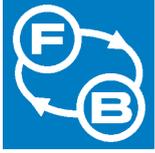


*Powerframes*  
**Electrical Circuits  
Student's Manual  
60-070-ECT-S**



# Feedback



Interactive Discovery Software



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Student's Manual**

**60-070-ECT-S**



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**Manual: 60-070-ECT-S** Ed01 052007

*Printed in England by FI Ltd, Crowborough*

Feedback Part No. 1160-60070ECTS

## Notes



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## THE HEALTH AND SAFETY AT WORK ACT 1974

We are required under the Health and Safety at Work Act 1974, to make available to users of this equipment certain information regarding its safe use.

The equipment, when used in normal or prescribed applications within the parameters set for its mechanical and electrical performance, should not cause any danger or hazard to health or safety if normal engineering practices are observed and they are used in accordance with the instructions supplied.

If, in specific cases, circumstances exist in which a potential hazard may be brought about by careless or improper use, these will be pointed out and the necessary precautions emphasised.

While we provide the fullest possible user information relating to the proper use of this equipment, if there is any doubt whatsoever about any aspect, the user should contact the Product Safety Officer at Feedback Instruments Limited, Crowborough.

This equipment should not be used by inexperienced users unless they are under supervision.

We are required by European Directives to indicate on our equipment panels certain areas and warnings that require attention by the user. These have been indicated in the specified way by yellow labels with black printing, the meaning of any labels that may be fixed to the instrument are shown below:



CAUTION -  
RISK OF  
DANGER



CAUTION -  
RISK OF  
ELECTRIC SHOCK



CAUTION -  
ELECTROSTATIC  
SENSITIVE DEVICE

Refer to accompanying documents

---

## PRODUCT IMPROVEMENTS

We maintain a policy of continuous product improvement by incorporating the latest developments and components into our equipment, even up to the time of dispatch.

All major changes are incorporated into up-dated editions of our manuals and this manual was believed to be correct at the time of printing. However, some product changes which do not affect the instructional capability of the equipment, may not be included until it is necessary to incorporate other significant changes.

---

### COMPONENT REPLACEMENT

Where components are of a 'Safety Critical' nature, i.e. all components involved with the supply or carrying of voltages at supply potential or higher, these must be replaced with components of equal international safety approval in order to maintain full equipment safety.

In order to maintain compliance with international directives, all replacement components should be identical to those originally supplied.

Any component may be ordered direct from Feedback or its agents by quoting the following information:

- |                        |                            |
|------------------------|----------------------------|
| 1. Equipment type      | 2. Component value         |
| 3. Component reference | 4. Equipment serial number |

Components can often be replaced by alternatives available locally, however we cannot therefore guarantee continued performance either to published specification or compliance with international standards.



*Powerframes*

**ELECTRICAL CIRCUITS  
STUDENT'S MANUAL**

**Preface**

---

**OPERATING CONDITIONS**

**WARNING:**

**This equipment must not be used in conditions of condensing humidity.**

This equipment is designed to operate under the following conditions:

Operating Temperature	10°C to 40°C (50°F to 104°F)
Humidity	10% to 90% (non-condensing)

---

**CE DECLARATION CONCERNING ELECTROMAGNETIC COMPATIBILITY**

Should this equipment be used outside the classroom, laboratory study area or similar such place for which it is designed and sold then Feedback Instruments Ltd hereby states that conformity with the protection requirements of the European Community Electromagnetic Compatibility Directive (89/336/EEC) may be invalidated and could lead to prosecution.

This equipment, when operated in accordance with the supplied documentation, does not cause electromagnetic disturbance outside its immediate electromagnetic environment.

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*Powerframes*

**ELECTRICAL CIRCUITS  
STUDENT'S MANUAL**

**Foreword**

**PURPOSE**

This manual provides practical assignments to support the use of this trainer as a teaching aid. Each assignment consists of exercises which, when performed, allow the students to discover for themselves the practical aspects of a particular subject. After results have been obtained and entered into tables and, if necessary, plotted on graph paper, they can be compared with typical answers and results given at the end of each assignment. Provided at the front of each assignment is any relevant theory pertaining to the subject and/or references to further reading.

**CONTENT**

This manual comprises:

- Chapter 1 Trainer Description. Provides a description of the trainer.
- Chapter 2 Preliminary Checks. Provides inspection and operation information and references Utility Sheets.
- Chapter 3 Assignments. Consists of practical assignments that can be performed by the student.
- Appendices. This area provides further theoretical information to that given in each assignment.



*Powerframes*  
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**Foreword**

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**FOREWORD**

**CHAPTER 1           Trainer Description**

**CHAPTER 2           Preliminary Checks**

**CHAPTER 3           Assignments**

**Assignment 1       Familiarisation**

**Practicals**

- 1.1   Resistive Network Construction
- 1.2   Patching Familiarisation

**Assignment 2       Current and Voltage**

**Practicals**

- 2.1   Current Flow in Circuit
- 2.2   Voltage Measurement

**Assignment 3       Resistance and Ohm's Law**

**Practicals**

- 3.1   Effect of Resistance
- 3.2   Resistance, Voltage and Current Relationship

**Assignment 4       Resistors in Series and Parallel**

**Practicals**

- 4.1   Resistors in Series
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<b>Assignment 5</b>	<b>Resistor Networks</b>
	<b>Practicals</b>
	5.1 Current Law
	5.2 Voltage Law
<b>Assignment 6</b>	<b>Power</b>
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	6.1 Voltage and Current Relationship to Power
	6.2 Power Transfer
<b>Assignment 7</b>	<b>ac Theory</b>
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	7.1 ac and dc Comparison
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<b>Assignment 8</b>	<b>Resistive Circuit at ac</b>
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	9.1 Current and Voltage Phase Relationship
	9.2 Reactance in Capacitive Circuit
	9.3 Calibration of Capacitors
	9.4 Capacitors in Series
	9.5 Capacitors in Parallel



**Assignment 10**

**Inductive Circuit at ac**

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- 10.1 Current and Voltage Phase Relationship
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- 10.4 Inductors in Series
- 10.5 Inductors in Parallel

**Assignment 11**

**Combinations of Load Elements**

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- 11.1 Resistor and Capacitor in Series
- 11.2 Resistor and Inductor in Series

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**Practicals**

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**Three Phase Voltage & Current Relationships**

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- 13.1 Voltage Relationships in a Balanced Star Supply Star Load
- 13.2 Current Relationships in a Balanced Star Supply Delta Load

**Assignment 14**

**Balanced Three Phase Resistive Load in Star and Delta Connections**

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- 14.1 Power and Power Factor using Star Load
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15.1    Three Phase Sequence Determination

**APPENDIX A            Units**

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**APPENDIX B            General Information**

B.1    Phasors

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B.3    Why Use Three Phase Systems

B.4    Measuring Instruments

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## **1 Trainer Description**

---

### **1.1 Introduction**

The Electrical Circuits Trainer 60-070-ECT option of the *Powerframes* range of trainers allows the properties of electric power in dc, single phase and three phase systems to be investigated. The measurement of these properties is accomplished using virtual instrumentation or conventional instrumentation.

Power supplies, loading and virtual instrumentation are all provided in the form of panels which are mounted into a purpose-designed, bench-standing frame. The panels can be arranged in an order convenient to the user as they can easily be slotted in and out of the frame.

To enable the assignments contained in this manual to be easily followed, the layout of the panels within the frame has been pre-determined.

The courseware provided in this manual assumes that a complete trainer is available. The assignments have been organised such that they can be carried out with systems that use *either* virtual or conventional instrumentation. Check your product to determine the type before commencing assignments for instrumentation supplied.

### **1.2 Power Supply Safety Features**

The Universal Power Supply 60-105 comes complete with a 3-phase circuit breaker to ensure mains supplies are automatically disconnected in the event of a current overload occurring or an inadvertent interruption of the ac mains supply. It is recommended that the 3-phase mains supply to this unit is connected via an earth leakage circuit breaker (such as Feedback 60-140-1).

An 'emergency power off' pushbutton is also provided which allows an operator to disconnect all supplies from the unit and frame equipment in the event of an emergency.

Variable ac and dc supply outputs are provided which are protected by a current operated circuit breaker. A fixed dc supply is available which is protected by a fuse.

All power connections for assignment work are made using 4 mm output shrouded plug leads.



**WARNING:**

All un-powered frame mounted units are provided with earth terminals on the front and/or back which must be connected to a protective earth point that is provided on all power supply units, using the earth leads supplied.



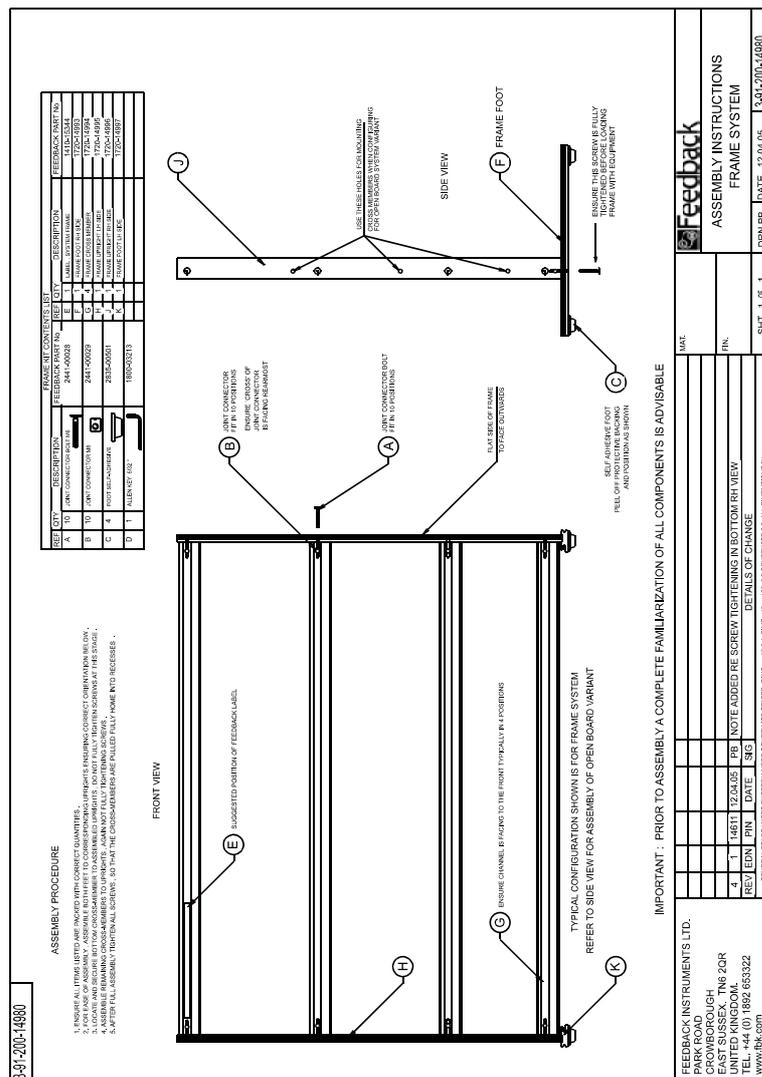
**1.3 Frame Construction**

The system frame (91-200) is constructed using captive nut and bolt fixings as shown in the 'Assembly Instructions – Frame System' drawing (Figure 1-1). Ensure all bolts including the bolts securing the frame feet (F), as shown in the side view of Figure 1-1, are fully tightened before loading the frame with equipment.

**WARNING:**



If the frame system fixings are not fully tight before equipment is mounted, the frame could be unstable or collapse with consequent damage to personnel and equipment.



**Figure 1-1: System Frame Fixings Location**



### 1.4 Equipment

The Electrical Circuits Trainer with Virtual Instrumentation is shown in Figure 1-2 and with Conventional Instrumentation in Figure 1-3 and comprises:

- Universal Power Supply 60-105 (core product supply)
- Switched Three Phase Resistance Load 67-142 (core product supply)
- Switched Three Phase Capacitive Load 67-212
- Switched Three Phase Inductive Load 67-312
- System Frame 91-200 (core product supply)
- Standard Set of Patch Leads 68-800 (core product supply)
- Either:

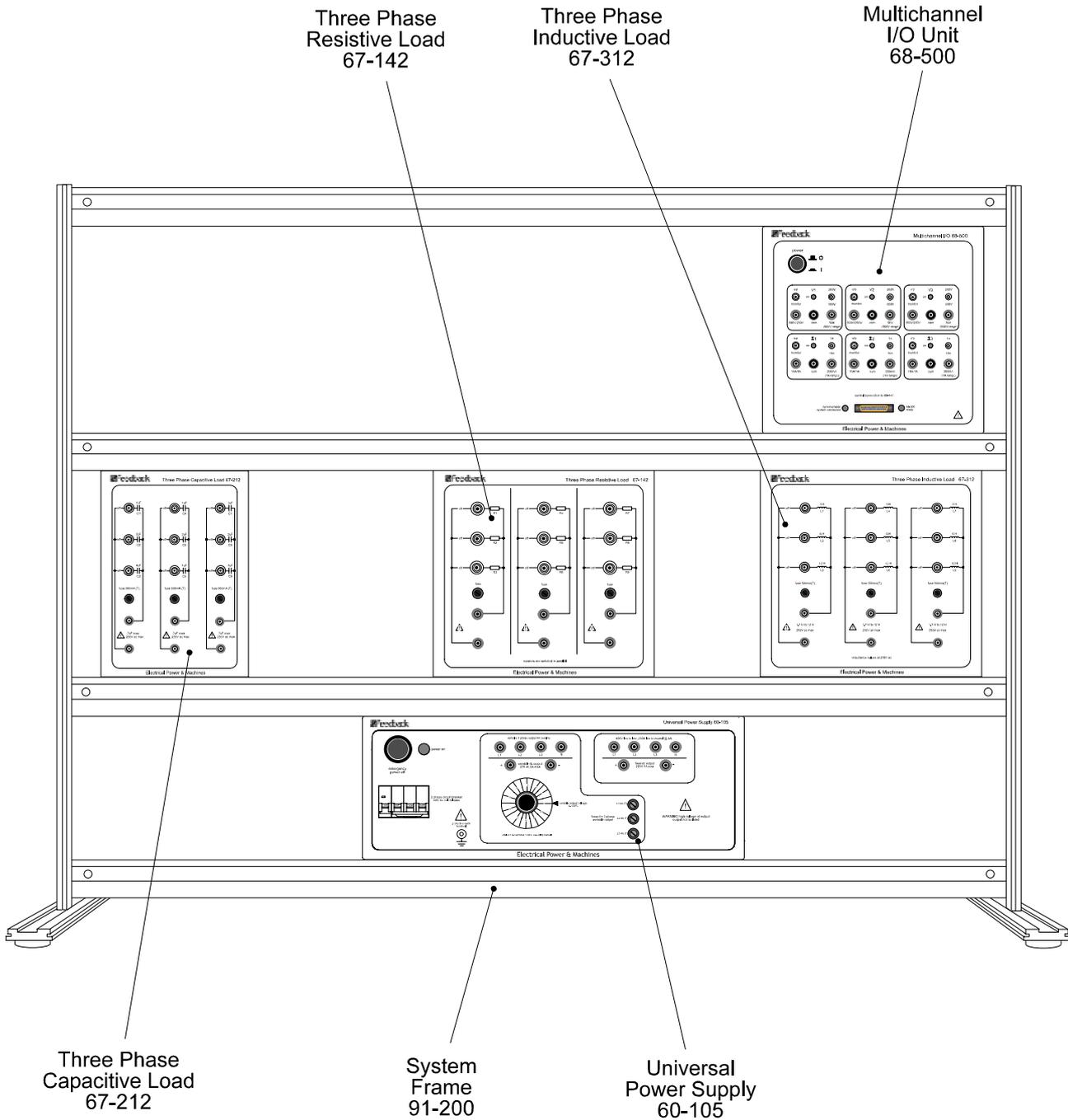
<a href="#">Virtual Instrumentation (Option 60-070-VIP)</a>	Multichannel I/O Unit Software Pack	68-500 68-912-USB
<b>or</b>		
<a href="#">Conventional Instrumentation (Option 60-070-CI1)</a>	Electronic Single & Three Phase Measurements dc Voltmeter & Ammeter (2 off)	68-100 68-110
<a href="#">Conventional Instrumentation (Option 60-070-CI2)</a>	Rectifier Voltmeter & Ammeter (2 off) Electrodynamic Wattmeter (2 off)	68-117 68-204
<a href="#">Ancillary Equipment</a>	Differential Voltage/Current Probe (2 off) For use with conventional instruments only. (Not supplied)  Two channel oscilloscope with at least 20 MHz bandwidth	68-150

