independent of  $\omega$ , ie In a balanced 3- $\emptyset$  system, the pulsating component of  $p(t)$  *which is present in single phase systems*, is absent, thereby eliminating vibration-associated (the vibration is caused by magnetostrictive effects)mechanical problems. This delivery of ‘smooth’ power’is a major advantage of using 3- $\emptyset$  systems.

It is useful to derive an expression for the total power in a 3- $\emptyset$  system using the ‘field-measurable’quantities which are the line voltage  $V_L$  and the line current  $I_L$ . It can be shown that for both types of connection,  $P = \sqrt{3} V_L I_L \cos \theta$  and  $Q = \sqrt{3} V_L I_L \sin \theta$  where  $\theta$  is the angle of the phase impedance.

[For a Y-connected load, we have  $I_{ph} = I_L$  and  $V_L = \sqrt{3} V_{ph}$ ; hence

$$P = 3 V_{ph} I_{ph} \cos \theta = 3 (V_L/\sqrt{3}) I_L \cos \theta = \sqrt{3} V_L I_L \cos \theta .$$

For a  $\Delta$ -connected load,  $V_{ph} = V_L$  and  $I_L = \sqrt{3} I_{ph}$ ; hence

$$P = 3 V_{ph} I_{ph} \cos \theta = 3 V_L (I_L/\sqrt{3}) \cos \theta = \sqrt{3} V_L I_L \cos \theta \text{ once again.}$$

The reactive power, for both Y and  $\Delta$  connections, can be similarly shown to be given by

$$Q = 3 V_{ph} I_{ph} \sin \theta = \sqrt{3} V_L I_L \sin \theta ]$$

The complex power  $S = P + jQ$  and its magnitude is given by  $|S| = \sqrt{P^2 + Q^2} = \sqrt{3} V_L I_L .$



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## APPENDIX -C

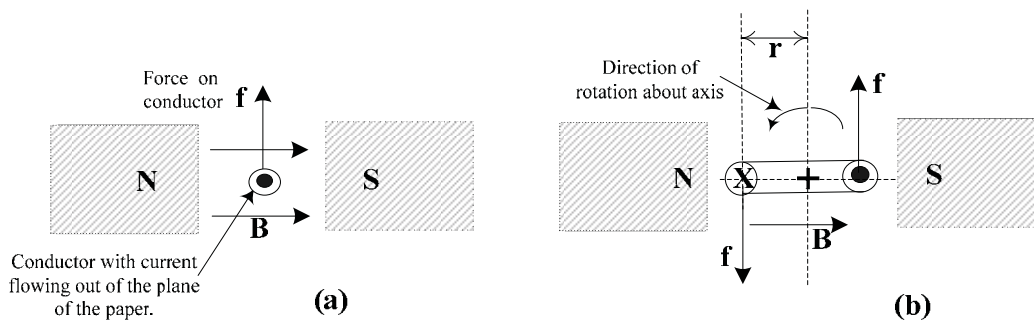
### BRIEF NOTES ON DC MOTORS

#### Electromechanical (EM) Energy Conversion

The electromechanical energy conversion occurring in electrical motors is based on interactions between electrical currents and magnetic fields and also on electrical/ mechanical energy balance. A fundamental law, stated as the ‘**Lorentz force-equation**’, gives the force  $\mathbf{f}$  on a charge  $q$  moving with a velocity  $\mathbf{v}$  in a space containing an electric field of intensity  $\mathbf{E}$  and a magnetic field of flux-density  $\mathbf{B}$  as