**NOTES:**

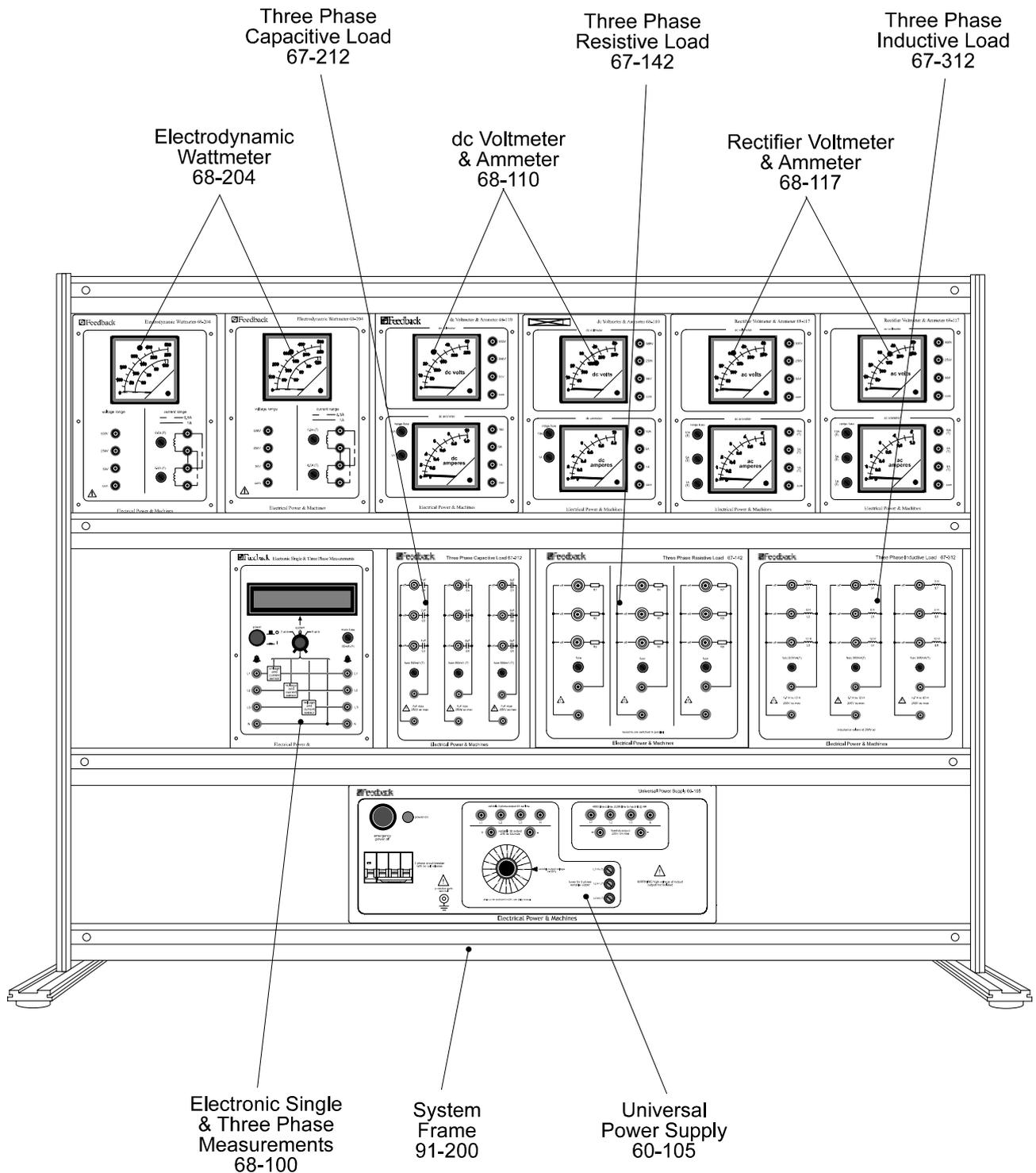
Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files. Model Set-Ups are provided with this model for each assignment.

Do refer to the Help information in the 65-500-USB software.

For a more detailed description of the individual units supplied, please consult the Utilities Manual 60-070-UM and the relevant product number that can be found on a label fixed to the rear panel of the instrument.



**Figure 1-2: Electrical Circuits Trainer (Virtual Instrumentation)**



**Figure 1-3: Electrical Circuits Trainer (Conventional Instrumentation)**



## **1.5 Main Modules**

Brief details of the main modules that constitute a trainer are given. For further details on individual modules, refer to the Utilities Manual 60-070-UM.

### **1.5.1 Common Modules**

#### **1.5.1.1 Universal Power Supply 60-105**

The power supplies in the 60-070 series are provided by a Universal Power Supply 60-105.

The power supply is designed to be fitted between the two narrow rails of the frame in the lowest area of the frame.

The Universal Power Supply 60-105 receives a three phase input from the mains supply and input connections are hard wired at the rear of the unit. After being connected to the unit 60-105, the supply is protected via a three phase circuit breaker which when closed provides power to three phase variable and fixed ac outputs and variable and fixed dc outputs (as indicated by a green 'power on' indicator light). An 'emergency power off' pushbutton is provided which allows an operator to remove all supply outputs from the panel and other units supplied from it. The supply outputs can be re-established by releasing the 'emergency power off' button (turn clockwise to release) and resetting the lever switches on the circuit breaker to up (on) position.

**WARNING:**

High voltages are present on front panel sockets. Ensure that only the shrouded safety connectors provided are used for all power and monitoring connections.

#### **1.5.1.2 Three Phase Resistive Load 67-142**

The Three Phase Resistive Load 67-142 unit provides a wide range of resistance variation making it ideally suited to the testing of electrical circuits, transformers and electrical machines.

Three resistance banks are provided for three phase applications; however, they may be used in series or parallel to provide the value required.

Note that the resistors in each section are identified with references R1, R2, R3 etc. These references will be used in the assignments to select specific resistances.

For further details refer to the Utilities Manual 60-070-UM.

**WARNING:**

High voltages are present on front panel sockets. Ensure that only the shrouded safety connectors provided are used for all power and monitoring connections. Also ensure that the earth terminal on the front panel is connected.



### 1.5.1.3 Three Phase Capacitive Load 67-212

The Switched Three Phase Capacitive Load 67-212 unit provides three capacitive banks of different capacitive values which can be used, for example, in three phase generator loading, power factor correction and reactive three phase circuits. Each bank maybe connected in series or parallel with another to extend the capacitive range.

### 1.5.1.4 Three Phase Inductive Load 67-312

The Switched Three Phase Inductive Load 67-312 unit provides a selection of inductive values in a three-bank configuration which can be used, for example, in three phase circuits for reactive loading on three phase systems or three phase alternators. Each bank maybe connected in series or parallel with another to extend the inductive range.

## **1.5.2 Virtual Instrumentation**

### 1.5.2.1 Multichannel I/O 68-500

The Multichannel I/O 68-500 unit allows a number of different parameters associated with transformers to be measured with a **Virtual Instrumentation** system. Used with a PC, the software provides on-screen ac and dc voltmeters and ammeters, dc wattmeter, single and three phase wattmeters, ac phase meter, ac power meter, ac frequency meter and single and three phase power factors.

The system requires the following:

- Virtual instrumentation software,
- PC interface hardware,
- PC with a minimum specification of 700 MHz, Pentium 3, 512 MB of memory, USB1 port and Windows 2000 or XP operating systems.

For further information, see the *Powerframes* Virtual Instrumentation 60-070-VIP manual and the Utilities Manual 60-070-UM.

## **1.5.3 Conventional Instrumentation 60-070-CI1**

### 1.5.3.1 Electronic Single & Three Phase Measurements

This unit allows parameter measurement of 3 or 4 wire, balanced, three phase systems. The parameters include voltage, current, power factor, watts, kVA, kVAR, kWh, etc.

### 1.5.3.2 dc Voltmeter & Ammeter 68-110

This equipment is used for all dc voltage and current measurements. These operate over the ranges 0–1, 0–5, 0–10 A and 1–50, 0–250, 0–500 V. All ammeters are fused protected for all ranges.



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**ELECTRICAL CIRCUITS  
STUDENT'S MANUAL**

**Chapter 1**

**Trainer Description**

***Conventional Instrumentation 60-070-C12***

1.5.3.3 Rectifier Voltmeter & Ammeter 68-117

This equipment is used for all voltage and current measurements. These operate over the ranges 0–1, 0–5, 0–10 A and 0–50, 0–250, 0–500 V. All ammeters are fused protected for all ranges.

For further details refer to the Utilities Manual 60-070-UM.

1.5.3.4 Electrodynamometric Wattmeter 68-204

This wattmeter is suitable for use in ac/dc circuits when measuring power up to 1 kW. The instrument is a direct indicating type requiring no external supply connections other than those to appropriate voltage and current terminals. Refer to the 68-204 Module Utility Sheet for instructions on connecting the wattmeter (see Utilities Manual 60-070-UM).

***Ancillary Equipment*** (not provided)

1.5.3.5 Differential Probe 68-150

This provides direct safe connection to the oscilloscope. Maximum input 1000 V dc or 700 V ac rms. Switched attenuation 1/200 or 1/20 to 15 MHz bandwidth.

Note: This item is not supplied with the 60-070-ECT product but can be purchased separately.

For further details refer to the Utilities Manual 60-070-UM.

Additional Items:

- General purpose two channel oscilloscope with at least 20 MHz bandwidth.



## **2 Preliminary Checks**

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### **2.1 Installation**

Hardware installation instructions are provided in the *Powerframes* Installation and Commissioning Manual 60-070-IC. For Virtual Instrumentation software installation and associated hardware installation, refer to manual 60-070-VIP.

### **2.2 Inspection**

Prior to use, check all equipment for mechanical damage and for any loose fittings, and secure these.

**WARNING:**

If the frame system fixings are not fully tight before equipment is mounted, the frame could be unstable or collapse with consequent damage to equipment and personnel. See Chapter 1 for further information.

### **2.3 Earth Protection**

Ensure all non-powered modules such as the Three Phase Resistive Load 67-142 are earthed through the supply by connecting all module earth terminals (normally situated on the back of each module) to any one of the earth terminals situated on the back of the Universal Power Supply 60-105 using the earth leads supplied.

Powered modules such as the Multichannel I/O Unit 68-500 are directly supplied with power and are earthed through the supply.

A protective earth terminal on the front panel of the power supply unit is provided to allow connection to non-direct mains powered equipment such as electrical machines, transformers etc that are bench-standing.

**WARNING:**

All non-direct powered panels must be earthed using the earth leads supplied, to the main power supply, 60-105.

### **2.4 Specification**

Specification details and safety aspects of the individual modules are provided in Module Utility Sheets which are provided with the equipment and in the *Powerframes* Utilities Manual 60-070-UM.



Notes



## **3 Assignments**

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### **3.1 Introduction**

This chapter contains assignments for the Electrical Circuits Trainer 60-070-ECT option. The assignments also require the use of equipment from the core system 60-070 of the *Powerframes* range of trainers.

The assignments are designed to allow the properties of electric power in dc, single phase and three phase to be investigated.

In all cases the results are evaluated, calculations are made and conclusions are drawn.

The assignments are grouped into three sections as follows:

#### Electrical Fundamentals

- 1 Familiarisation
- 2 Current and Voltage
- 3 Resistance and Ohm's Law
- 4 Resistors in Series and Parallel
- 5 Resistor Networks
- 6 Power

#### Alternating Current

- 7 ac Theory
- 8 Resistive Circuit at ac
- 9 Capacitive Circuit at ac
- 10 Inductive Circuit at ac
- 11 Combinations of Load Elements
- 12 Power in ac Circuit

#### Three Phase Circuits

- 13 Three Phase Voltage & Current Relationships
- 14 Balanced Three Phase Resistive Load in Star and Delta Connections
- 15 Three Phase Sequence Determination



### **3.2 Assignment Composition**

Each assignment comprises:

- An **Introduction** giving theory relevant to the assignment as a whole.
- **Practicals**, which contain operating procedures, and exercises pertaining to the results obtained. For each practical, a circuit diagram is provided (see below), and, for the more complex circuits, the patching diagram is also given.
- **Results tables** for each practical in which measured data is recorded.
- **Typical results and answers** which provide completed tables and graphs, and answers to all questions are provided in the Reference Manual 60-070-ECT.

### **3.3 Wiring Diagrams**

In Assignment 1, wiring and circuit diagrams are given for both Conventional Instrumentation and Virtual Instrumentation equipment set ups.

After this assignment, the student should have become familiar with interpreting the circuit diagram such that the various equipment meters, power supply motor etc can be interconnected without fully detailed information. Wiring diagrams are shown only for the more complex circuits, or where new items of equipment are being introduced which have not been used in previous assignments.

### **3.4 Trainer Versions (230 V and 120 V)**

The practicals provided in each assignment cover both 230 V and 120 V versions of the trainer.

Check your product for the version in use.

Where parameters specific to an appropriate trainer version are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **1 Familiarisation**

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### **1.1 Assignment Information**

#### **1.1.1 Objectives**

When you have completed this assignment you will know:

- how to interpret patching shown on circuit diagrams in order to wire up the trainer panels in readiness for the practicals in other assignments.
- where to find information relating to the operation of virtual instrumentation and displaying the measured data.
- how to select resistive, capacitive and inductive component values and create component networks.
- how assignments in this manual are organised.

#### **1.1.2 Knowledge Level**

Before you start this assignment:

- if you have a Virtual Instrumentation System, you should be familiar with its use.

For details on the connections between the PC and the 68-500 Multichannel I/O Unit, see Virtual Instrumentation System manual 60-070-VIP. See also this manual for details of the Virtual Instrumentation software 68-912-USB.

#### **1.1.3 Practicals**

1. Resistive Network Construction
2. Patching Familiarisation

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **1.2 Theory**

### **1.2.1 Introduction**

This assignment instructs the student in Practical 1.1 on how to wire a simple circuit together which utilises many of the trainer's panels and is monitored by both virtual and conventional instrumentation. By this means, the student will become familiar with interpreting the patching shown on circuit diagrams, as physical panel layout diagrams with patching shown are available for comparison. Further assignments only provide circuit diagrams of a required patching arrangement.

### **1.2.2 Use of Virtual Instrumentation**

Operation of the Virtual Instrumentation is fully explained in the Virtual Instrumentation manual 60-070-VIP. This document also provides details on how to display measured data in a Microsoft Excel spreadsheet. This is a convenient method of recording results as graphs can be drawn automatically using the Excel facility.

### **1.2.3 Component Switching**

Many of the circuits constructed for assignments utilise the components found on the switched three phase load units (67-142, 67-212, 67-312). To enable the correct values of components required to be selected, reference should be made to the appropriate utility sheet in manual 60-070-UM.

### **1.2.4 Unit of Electrical Resistance**

The unit of electrical resistance is called the ohm, named after the German physicist Georg Simon Ohm (1787–1854) who first investigated the relationship between voltage and current. The symbol for the ohm is  $\Omega$  (the Greek letter omega). We will look at resistance again in Assignment 3.



### 1.3 Content

The practicals in this assignment familiarise the student with interpreting circuit diagrams, the construction of component networks, and the units and measurement facilities that make up the Electrical Circuits Trainer.

### 1.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- Switched Three Phase Inductive Load 67-312
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation (Option 60-070-CI2)	Rectifier Voltmeter & Ammeter (2 off)	68-117
Ancillary Equipment	Digital Multimeter (Not supplied)	

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 1.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



**1.6 Practical 1.1 - Resistive Network**

Ensure all power supplies to the trainer are disconnected.

On the three phase resistive load unit 67-142, make all connections shown in Figure 3-1-1(a) and (b), and then set resistance of the banks as follows:

Set the resistance of Bank 1 to .....

Set the resistance of Bank 2 to .....

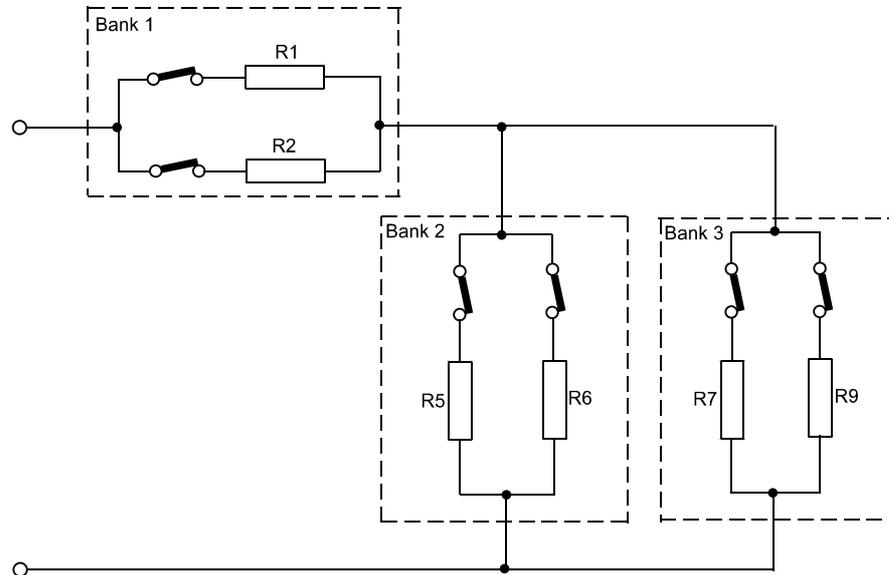
Set the resistance of Bank 3 to .....

Using the multimeter set to the resistance range, measure the total resistance across the constructed network. The multimeter should indicate..

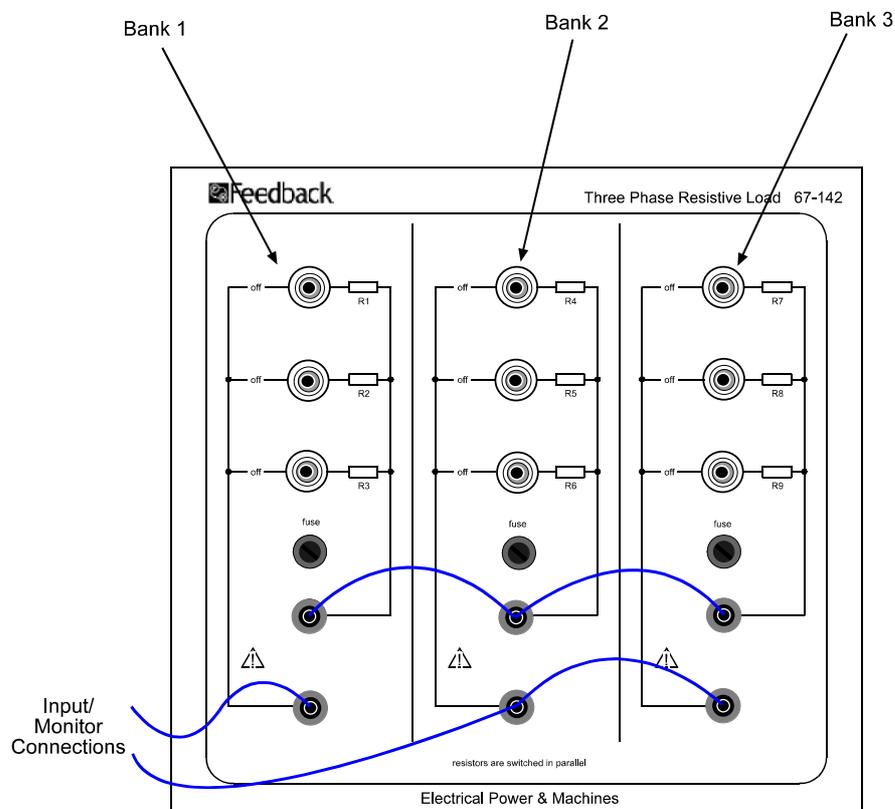
Product Version	
230 V	120 V
640 $\Omega$ (R1 & R2 closed)	
1285 $\Omega$ (R5 & R6 closed)	
759 $\Omega$ (R7 & R9 closed)	
1117 $\Omega$	

Open and close different switch settings of the banks and observe the change of resistive values.

From this practical, it can be seen that various types of resistive network can be constructed and different values of resistive load obtained.



**Figure 3-1-1(a): Practical 1.1 Circuit Diagram**



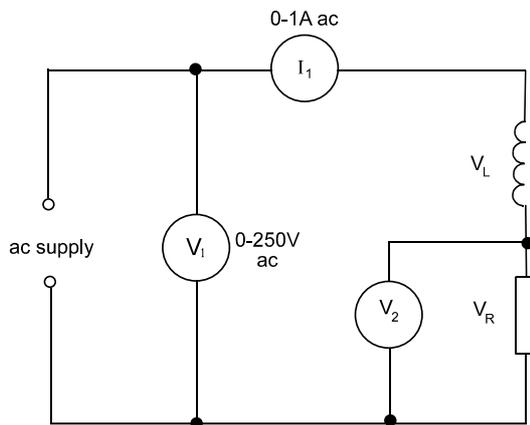
**Figure 3-1-1(b): Practical 1.1 Wiring Diagram**



**1.7 Practical 1.2 - Wiring Familiarisation**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-1-3(a) and (b) or (c), which equates to the theoretical circuit shown in Figure 3-1-2.



**Figure 3-1-2: Theoretical Circuit**

If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1 and V2 channels to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected.

On the switched three phase inductive load 67-312, set banks 1 to 3 switches to on to give an inductance of.....

560 mH

On the switched three phase resistive load 67-142, set banks 1 to 3 switches to on to give a resistive load of.....

182 Ω

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is to 0%, and then switch on the '3 phase circuit breaker'.

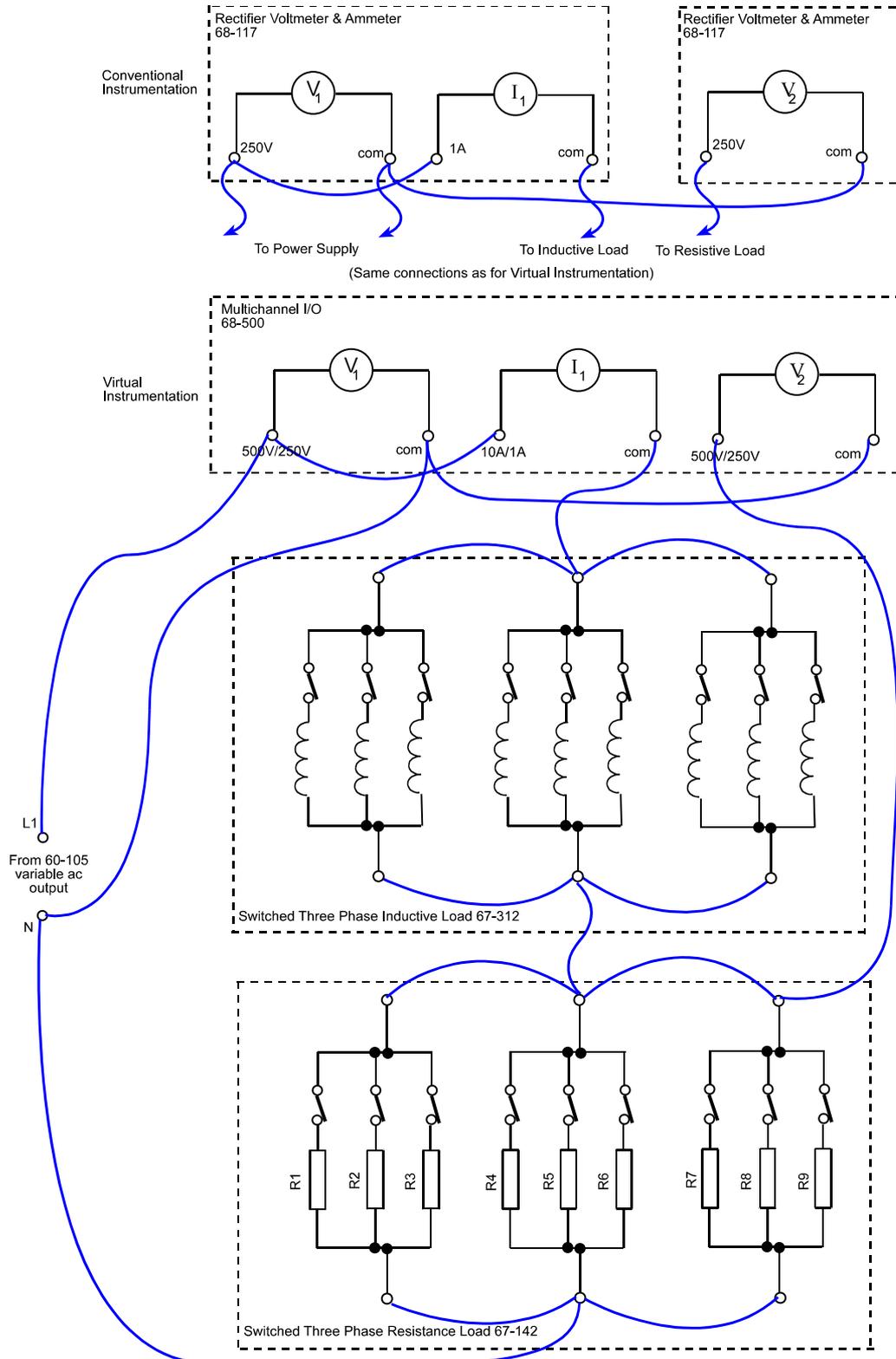
Turn the dial on the power supply to ..... as shown on the virtual or conventional voltmeter V1.

100 V rms

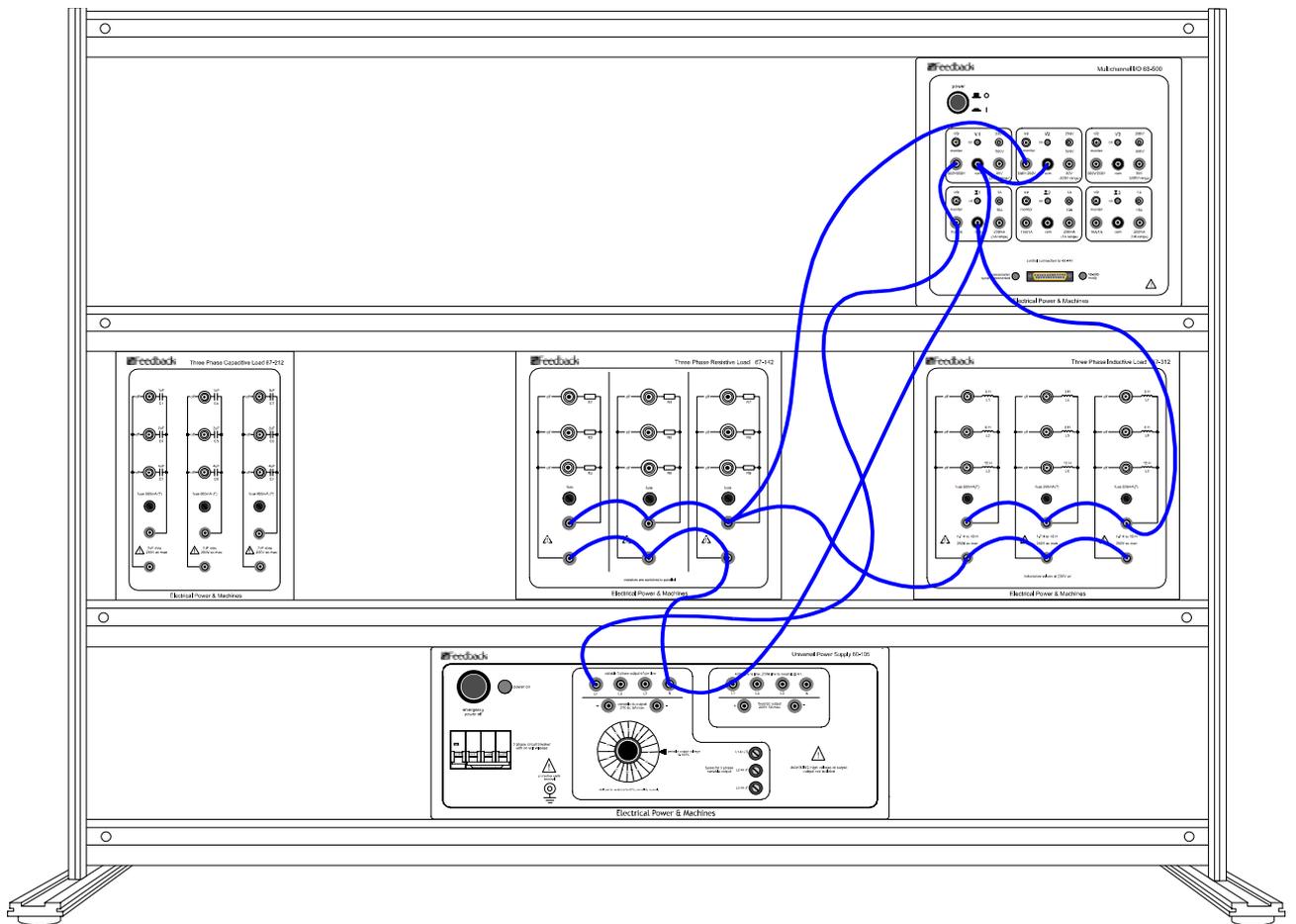


Using either virtual or conventional instrumentation (see Figure 3-1-3(a)), measure the voltage across the resistor ( $V_R$ ) on voltmeter  $V_2$  and current flowing through the circuit on ammeter  $I_1$ . Record the results on a copy of the appropriate Practical 1.2. Results Table (230 V or 120 V product version) located in the Results Tables section at the end of this assignment.