$$\mathbf{f} = q\mathbf{E} + q(\mathbf{v} \times \mathbf{B})$$

where the quantities in bold are vectors. The second term in this equation is the force utilized in conventional motor action., and the charges involved are those corresponding to currents flowing in a conductor (or conductors). The vector cross-product  $\mathbf{v} \times \mathbf{B}$  is defined as a vector of magnitude  $vB \sin\theta$  (where  $v, B$  are scalars and  $\theta$  is the angle between the two vectors) and a direction which is perpendicular to both  $\mathbf{v}$  and  $\mathbf{B}$ . The direction of this product vector is given by the ‘right-handed screw rule’: it is the direction in which a right-handed-screw will progress as it is tightened, in the sense of vector  $\mathbf{v}$  being rotated towards vector  $\mathbf{B}$ . For an elementary conductor of length  $\ell$  carrying a current  $i$  located at an angle  $\theta^\circ$  with respect to a magnetic field of flux density  $B$ , the above force can be expressed by the scalar equation  $f = B \ell i \sin\theta$ , its direction being given by the above ‘right-handed screw rule’. In particular, if the conductor is moving at right-angles to the magnetic flux, then  $\theta = 90^\circ$  and the force magnitude on the conductor can be written as  $f = B \ell i \sin 90^\circ = B \ell i$ . This expression, commonly called the “ $Bli$ ” law, gives the force  $f$  is Newtons, if  $B$  is in Teslas ( $1 \text{ Tesla} = 1 \text{ Weber/m}^2$ ),  $\ell$  is in metres and  $i$  is in Amperes. The direction of  $f$ , given by the ‘right-handed screw rule’, is popularly expressed as “Fleming’s Left Hand Rule” (also called the “Left-hand Motor Rule”): With the fore-finger, middle-finger and thumb of the left hand extended perpendicular to one another, if the fore-finger points to the direction of flux  $\phi$  and the middle-finger to the current direction, then the extended thumb gives the direction of the resulting force on the current-carrying conductor. The direction of motion is graphically shown in Figure C1, in (a) for a single conductor moving in the direction perpendicular to the magnetic field  $B$ , and in (b) for a pair of conductors formed into a one-turn coil, pivoted for rotary motion (CCW in the figure)..



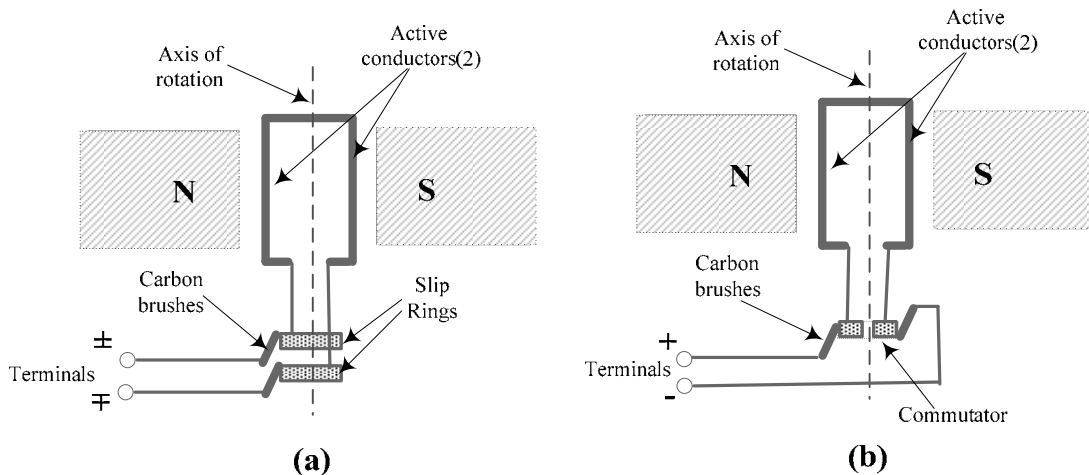
**Figure C1:** Sketches illustrating Fleming’s Left-hand (motor) Rule.

In (a), the force on the conductor is  $f = B \ell i$ . In (b), a mechanical ‘couple’ is created by the forces acting on the two lengths of conductor which run perpendicular to  $B$  and the maximum torque  $T$  on the coil, occurring at the pole-centerline as shown, is  $T = 2 f r = 2B \ell I r$ , N-m.

The rotation caused by  $T$ , however, gives rise to another phenomenon : whenever a conductor moves such that it intersects with the lines of force of a magnetic field, a voltage is induced in it .This voltage, given **Faraday's law of Induction**, is  $E = d\phi/dt$ , where the rate of change of flux ( $d\phi/dt$ ) is produced by the physical motion. The polarity of the induced voltage is always such that it tends to reduce the current that caused the motion of the conductor. In other words, the induced voltage acts in opposition to the applied voltage. For this reason, the induced voltage is called the “back emf”  $E$  . For an elementary conductor of length  $\ell$  moving with a velocity  $u$ , perpendicular to the field [ as in (a) of Figure C1] it can be shown that  $E = d\phi/dt = B \ell u$ , which is commonly called the “Blu” law . For the case of the rotating coil in (b) of Figure C1,  $E = 2 B \ell u = 2 B \ell r \omega$ , where  $\omega$  is the angular velocity of rotation.