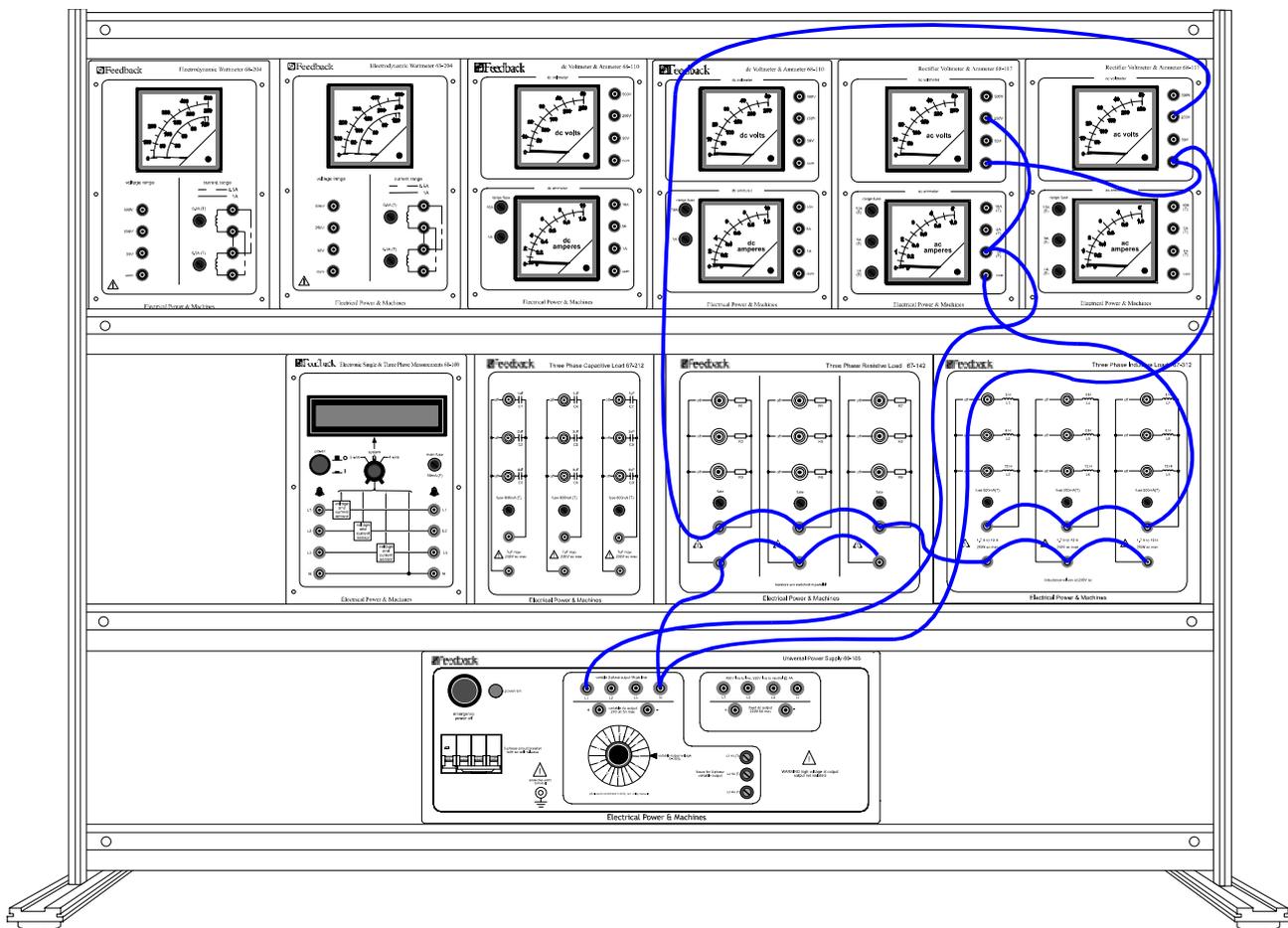
Turn the '*variable output voltage*' control to 0% on the Universal Power Supply 60-105 and then switch off the '*3 phase circuit breaker*'.



**Figure 3-1-3(a): Practical 1.2 Circuit Diagram**



**Figure 3-1-3(b): Practical 1.2 Wiring Diagram (Virtual Instrumentation)**



**Figure 3-1-3(c): Practical 1.2 Wiring Diagram (Conventional Instrumentation)**



**1.8 Practical 1.2 - Results Tables (230 V Product Version)**

Supply Voltage ( $V_1$ )	Current ( $I_1$ )	Resistor Voltage ( $V_2$ )



**1.9 Practical 1.2 - Results Tables (120 V Product Version)**

Supply Voltage ( $V_1$ )	Current ( $I_1$ )	Resistor Voltage ( $V_2$ )



## **2 Current and Voltage**

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### **2.1 Assignment Information**

#### **2.1.1 Objectives**

When you have completed this assignment you will:

- have explored the ideas of current and voltage in a circuit

#### **2.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignment 1, Familiarisation
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **2.1.3 Practicals**

1. Current Flow in a Circuit
2. Voltage Measurement

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **2.2 Theory**

### **2.2.1 Introduction**

In this assignment, current and voltage in an electrical circuit are considered. Before embarking on these topics, it is helpful to discuss energy and power.

### **2.2.2 Energy and Electromotive Force (Voltage)**

Energy is defined as the ability or capacity to do work. Work is accomplished, in a scientific sense, only when a force acting on a body (mass) moves that body a definite distance.

There are two distinct types of energy: potential energy and kinetic energy.

#### **2.2.2.1 Potential Energy**

This is the energy stored in a body, or the energy a body possesses because of its position relative to another position, called a reference level.

#### **2.2.2.2 Kinetic Energy**

This is energy due to motion. Whenever a physical object is in motion, it has kinetic energy and is capable of doing work by coming to rest.

As an example, consider a coiled spring with a weight attached. Work is needed to stretch the spring. If the spring is stretched, the work that is put into the system to stretch it is held as potential energy in the spring. When the weight is released, it will move and the potential energy is converted into kinetic energy. It will continue to move up and down until all of this kinetic energy is used up; then the weight will come to rest.

### **2.2.3 Power**

It may be noted from the above explanation that the time required to perform a task is not a factor in determining the amount of work done. Time, however, is very important when considering power.

*The time rate of doing work is power.*

Expressed another way, a certain amount of work, done in a given amount of time, determines the power used. That is, it takes a definite amount of power when a given quantity of work is performed in a certain time interval.

Work and energy are measured in **joules**, power is measured in **watts**.

When you expend  $x$  joules of energy to do work, and the work is done in  $t$  seconds, the power (in watts or joules/second) used is  $x/t$ .

The watt is a common unit used to measure the amount of electrical power used. For example, your electric power bill is based on the number of watts used. The watt may be converted into mechanical units by the relationship:

$$1 \text{ horsepower} = 746 \text{ watts}$$



The transformation of energy from one form (mechanical, chemical, electrical, heat, light, atomic or mass) to another obeys the conservation of energy law which states that **energy may be changed from one form to another but it cannot be created or destroyed.**

#### **2.2.4 Voltage or Potential Difference**

The electric intensity at a point in an electric field is the ratio of the force on a charge at that point to the magnitude of the charge, or it is the force per unit charge.

Similarly, the **potential** at a point in an electric field is defined as the ratio of potential energy of a charge to the magnitude of the charge, or as the **potential energy per unit charge.**

If a coulomb of charge is moved and a joule of energy is used, then the potential energy has changed by one volt. A potential energy, **or potential, for short, of one joule per coulomb is called one volt.**

The unit of volt is named in honor of Alessandro Volta (1745–1827), an Italian scientist and the inventor of the “voltaic pile”, the first battery cell.

The **potential difference** between points  $a$  and  $b$  is one volt if one joule of work per coulomb of charge is done against electrical forces when a charge is moved from point  $a$  to point  $b$ .

The concept of potential difference is an extremely important one, both in electrostatics and in electronic circuits. It has the unit of volts (V), and has a polarity associated with it. It is commonly referred to as **voltage, voltage drop, voltage difference, electromotive force (electron moving force), or EMF.**

For example, the potential difference between the terminals of a common automobile storage battery is about 12 volts. The terminal with the higher potential is designated by a “+” sign; that with the lower potential by a “-” sign. The potential difference between two points is measured by a voltmeter.

#### **2.2.5 Electric Current**

Now, we are ready to discuss the motion of charge in a conductor when an electric field is maintained within the conductor. This motion of charges constitutes an electric current.

#### **2.2.6 Random Drift of Electrons**

All materials are composed of atoms, each of which is capable of being ionized. If some form of energy, such as heat, is applied to a material, some electrons acquire sufficient energy to move to a higher energy level. As a result, some electrons are freed from their parent atoms and the atoms become ions. Other forms of energy, particularly light, a magnetic or an electric field, can cause ionization to occur. The number of free electrons resulting from ionization is dependent upon the amount of energy applied to the material as well as the atomic structure of the material.

Suppose heat is applied to a conductor made up of atoms that have loosely bound electrons in their valence shell. As the energy of the valence electrons increases due to the added energy and they break away from their atoms, they freely drift about the material in a haphazard manner. Their path is not predictable, and so such movement is termed **random drift.**



### **2.2.7 Directed Drift or Current**

A free electron will be affected by an electrostatic field. It is repelled by a negative charge and attracted by a positive charge. If a conductor has a difference in potential impressed across it, a direction is imparted to the electron drift.

**This directed drift of free electrons due to the potential difference constitutes an electric current.**

Prior to the use of atomic theory to explain the composition of matter, scientists mistakenly defined electric current as the motion of positive charges in a conductor from a point of positive polarity to a point of negative polarity. In many electrical engineering and physics textbooks, current is still considered to be conventionally from positive to negative. Such a current is termed **conventional current** and many concepts and explanations are based on this theory. We have learned since that current is based on the flow of electrons, or a negative charge. Therefore, electron current is in the opposite direction from conventional current. Whichever direction that charge is assumed to move or flow, it constitutes an electric current.

### **2.2.8 Magnitude of Current**

The magnitude of current is measured in amperes. The unit symbol for amperes is A. The symbol for current in equations and on diagrams is either the lowercase or the uppercase I. Amperes is a measure of the rate at which charge is transported across a section of a wire or other conductor.

**One ampere is a coulomb of charge moving past a point in one second.**

An electric current seems to move instantaneously through a wire.

The concept of electric current is analogous to a pipe filled with red marbles, where the pipe is the conductor (such as wire) and the marbles are free electrons in the wire. When a white marble is inserted in one end of the pipe, a red marble is pushed out the opposite end.

Thus, the effect of inserting a marble at one end of the pipe appears almost instantaneously at the opposite end, though the white marble would move relatively slowly through the pipe.

Even though the effect of the moving charge seems to be instantaneous, the movement of a single electron is much slower. Just as the accumulation of marbles depends on the rate of movement of the marbles and the amount of time, the amount of electricity (coulombs of charge) depends on the amount of current and the length of time.



### 2.3 Content

The practicals in this assignment familiarise the student with the concepts of current flowing round, and the potential difference across, an electric circuit.

### 2.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation	dc Voltmeter & Ammeter (60-070 option CI1)	68-110

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 2.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



**2.6 Practical 2.1 - Current Flow in a Circuit**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-2-1. The power supply unit connections should be made via a voltmeter which should be set to.....

If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 to '250 V' and set the 1 A/10 A range switch for I1 to '1 A'. This allows currents up to 1 A to be monitored when the 10 A/1 A socket is connected.

On the Switched Three Phase Resistance Load 67-142, set all the banks of switches to the 'on' position so that the resistance in circuit is.....

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Set the power supply 'variable output voltage' control to give an output of... as shown on the voltmeter. This is the voltage applied to the switched three phase resistance load 67-142.

Measure and record on a copy of the appropriate Results Table (230 V or 120 V), the current flowing in the circuit as read by virtual or conventional ammeter (in the first reading column).

On the Universal Power Supply 60-105, switch off the '3 phase circuit breaker' without altering the position of the 'variable output voltage' control.

Disconnect virtual or conventional instrumentation.

Make all connections shown in Figure 3-2-2. Ensure that the positive (10 A/1 A) side of the virtual or conventional ammeter is connected to the resistive load.

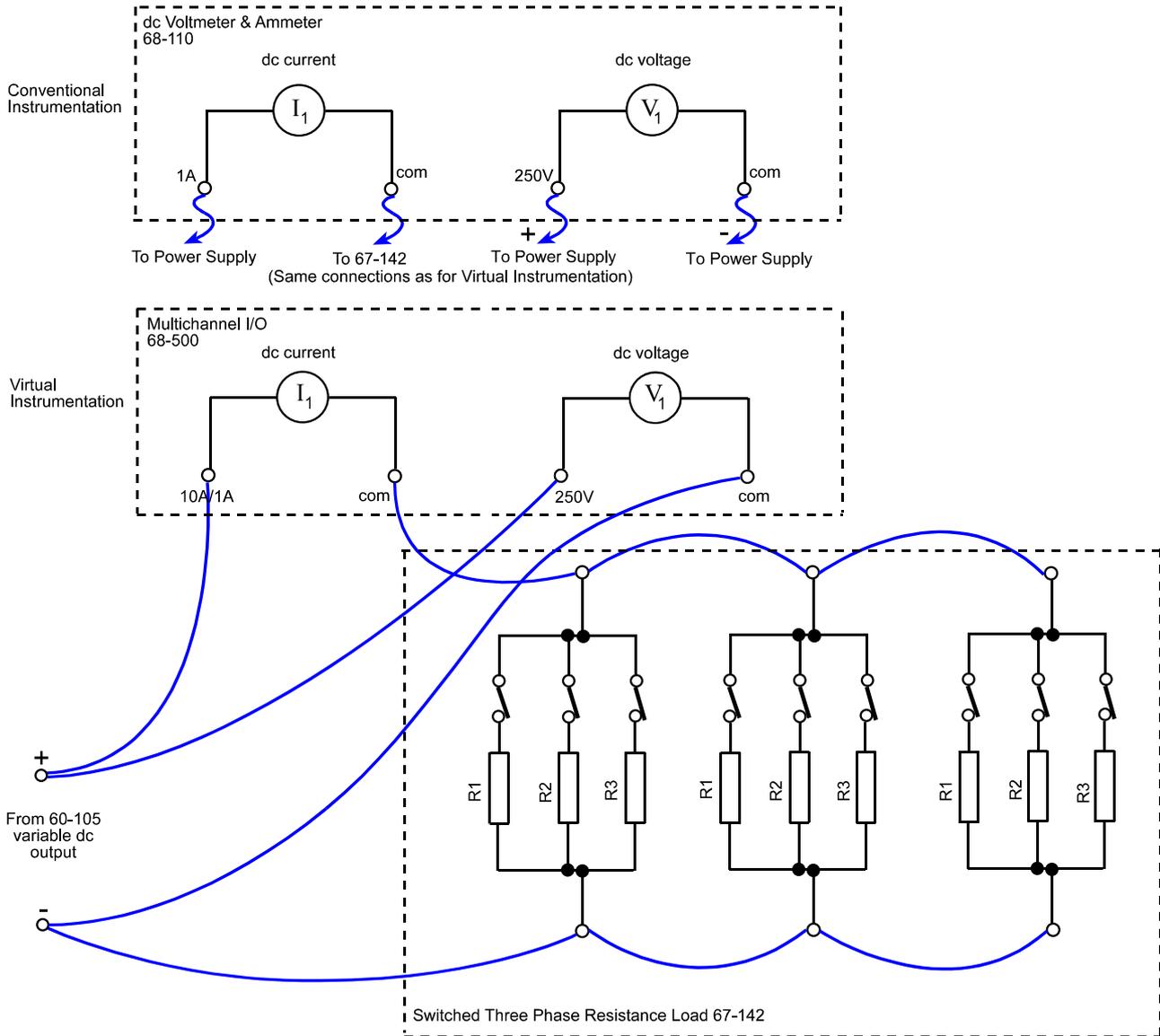
If virtual instrumentation is being used, ensure the 1 A/10 A range switch for I1 is still set to '1 A'.

Switch on the power supply 60-105 without altering the position of the 'variable output voltage' control and measure and record on your copy of the Results Table the current flowing in the circuit (in the second reading column) on the virtual or conventional ammeter.

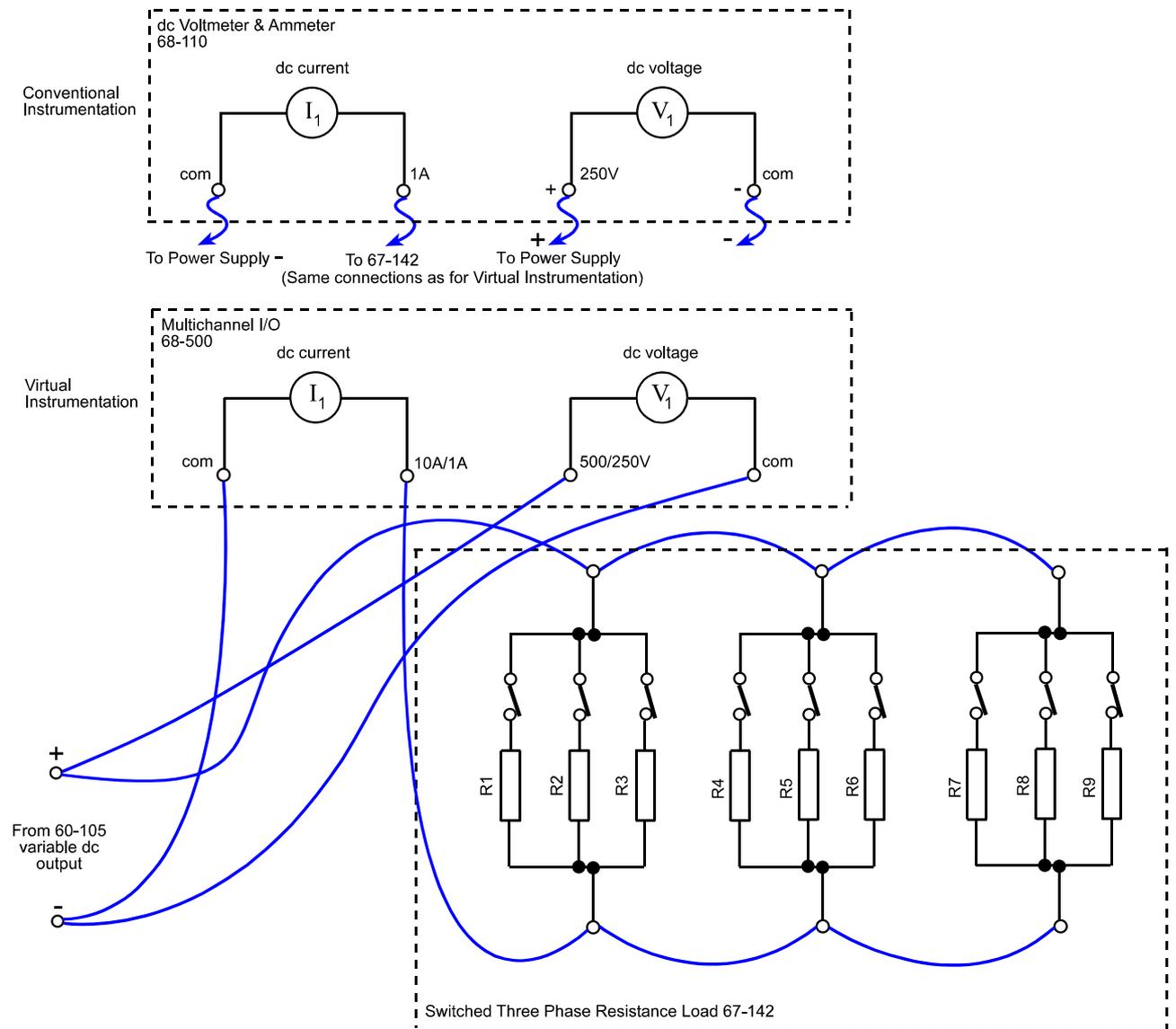
Product Version	
230 V	120 V
500 V dc	
182 Ω	
100 V dc	



On the Universal Power Supply 60-105, switch off the '*3 phase circuit breaker*' without altering the position of the '*variable output voltage*' control and disconnect virtual or conventional instrumentation.



**Figure 3-2-1: Practical 2.1 Circuit Diagram – First Configuration**



**Figure 3-2-2: Practical 2.1 Circuit Diagram – Second Configuration**

### 2.6.1 Questions

*Question 2.1 How do the first and second current readings compare?*

Because there is a potential difference across the circuit and the circuit is a complete loop, a current will flow through both the resistor and the virtual or conventional ammeter.

It doesn't matter where in the loop (circuit) you connect the ammeter, the same current will be indicated.

Currents are said to flow **through** components and **round** circuits.



## **2.7 Practical 2.2 - Voltage Measurement**

On the Universal Power Supply 60-105, ensure the '*3 phase circuit breaker*' is switched off.

Make all connections shown in Figure 3-2-3. Ensure that the positive (500 V/250 V) side of the virtual or conventional voltmeter is connected to the positive side of the supply.

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows up to 250 V to be monitored when the '500 V/250 V' socket is connected.

Switch on the power supply 60-105 without altering the position of the '*variable output voltage*' control and measure and record on your copy of the Results Table the voltage across the circuit (in the third reading column) on the virtual or conventional voltmeter.

Switch off the power supply 60-105 without altering the position of the '*variable output voltage*' control.

Make all connections shown in Figure 3-2-4. Ensure that the positive side of the virtual or conventional voltmeter and ammeter are connected to the positive side of the supply.

Switch on the power supply unit 60-105 without altering the position of the dial and measure and record on your copy of the Results Table, the voltage across the circuit (in the fourth reading column) on the virtual or conventional voltmeter, and the current flowing in the circuit (in the fifth reading column) on the virtual or conventional ammeter.

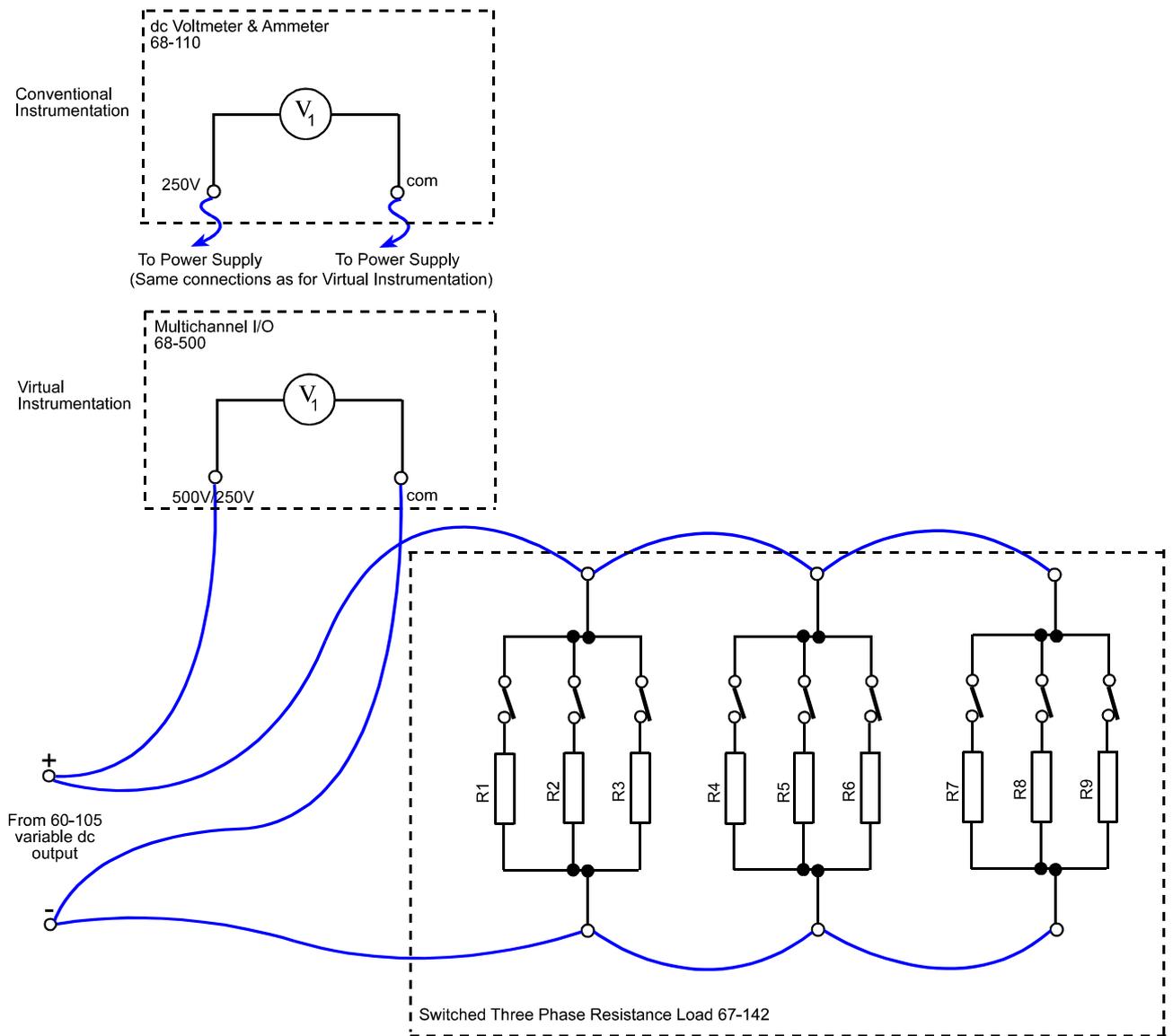
Switch off the power supply 60-105 without altering the position of the '*variable output voltage*' control and disconnect the virtual or conventional ammeter.

Make all connections shown in Figure 3-2-5. Ensure that the positive (500 V/250 V) side of the virtual or conventional voltmeter is connected to the positive side of the supply and the positive side (10 A/1 A) side of the virtual or conventional ammeter is connected to the resistive load.

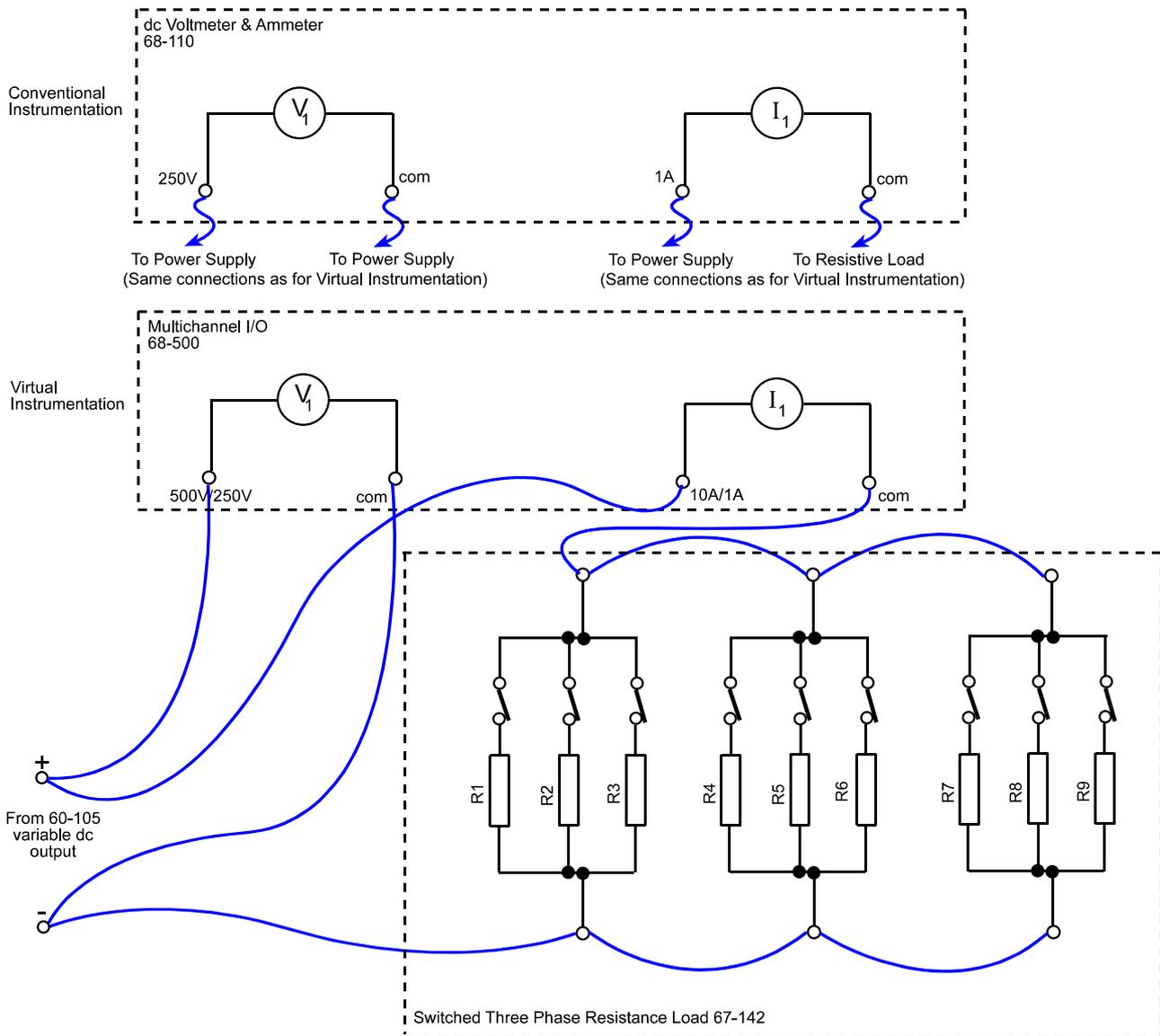
Switch on the power supply unit 60-105 without altering the position of the dial and measure and record on your copy of the Results Table, the voltage across the circuit (in the sixth reading column) on the virtual or conventional voltmeter, and the current flowing in the circuit (in the seventh reading column) on the virtual or conventional ammeter.

Turn the '*variable output voltage*' control to 0% on the Universal Power Supply 60-105 and then switch off the '*3 phase circuit breaker*'.