In general, any conductor moving in a magnetic field due to an applied current will be simultaneously subject to both the ‘Bli’ and the ‘Blu’ laws . The distinction between motor action and generator action is determined only by the net power flow direction. To produce motor action, for example, the applied voltage  $V_i$  must exceed the developed ‘back emf’  $E = B \ell u$  (i.e.  $V_i > B \ell u$  ). From a viewpoint of power, the electrical power input must be equal to the sum of the useful mechanical output, electrical (ohmic) losses as well as mechanical losses such as friction in bearings and aerodynamics (‘windage’).

Consider the coil configuration of Figure C2(b). An electrical input or output to the coil will require ‘rotating electrical contacts’ known as “slip rings” as shown in Figure C2(a). Further, if DC is supplied to the coil terminals, a unidirectional torque (CW or CCW) will result only for one-half of the rotation. When the coil position changes by  $180^\circ$ , the relative orientations of current and field will be such as to produce a torque in the opposite direction. Unidirectional rotation will require an AC input voltage, with the polarity changing at every  $180^\circ$  change in



**Figure C2 : Basic 2-pole motor/generator**

coil orientation. Conversely, unidirectional rotation of the coil in Figure C2(a) will produce an AC output voltage. In order to achieve DC operation (either as a motor or generator), the two slip rings are replaced by a single ‘split slip ring’, called a commutator. The commutator effectively ensures that the relative orientations of current and field in the conductors are such as to produce unidirectional torque. In practical motors, the armature is made up of a large number of coils connected to a multi-segmented commutator such that a ‘smooth’ torque is produced. In conventional DC motors the magnetic field is provided by field coils located in the stator. The armature coils are located in the rotor and are connected to the commutator. The input voltage is applied to the brushes which make contact with the commutator. The general

circuit of a so-called “separately excited” DC motor is shown in Figure C3. The voltage source in the armature circuit represents the motional emf or ‘back emf’  $E_b$ , which is always present during rotation. The commutator is not shown explicitly, but the two rectangular ‘block’ terminals added to the  $E_b$  source can be taken to represent the brushes of the commutator. The mechanical aspect of the motor, namely the torque developed  $T$  and the shaft speed  $\omega$ , are shown by thick dotted line axis as in the figure).

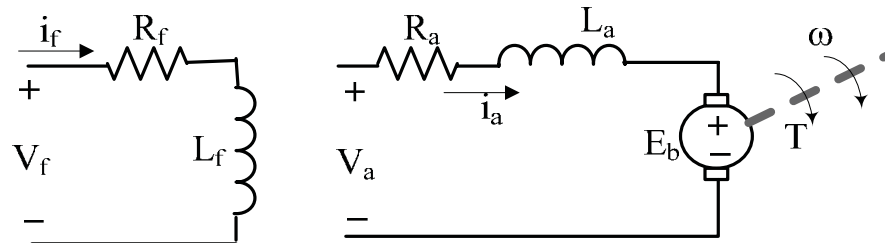


Figure C3

The voltages across the armature and field terminals are, respectively,  $V_a$  and  $V_f$ . The armature and field windings have resistance and inductance, both of which are important in the analysis of the time-response of the motor. Under DC steady state (DCSS) conditions, however, the inductances behave like short-circuits and need not be included in a motor circuit model. The equivalent DCSS circuit is shown in Figure C4, in which  $E_b$  is shown using the conventional voltage source symbol and the mechanical output is not shown explicitly.

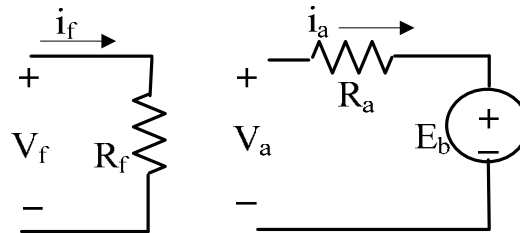


Figure C4

The motor can be controlled through the armature circuit or through the field circuit. Also, these two circuits may be interconnected in different ways, leading to various defined configurations such as ‘Shunt’, ‘Series’ and ‘Compound’ motor types, each yielding different output characteristics. A fourth type in which the field is provided by a permanent magnet is called a **permanent-magnet DC motor** (PMDC motor). The equivalent circuit of the PMDC motor only consists of the armature circuit of Figure C4, the field being provided by the permanent magnet.