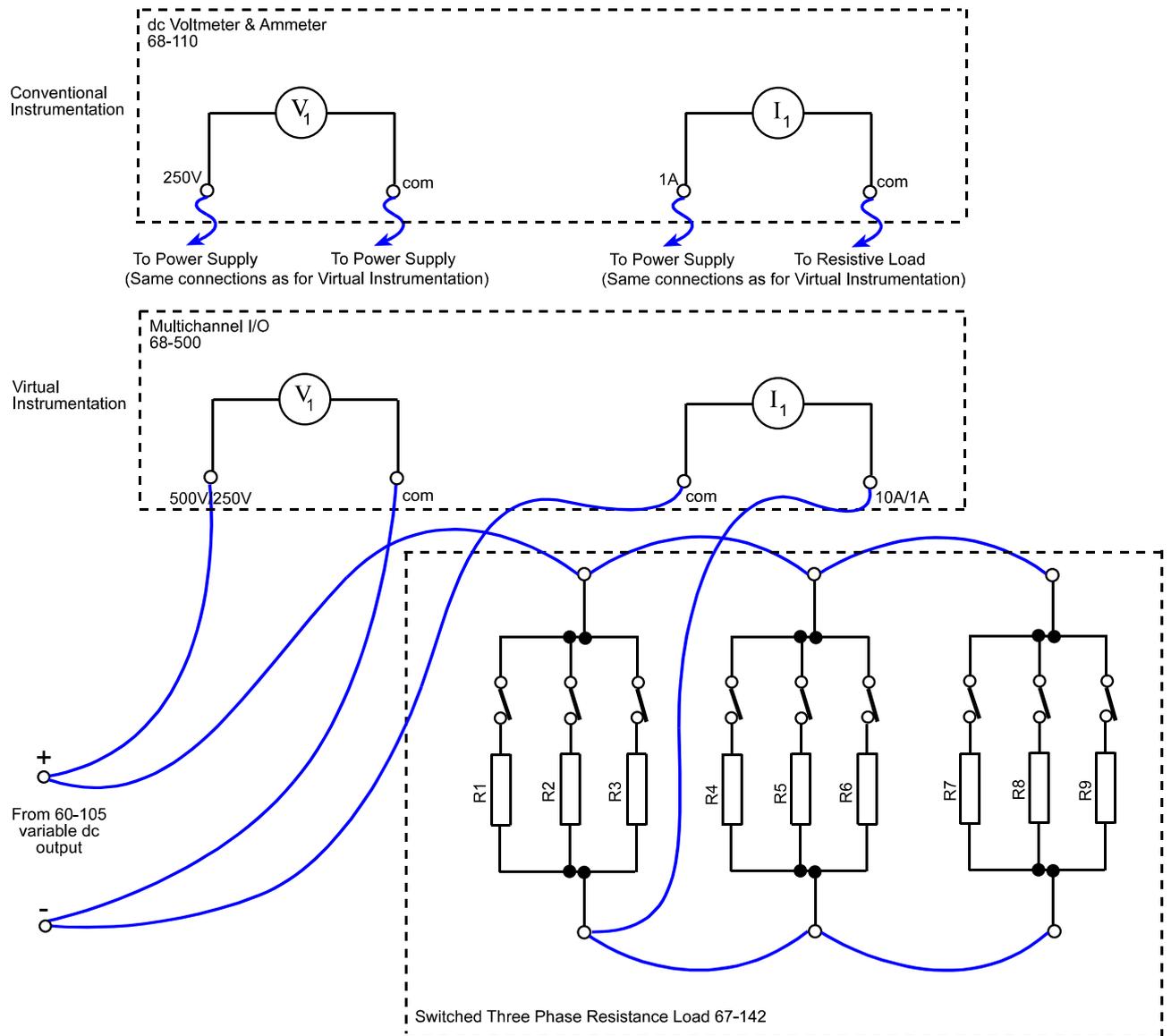
Disconnect all test equipment.



**Figure 3-2-3: Practical 2.2 Circuit Diagram – First Configuration**



**Figure 3-2-4: Practical 2.2 Circuit Diagram – Second Configuration**



**Figure 3-2-5: Practical 2.2 Circuit Diagram – Third Configuration**



### **2.7.1 Questions**

Question 2.2                      *How do the three current readings compare?*

Question 2.3                      *How do the three voltage readings compare?*

Again, a current will flow through round the circuit but this time the voltage across the circuit is also being monitored.

It does not matter where in the loop (circuit) you connect the ammeter, because the same voltage and the same current will be indicated.

Voltages are said to be present **across** components and circuits.

### **2.8 Practical Aspects**

Knowing the basic principles, we will now put these concepts of voltage and current to work as we consider dc and ac electricity in the assignments that follow.



**2.9 Practical 2.1 and 2.2 - Results Table (230 V Product Version)**

<b>Instrumentation Reading</b>	<b>1<sup>st</sup></b>	<b>2<sup>nd</sup></b>	<b>3<sup>rd</sup></b>	<b>4<sup>th</sup></b>	<b>5<sup>th</sup></b>	<b>6<sup>th</sup></b>	<b>7<sup>th</sup></b>
<b>Voltage (V)</b>	X	X					
<b>Current (mA)</b>			X	X			



**2.10 Practical 2.1 and 2.2 - Results Table (120 V Product Version)**

<b>Instrumentation Reading</b>	<b>1<sup>st</sup></b>	<b>2<sup>nd</sup></b>	<b>3<sup>rd</sup></b>	<b>4<sup>th</sup></b>	<b>5<sup>th</sup></b>	<b>6<sup>th</sup></b>	<b>7<sup>th</sup></b>
<b>Voltage (V)</b>	X	X					
<b>Current (mA)</b>			X	X			



## **3 Resistance and Ohm's Law**

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### **3.1 Assignment Information**

#### **3.1.1 Objectives**

When you have completed this assignment you will:

- have explored the idea of the resistance of a component and be able to use Ohm's Law.

#### **3.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignments 1 and 2
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **3.1.3 Practicals**

1. Effect of Resistance
2. Resistance, Voltage and Current Relationship

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters are specific to an appropriate trainer version they are given within a practical, and appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.

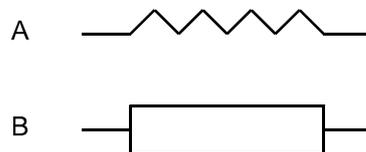


## 3.2 Theory

### 3.2.1 Introduction

Every conductor possesses some resistance. Some conductors like connecting wires, are chosen to have the lowest possible resistance. Other conductors are deliberately constructed to have particular values of resistance; a component whose essential property is its resistance is called a 'resistor'.

Figure 3-3-1 shows symbols used to denote a resistor in circuit diagrams. Symbol A is becoming outdated and symbol B is the preferred style.

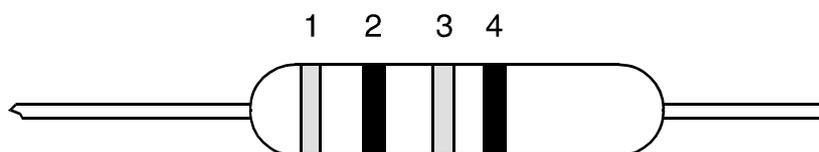


**Figure 3-3-1 Circuit symbol for a resistor**

Resistors are used in all types of electrical circuit to control the current flow in various parts of the circuit.

Electrical energy is converted into heat in a resistor (see Assignment 6), thus the design of a resistor for a particular purpose must take into account both the value of resistance required and also the amount of heat that will be generated in the resistor, in order that the temperature of the resistor does not exceed a safe value.

Most fixed resistors (except certain high wattage or high precision types) are coded by a set of coloured bands as shown in Figure 3-3-2.



**Figure 3-3-2**



The colours used and their meanings are shown in the table of Table 3-3-1.

<b>COLOUR</b>	<b>BAND 1</b> Value of 1st digit	<b>BAND 2</b> Value of 2nd digit	<b>BAND 3</b> Number of zeros	<b>BAND 4</b> Tolerance
BLACK	0	0	0	–
BROWN	1	1	1	–
RED	2	2	2	–
ORANGE	3	3	3	–
YELLOW	4	4	4	–
GREEN	5	5	5	–
BLUE	6	6	6	–
VIOLET	7	7	7	–
GREY	8	8	8	–
WHITE	9	9	9	–
GOLD	–	–	–	5%
SILVER	–	–	–	10%
NONE	–	–	–	20%

**Table 3-3-1**

As an example, if the bands of a resistor are coloured:

- 1 Yellow
- 2 Violet
- 3 Red
- 4 Gold

... the resistor is of value 4700 ohms (4.7 kΩ) and has a tolerance of 5%.

The unit of resistance, called the ohm, is named after the German physicist Georg Simon Ohm (1787–1854) who first investigated the relationship between voltage and current. One ohm is defined as the resistance between two points of a conductor when a potential difference of one volt between the points produces a current flow of one ampere.



### 3.2.2 Ohm's Law

Resistance is determined by the ratio of voltage to current. The relationship between voltage and current in a resistive circuit is known as Ohm's Law, and is one of the basic laws of electricity. At a constant temperature, the current (I) flowing through a conductor is directly proportional to the potential difference (V) applied across it. The constant of proportionality is the resistance (R). The formula for this law is:

$$\frac{\text{Voltage}}{\text{Current}} = \text{Resistance}$$
$$\frac{V \text{ (volts)}}{I \text{ (amperes)}} = R \text{ (ohms)}$$

This formula can be re-arranged to give two others: one for voltage and one for current in terms of the other variables. The triangle shown in Figure 3-3-3 is a handy way to remember these formulae.

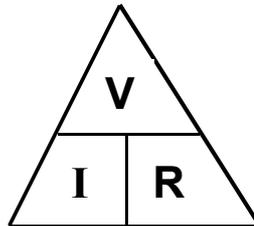


Figure 3-3-3

To use the triangle, just put your finger over the term that you wish to find and the formula for that term is given by how the two remaining ones are shown.

For example: if you want to know the formula for volts, put your finger over the 'V' and you are left with 'I' and 'R' at the bottom - signifying that you multiply these two together.

This gives  $V = I \times R$ . See Figure 3-3-4.

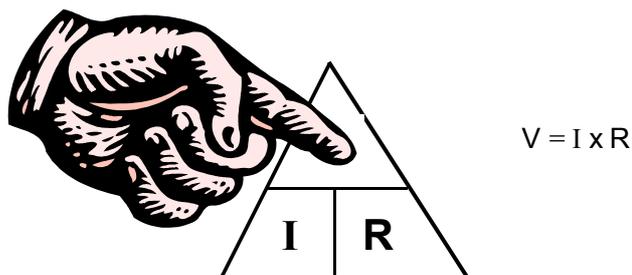


Figure 3-3-4



### 3.3 Content

The practicals in this assignment familiarise the student with the concept of resistance in an electric circuit and its relationship with current and voltage.

### 3.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation	dc Voltmeter & Ammeter (Option CI1)	68-110

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 3.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



**3.6 Practical 3.1 - Effect of Resistance**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-3-5.

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase resistance load 67-142, set all the banks of switches to the on position so that the resistance in circuit is.....

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

By use of the 'variable output voltage' control, set the power supply output to ..... (as read by virtual or conventional instrumentation). This voltage is applied to the switched three phase resistance load 67-142.

Record the voltage on a copy of the appropriate Practical 3.1, Results Table (230 V or 120 V product version)

Measure and record on your copy of Practical 3.1, Results Table, the current flowing in the circuit as read by the virtual or conventional ammeter for a resistive load of.....

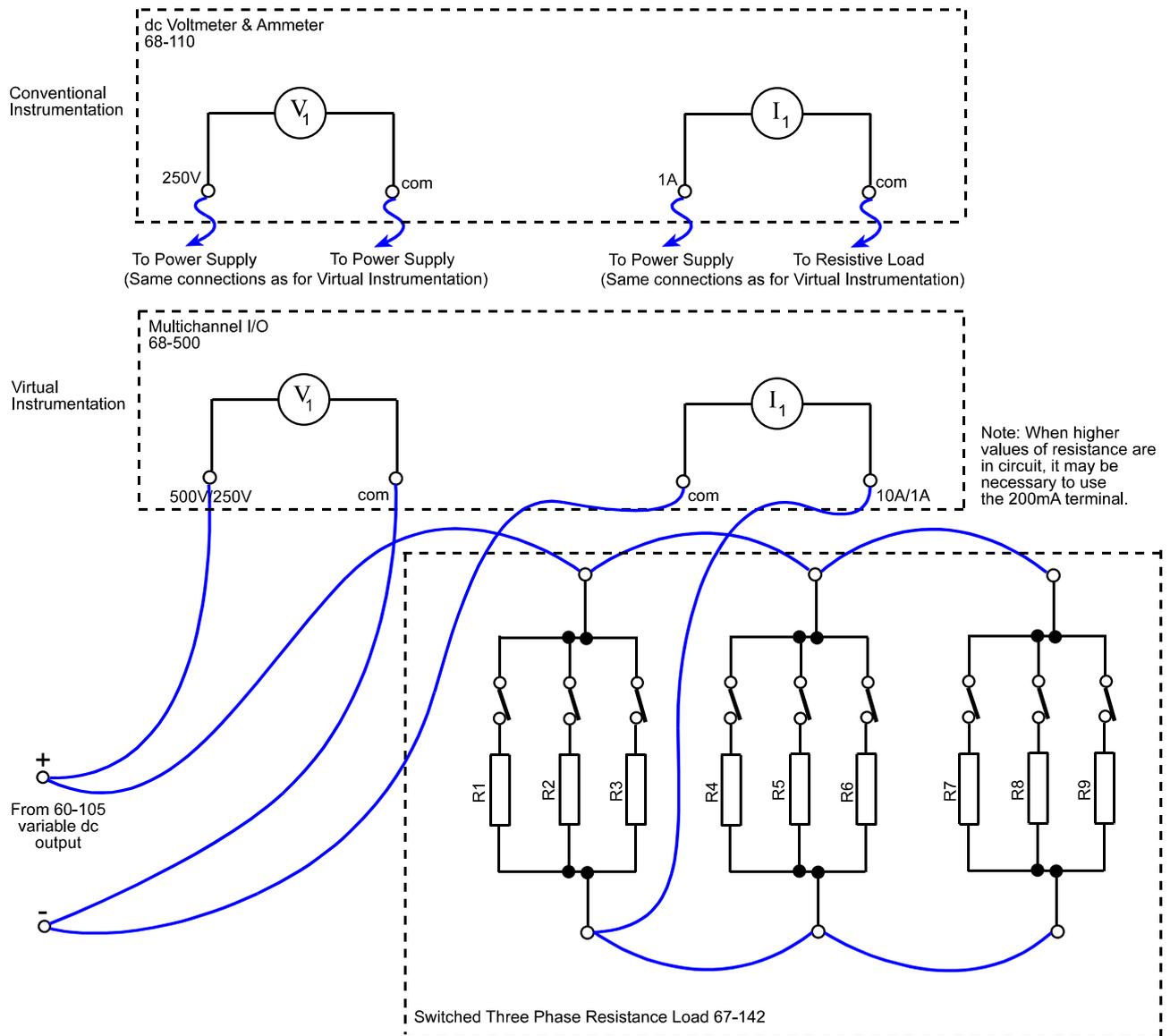
On the Universal Power Supply 60-105, switch off the '3 phase circuit breaker' without altering the position of the 'variable output voltage' control.