Equations applicable to a PMDC motor will now be given since it is the type of motor used in Experiment #5

In the PMDC motor, the field  $\phi$  is provided by permanent magnets. PMDC motors became popular after the development of high strength ceramic magnets. With the field constant, the torque  $T$  and back-emf  $E_b$  are respectively given by :

$$T = K_T I_a \quad \text{and} \quad E_b = K_b \omega$$

where the torque-constant  $K_T$  and the back emf-constant  $K_b$  can be shown to have the same numerical value when calculated in basic units.\*

[\*The mechanical power developed is  $P_m = T\omega = K_T I_a \omega$  and the electrical power that is involved in EM conversion is  $P_e = E_b I_a = K_b \omega I_a$ . Equating  $P_m = P_e$ , yields  $K_T = K_b$  ]

From the armature circuit, assuming  $K_T = K_b = K$ , KVL yields

$$V_t = i_a R_a + K\omega$$

$$= (T/K) R_a + K\omega$$

from which

$$T = \frac{KV_t}{R_a} - \frac{K^2\omega}{R_a} \quad \text{which is of the form } T = k_1 - k_2\omega$$

where  $k_1$  and  $k_2$  are constants,

and

$$\omega = \frac{V_t}{K} - \frac{TR_a}{K^2}$$

The  $T$  versus  $\omega$  curve is shown in Figure C5

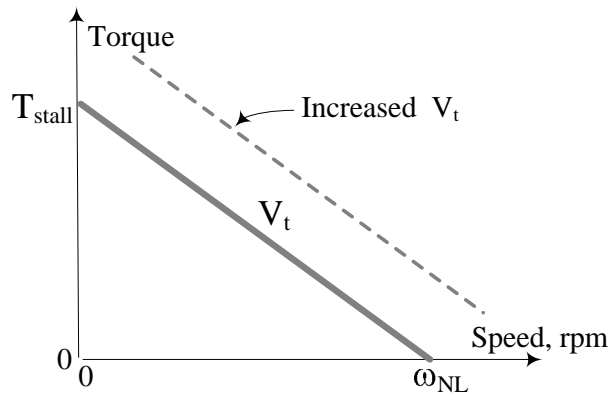


Figure C5

The stall torque is given by setting  $\omega = 0$ ,

$$T_{\text{stall}} = KV_t/R_a$$

and

the no-load speed is given by setting  $T = 0$ ,

$$\omega_{\text{NL}} = V_t/K.$$

DC motors are made in a very wide variety of physical configurations and sizes. Their wide use is mainly due to the ease with which they can be controlled. Their main disadvantage is the maintenance required due to the presence of the commutator and brushes, which wear out in time. Also, the possible presence of sparking at the brushes can be a potential hazard in explosive environments. PMDC motors with extremely lightweight armatures ('moving coil motors') are found in many instruments where fast time response is a primary requirement. They are also extensively used in robotic mechanisms.

Efficiency of a DC motor: The power efficiency is given by

$$\eta = 100 [P_{out}/P_{in}] \%$$

where

$$\text{Power output } P_{out} = T\omega \quad , \text{ N-m/sec}$$

and

$$\text{Power input } P_{in} = V_{in}I_{in} \quad , \text{ Watts}$$

In large motor test setups, the output torque T and speed  $\omega$  are measured using a torque-meter and a tachometer respectively.

Speed Regulation of motors: ‘Feedback control systems’ are generally used with motors, in order to precisely control or regulate their output. The ‘loading’ capacity of motors in speed control applications is usually specified by a figure of merit called the ‘speed regulation’ S , which is expressed as :

$$S = 100 [ (\omega_{no \text{ load}} - \omega_{full \text{ load}}) / \omega_{full \text{ load}} ] \%$$

where  $\omega$  is the angular velocity expressed in any consistent set of units (ie in radians/sec or in RPM) .

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## APPENDIX -D

### Faculty of Engineering and Computer Science Expectations of Originality

This form sets out the requirements for originality for work submitted by students in the Faculty of Engineering and Computer Science. Submissions such as assignments, lab reports, project reports, computer programs and take-home exams must conform to the requirements stated on this form and to the Academic Code of Conduct. The course outline may stipulate additional requirements for the course.

1. Your submissions must be your own original work. Group submissions must be the original work of the students in the group.
2. Direct quotations must not exceed 5% of the content of a report, must be enclosed in quotation marks, and must be attributed to the source by a numerical reference citation<sup>1</sup>. Note that engineering reports rarely contain direct quotations.
3. Material paraphrased or taken from a source must be attributed to the source by a numerical reference citation.
4. Text that is inserted from a web site must be enclosed in quotation marks and attributed to the web site by numerical reference citation.
5. Drawings, diagrams, photos, maps or other visual material taken from a source must be attributed to that source by a numerical reference citation.
6. No part of any assignment, lab report or project report submitted for this course can be submitted for any other course.
7. In preparing your submissions, the work of other past or present students cannot be consulted, used, copied, paraphrased or relied upon in any manner whatsoever.
8. Your submissions must consist entirely of your own or your group's ideas, observations, calculations, information and conclusions, except for statements attributed to sources by numerical citation.
9. Your submissions cannot be edited or revised by any other student.
10. For lab reports, the data must be obtained from your own or your lab group's experimental work.
11. For software, the code must be composed by you or by the group submitting the work, except for code that is attributed to its sources by numerical reference.

You must write one of the following statements on each piece of work that you submit:

For individual work: **“I certify that this submission is my original work and meets the Faculty's Expectations of Originality”**, with your signature, I.D. #, and the date.

For group work: **“We certify that this submission is the original work of members of the group and meets the Faculty's Expectations of Originality”**, with the signatures and I.D. #s of all the team members and the date.

A signed copy of this form must be submitted to the instructor at the beginning of the semester in each course.

I certify that I have read the requirements set out on this form, and that I am aware of these requirements. I certify that all the work I will submit for this course will comply with these requirements and with additional requirements stated in the course outline.

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<sup>1</sup> Rules for reference citation can be found in “Form and Style” by Patrich MacDonagh and Jack Bordan, fourth edition, May, 2000, available at <http://www.encs.concordia.ca/scs/Forms/Form&Style.pdf>.  
Approved by the ENCS Faculty Council February 10, 2012



Course Number: \_\_\_\_\_ Instructor: \_\_\_\_\_  
Name: \_\_\_\_\_ I.D. # \_\_\_\_\_  
Signature: \_\_\_\_\_ Date: \_\_\_\_\_

# IN CASE OF EMERGENCY REMAIN CALM AND FOLLOW THESE INSTRUCTIONS

## Fire/Evacuation



- Fire:**
- If you see smoke or fire activate the nearest fire alarm.
- Evacuation:**
- Stay calm; do not rush or panic
  - Safely stop your work,
  - Gather your personal belongings; coat, purse, etc...
  - Close and lock your door and windows.
  - Use stairs only; do not use elevators or escalators,
  - Once outside, move away from the building.
  - Do not re-enter the building until instructed to do so by Security.

## Shelter In Place



- Communication:**
- Shelter-in-Place will be announced by intercom P.A. voice communication, text messaging,
  - Fire alarms will not be sounded.

- Procedures:**
- Lock classroom, office and lab doors if possible, remain quiet and do not enter the hallway,
  - Should the fire alarm sound, DO NOT evacuate the building unless:
    1. You have first hand knowledge that there is a fire in the building,
    2. You are in imminent danger, or
    3. You have been advised by Security or Police to evacuate the building.
  - Crouch down in the areas that are out of sight from doors and windows,
  - Anyone in the hallways are to seek shelter in the nearest classroom,
  - Anyone outdoors on campus should immediately take cover,
  - If safe you can call 514-848-(8800) for more information on the situation.

## Suspicious Person/Package



- Suspicious Person:**
- Do not physically confront the person,
  - Do not let anyone into a locked building/office,
  - Call Security @ 514-848-(3717),
  - Provide as much information as possible about the person and his or her direction of travel.

- Suspicious Package:**
- Do not touch or disturb object,
  - Call Security @ 514-848-(3717),
  - Notify your Supervisor.

## Medical Emergencies



- In the event of a serious or life threatening injury or illness;
- From a safe location; call Security immediately at 514-848-(3717),
- Ensure your personal security before attempting first-aid,
- Provide the victim appropriate first-aid & comforting,
- Do not give the victim anything to drink or eat.

*\*If the injury is the result of a fall or significant trauma:  
Do not move the victim unless absolutely necessary.*

## Hazardous Materials



- If an emergency develops or if anyone is in danger, call 514-848-(3717),
- Move away from the site of the hazard to a safe location,
- Follow the instructions of Emergency Personnel,
- Alert others to stay clear of the area,
- Notify Emergency Personnel if you have been exposed to the hazard or have information about the release.

## Power Failure



- Remain calm and move cautiously to a lighted area,
- Do not evacuate unless asked to by Emergency Personnel,
- Do not use candles!
- For localized outages, contact Security at 514-848-(3717).