On the switched three phase resistance load 67-142, set switch 1 (upper) in each bank to 'off' and all other switches (middle and lower) to the on position so that the resistance in circuit is.....

Product Version	
230 V	120 V
182 Ω	
100 V dc	
182 Ω	
428 Ω	

**NOTE:**

For larger values of resistance, it might be necessary when using the virtual instrumentation to connect the ammeter via its 200 mA socket.



**Figure 3-3-5: Practical 3.1 Circuit Diagram**



Product Version	
230 V	120 V
On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.	
428 Ω	
On the Universal Power Supply 60-105, switch off the '3 phase circuit breaker' without altering the position of the 'variable output voltage' control.	
1257 Ω	
On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.	
1257 Ω	

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.

Measure and record on your copy of Practical 3.1, Results Table, the current flowing in the circuit as read by the virtual or conventional ammeter for a resistive load of.....

On the Universal Power Supply 60-105, switch off the '3 phase circuit breaker' without altering the position of the 'variable output voltage' control.

On the switched three phase resistance load 67-142, set switches 1 and 2 (upper and middle) in each bank to 'off' and all other switches (lower) to the on position so that the resistance in circuit is.....

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.

Measure and record on your copy of Practical 3.1, Results Table, the current flowing in the circuit as read by the virtual or conventional ammeter for a resistive load of.....

On the Universal Power Supply 60-105, switch off the '3 phase circuit breaker' without altering the position of the 'variable output voltage' control.

From observation of the results in your copy of Practical 3.1, Results Table, it can be seen that as the resistance in the circuit increases, the current decreases provided the supply voltage remains constant. In the next practical, the relationship between the value of a resistor, the voltage applied to it and the current flow is examined further.



**3.7 Practical 3.2 – Resistance, Voltage and Current Relationship**

It has been shown how the current changes for a change of resistance when a fixed voltage is applied; now let us see if there is any recognisable relationship between current and voltage for each of the resistances in turn.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-3-6.

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase resistance load 67-142, set all the banks of switches to the on position so that the resistance in circuit is.....

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

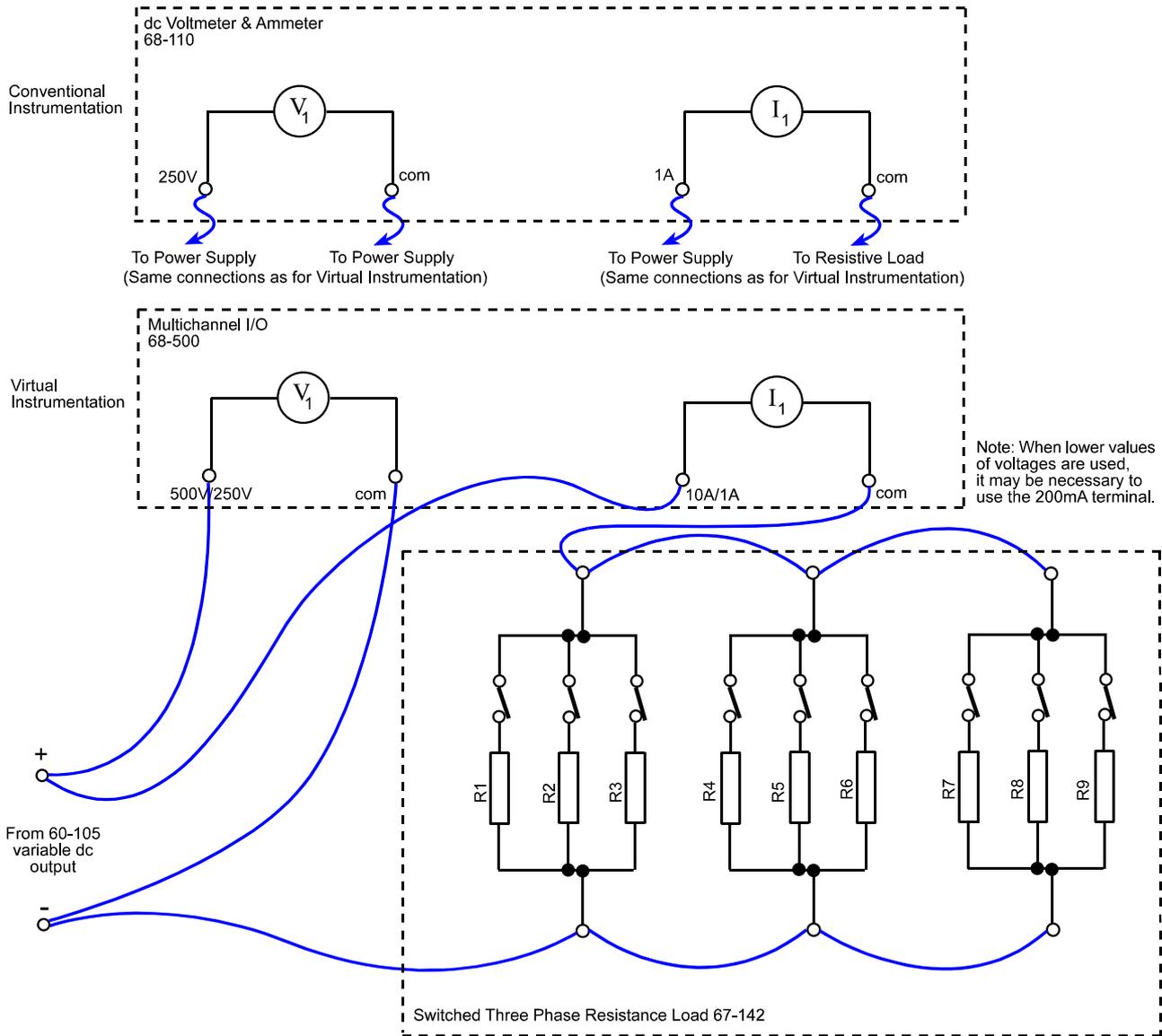
By use of the 'variable output voltage' control, increase the power supply voltage output from 0 V to ..... (as read by virtual or conventional instrumentation). This voltage is applied to the switched three phase resistance load 67-142.

At each step, measure the current flowing in the ..... load, as shown on the virtual or conventional ammeter. Record all results in the appropriate load column of a copy of Practical 3.2, Results Table (230 V or 120 V product version).

Product Version	
230 V	120 V
182 Ω	
100 V dc in 10V dc steps	
182 Ω	

**NOTE:**

For lower values of voltage (eg, 0–30 V), it might be necessary to connect the ammeter via its 200 mA socket when using the virtual instrumentation.



**Figure 3-3-6: Practical 3.2 Circuit Diagram**



Product Version	
230 V	120 V

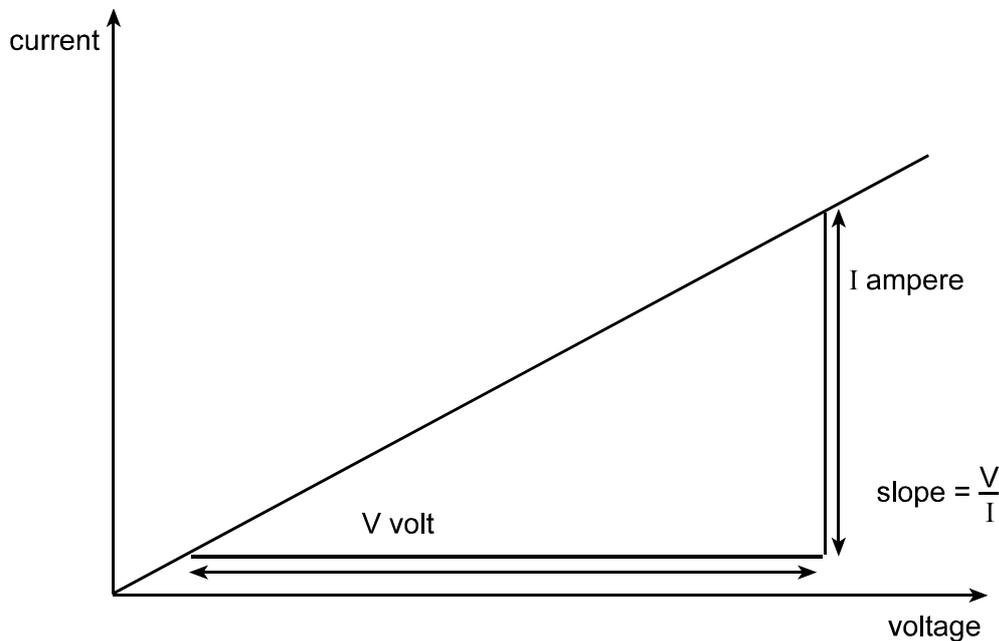
**3.7.1 Exercise 3.1**

Using the results obtained in Practical 3.2 Results Table, plot a graph of applied voltage (V) against current flow (I) using a copy of the axis shown in the Results Tables section for Exercise 3.1 at the end of this assignment.

*Question 3.1 - What is the shape of the graph you obtain?*

*Question 3.2 - With this shape of graph, can you come to any conclusions as to the relationship between current and resistance?*

Calculate the slope of the graph as outlined in Figure 3-3-7.



**Figure 3-3-7**

On the Universal Power Supply 60-105 , turn the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.

On the switched three phase resistance load 67-142, set switch 1 (upper) in each bank to 'off' and all other switches (middle and lower) to the on position so that the resistance in circuit is.....

Product Version	
230 V	120 V

428 Ω	
-------	--



Product Version	
230 V	120 V
On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.	
100 V dc in 10V dc steps	
428 Ω	
On the Universal Power Supply 60-105, turn the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.	
1257 Ω	
On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.	
100 V dc in 10V dc steps	
1257 Ω	

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

By use of the 'variable output voltage' control, increase the power supply voltage output from 0 V to ..... (as read by virtual or conventional instrumentation). This voltage is applied to the switched three phase resistance load 67-142.

At each step, measure the current flowing in the ..... load, as shown on the virtual or conventional ammeter. Record all results in the appropriate load column of your copy of Practical 3.2, Results Table.

On the Universal Power Supply 60-105, turn the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.

On the switched three phase resistance load 67-142, set switch 1 (upper) in each bank to 'off' and all other switches (middle and lower) to the on position so that the resistance in circuit is.....

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

By use of the 'variable output voltage' control, increase the power supply voltage output from 0 V to ..... (as read by virtual or conventional instrumentation). This voltage is applied to the switched three phase resistance load 67-142.

At each step, measure the current flowing in the ..... load, as shown on the virtual or conventional ammeter. Record all results in the appropriate load column of your copy of Practical 3.2, Results Table.

On the Universal Power Supply 60-105, turn the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.

### 3.7.2 Exercise 3.2

Using the results obtained in your copy of Practical 3.2 Results Table, plot a graph of applied voltage (V) against current flow (I) using another copy of the axis shown in the Results Tables section for Exercise 3.1 at the end of this assignment.

*Question 3.3 - Is the graph the same shape as before?*



*Question 3.4 - What is the slope of this second graph?*

*Question 3.5 - Remembering what was said at the beginning of this practical, is there any relationship between the relative slopes of the graphs of the two resistive loads and their values? If so, what is this relationship?*

*Question 3.6 - Do you think that the ratio of voltage to current in a resistor, at dc, could be used as a measure of its resistance?*

### **3.8 Notation for Resistance**

The symbol for the ohm is the Greek letter  $\Omega$  which is prefixed with a standard decimal multiplier symbol when necessary.

eg, 1200 ohms  $\equiv$  1.2 k $\Omega$

An alternative notation, commonly used in circuit diagrams, is to replace the decimal point with the decimal multiplier, and omit the  $\Omega$  symbol.

eg, 1.2 k $\Omega$   $\equiv$  1k2

Using this method, the capital letter R replaces the decimal point when no decimal multiplier is required.

eg, 4.7 ohms  $\equiv$  4R7

*Question 3.7 How would the value of a 470 ohm resistor be written using this notation?*

Now look up 'electric resistance' in Appendix A.2, at the end of the handbook, and confirm that the definition given there agrees with what you have found by experiment.



### 3.9 Practical Aspects

Resistors can be made of many materials, but materials which permit high values to be obtained in components of small physical size are normally used. Perhaps the most common materials are high-resistivity wire (ie, wire that has a high resistance for a short length of it) and carbon, or mixtures containing carbon.

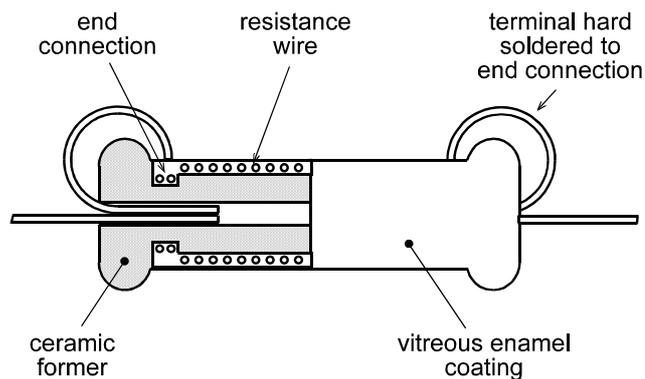


Figure 3-3-8

The construction of a typical wire-wound resistor is shown in Figure 3-3-8.

Normally the resistance wire consists of either nickel-chromium, nickel-copper or any other similar alloy which has high resistance per unit length and small resistance change with change of temperature. The wire is wound on a ceramic former and is welded to end connections of similar alloy to itself. Each end connection is bound securely in a groove at each end of the former.

For ease of use, tinned copper strips or wire terminals, are hard-soldered to the end connections. A folded portion of the terminal is forced into a central hole in the former, the terminals being thus secured directly to the former so that no mechanical stress can be transmitted to the resistance element by movement of the terminals.

Vitreous enamel is applied evenly to the former and fused at red heat, this flows evenly between the turns of wire forming a moisture-proof protective covering with good insulating properties. The vitreous enamel provides chemical and mechanical protection and enables very fine resistance wire to be used.

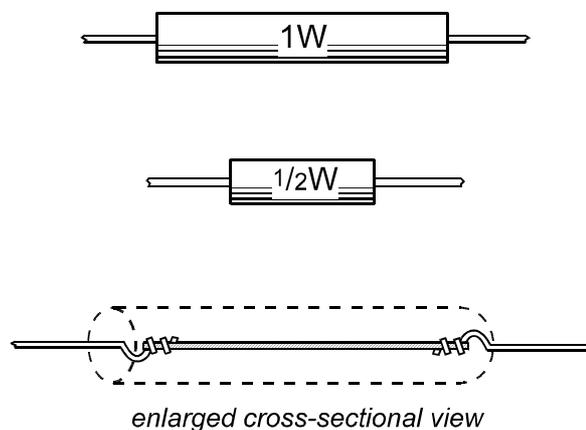


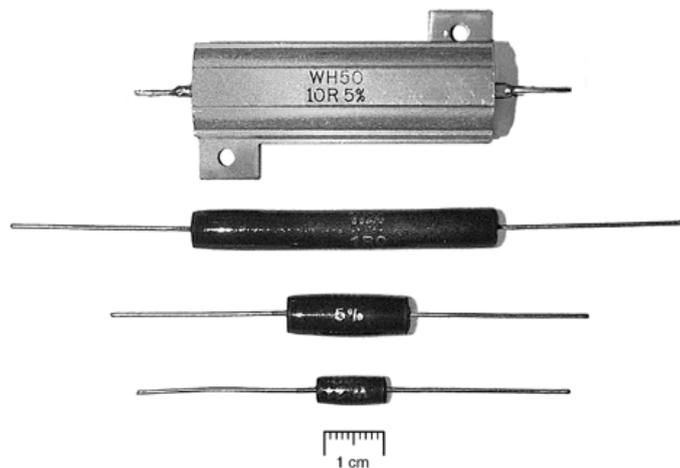
Figure 3-3-9



Another type of wire-wound resistor (low-wattage) is shown in Figure 3-3-9. It consists of a nickel-copper, or nickel-chromium resistance element to which are hard soldered two short lengths of copper wire which form end connections. The element is completely enclosed in a cylindrical layer of china-clay or some similar ceramic material which protects the winding against damage.

The desired properties of material to be used for the resistive element of a wire-wound resistor are as follows:

- a) High resistivity, to permit the required resistance to be obtained in a small volume.
- b) The resistance materials should have a melting point ranging from 1000°C to 1400°C; ie, well above the operating temperature.
- c) Low temperature coefficient of resistance to minimise the increase of resistance with increase of temperature.
- d) The wire should be ductile to avoid strains and cracks when wound around formers of small diameter.
- e) The diameter of the wire should not vary beyond certain close tolerances.
- f) Ability to be soldered or welded.



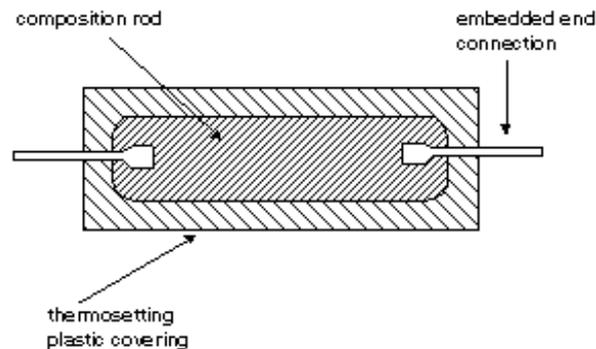
**Figure 3-3-10**

The majority of the resistors used in radio or television receivers, and generally in electronic circuits where resistance values are not critical, are made of a carbon composition. They are commonly referred to as 'carbon resistors', although this term does not include also carbon film resistors discussed later.

Carbon resistors are particularly liable to damage by excessive heat, and cannot be run at high temperatures. The most common wattage ratings available are low, therefore, being  $\frac{1}{8}$ ,  $\frac{1}{4}$ ,  $\frac{1}{2}$  or 1 watt, although it is possible to get carbon resistors with ratings in excess of 5 watts.



Composition resistors are very commonly used. Various manufacturers adopt different methods of construction, but the type shown in Figure 3-3-11 illustrates the general principle.

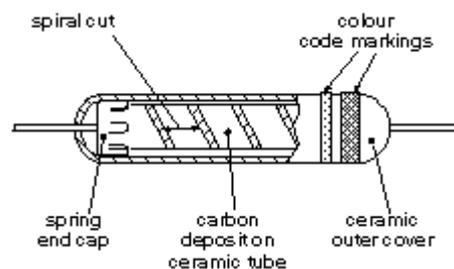


**Figure 3-3-11**

The composition resistor shown is usually described as the insulated type. The constituents of the resistance element are carbon black, a resin binder and a filling. These are first graded, then mixed in the required proportions, and sifted. The mix is compressed into the required shape and subjected to heat treatment which solidifies the unit. Connections are made to the resistor by moulding the enlarged ends of tinned copper wire directly into the carbon rod, or by one or two turns of tinned copper wire forming a tight band. Tests are carried out with automatic sorting of resistance values before marking with the standard colour code or resistance value on the outer insulating cover. A plastic insulation is moulded around the resistance element.

Other forms of construction use a ceramic material to insulate the resistance element.

There is a considerable need for resistors of better stability than that of carbon composition, since the resistance of a composition resistor can change considerably with temperature and age. Wire-wound resistors are not an adequate answer because of their cost, and the impossibility of making a wide range of values in compact form.



**Figure 3-3-12**

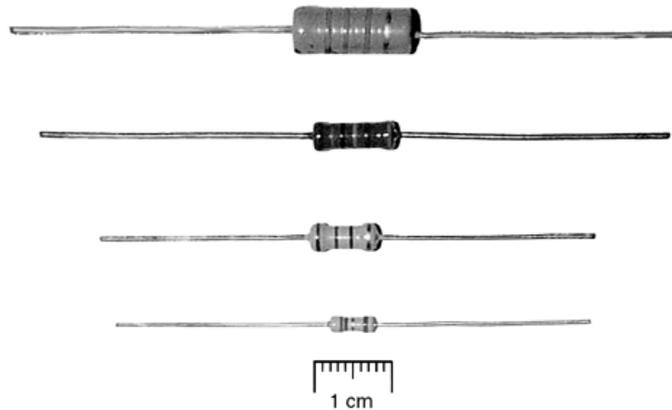
The gap is filled by a variety of film type resistors. Figure 3-3-12 shows the construction of a typical film resistor. The film itself is the resistive element, and is a surface coating on an insulating rod, usually of ceramic material. Various materials are used for the film. The earliest type in general use was the carbon film resistor. Carbon in crystalline form was formed by heat treatment on the rod. This, though appreciably more stable than carbon composition, is generally superseded nowadays by films of metal oxide, or if very high stability is required, by sputtered metal, which is slightly more expensive.



When the film, of whatever material, has been formed on the rod, a layer of conductive material may be applied at the ends to facilitate the making of a good electrical contact. A spiral cut in the film is then commonly used as a means of adjusting the resistance accurately to be desired value. Metal caps are then sprung on the ends of the rod to provide a rigid terminal with good electrical contact, to which the connecting wires are soldered. The resistance element is then provided with a protective outer cover; this may be a ceramic case as shown, although a dip-coating in a synthetic resin is becoming usual as the effectiveness of these resins improves. The complete resistor is marked in the standard colour code, or its resistance and tolerance are imprinted in figures.

The characteristics and performance of the composition and surface-film type resistors are:

- a) Small-power handling capacity when compared with wire-wound types, typical values being up to 2-watt, but rarely above 5-watt.
- b) The ability of a resistor to maintain its characteristics under storage or working conditions is called its stability, and is generally expressed in terms of the permanent change in resistance. For a one year storage period, the stability of composition types is about 5%, and that of the surface-film type about 0.5%. Under normal working conditions the stability of composition types is about 5% but may worsen to 25% under severe working conditions, while that of the surface-film type is 1% to 3%. The smaller the changes in characteristics the higher the stability.
- c) Very few composition type resistors are accurate to better than  $\pm 5\%$ . The usual graded tolerances are  $\pm 5\%$ ,  $\pm 10\%$ , and  $\pm 20\%$  of the nominal value. Surface-film type resistors are available with accuracy from 0.1% to 2% if required.
- d) For both types of resistor the maximum operating temperature is low. This is due to the fact that the thermal conductivity of carbon is low, thus the resistor is subjected to unequal heating with its body. For composition types, where this effect is most apparent, the maximum surface temperature is limited to approximately  $115^{\circ}\text{C}$ . For surface-film type resistors a maximum surface temperature of  $150^{\circ}\text{C}$  is usually specified.
- e) The variation of resistance with temperature for composition types is considerably higher than that of the surface-film type, mainly due to change in the structure of the binding agent.
- f) Humidity changes bring about an increase in resistance, but this effect is not permanent. The change in resistance of composition types is approximately seven times that of the surface-film type.
- g) When soldered into a circuit, the heat required during soldering, unless deflected from the resistance element, may permanently change the resistance value. Surface-film resistors are less prone to this effect than the composition type.



**Figure 3-3-13: Carbon Resistors**

The advantages of the carbon, or composition type resistors, shown in Figure 3-3-13, as compared with the wire-wound type are: low cost, small size, availability in a large range of values and negligible self-inductance. They do not require special mounting facilities as, owing to their small size and light weight, they are readily self-supporting and can be easily wired between solder tags, or to printed wiring conductors, etc.

Resistors are normally specified as a nominal value, and a tolerance about that value. To simplify manufacture, resistors are made to what are known as 'preferred values'. These are such that, when the spread of actual values within the tolerance limits is taken into account, the entire range of resistance required can be covered by manufacture of the minimum number of preferred values. See Table 3-3-2.

Preferred values	
10% tolerance	20% tolerance
10	10
12	
15	15
18	
22	22
27	
33	33
39	
47	47
56	
68	68
82	

**Table 3-3-2**



**3.10 Practical 3.1 - Results Tables (230 V Product Version)**

<b>Resistance (ohms)</b>	<b>182</b>	<b>428</b>	<b>1257</b>
<b>Current (A)</b>			
<b>Voltage (V)</b>			

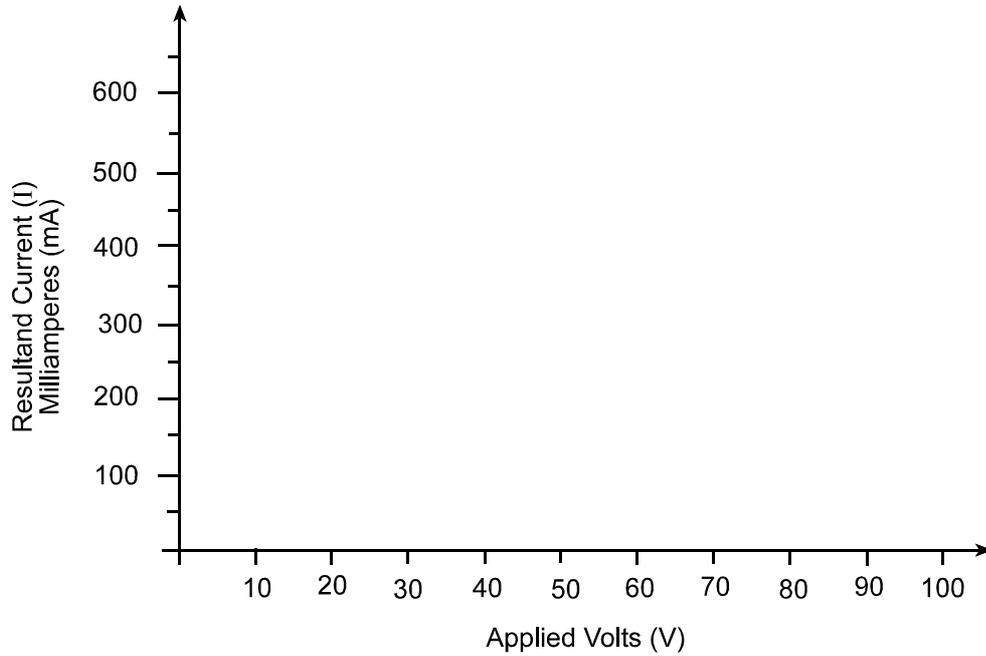
**3.11 Practical 3.2 - Results Tables (230 V Product Version)**

<b>Applied Volts (V)</b>	<b>Resultant Current (mA)</b>		
	<b>182 <math>\Omega</math> Load</b>	<b>428 <math>\Omega</math> Load</b>	<b>1257 <math>\Omega</math> Load</b>
0			
10			
20			
30			
40			
50			
60			
70			
80			
90			
100			



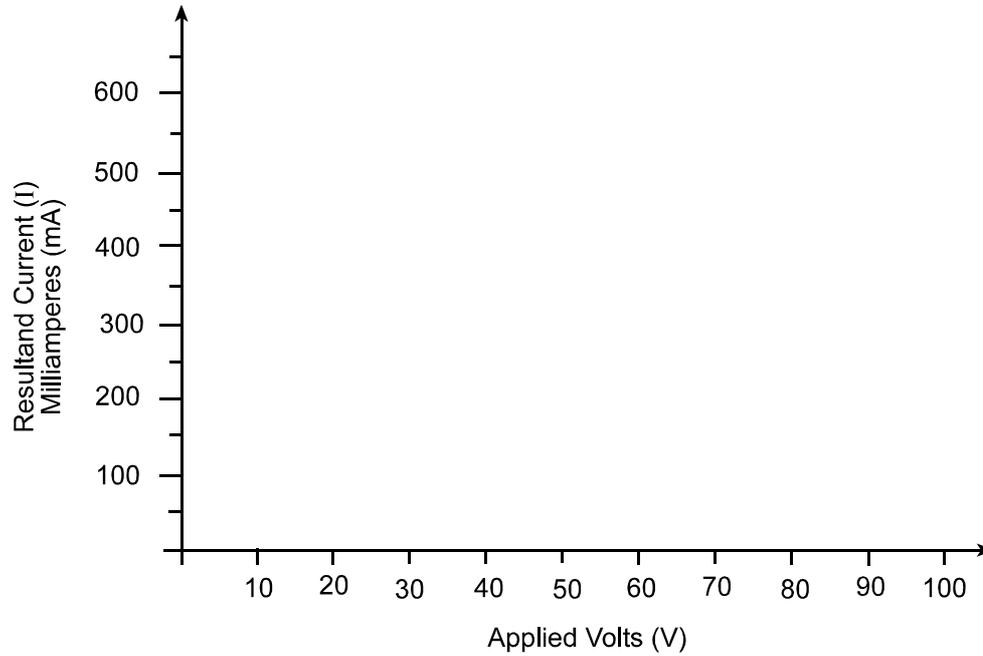


**3.14 Exercises 3.1 & 3.2 - Graph Axis (230 V Product Version)**





**3.15 Exercises 3.1 & 3.2 – Graph Axis (120 V Product Version)**





## **4 Resistors in Series and Parallel**

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### **4.1 Assignment Information**

#### **4.1.1 Objectives**

When you have completed this assignment you will:

- have investigated the connection of resistors in series and parallel in a circuit.

#### **4.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignments 1, 2 and 3.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **4.1.3 Practicals**

1. Resistors in Series,
2. Resistors in Parallel

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



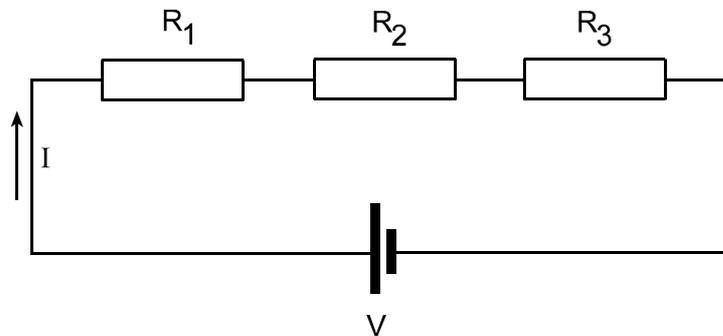
## 4.2 Theory

### 4.2.1 Introduction

In this assignment, circuits comprising resistors connected in series and parallel are considered.

### 4.2.2 Resistors in Series

As detailed in Assignment 3, current decreases as the resistance increases in a circuit (Ohm's Law). Since all the current in a series circuit must go through each element of the circuit, each resistive element will contribute to the total resistance to current flow in the circuit. It therefore follows that the total resistance in the circuit is the sum of individual resistances as shown in Figure 3-4-1.



**Figure 3-4-1: Resistors in Series**

In mathematical form:

$$V = IR_1 + IR_2 + IR_3$$

$$V = I(R_1 + R_2 + R_3)$$

$$V = IR_{\text{Total}}$$

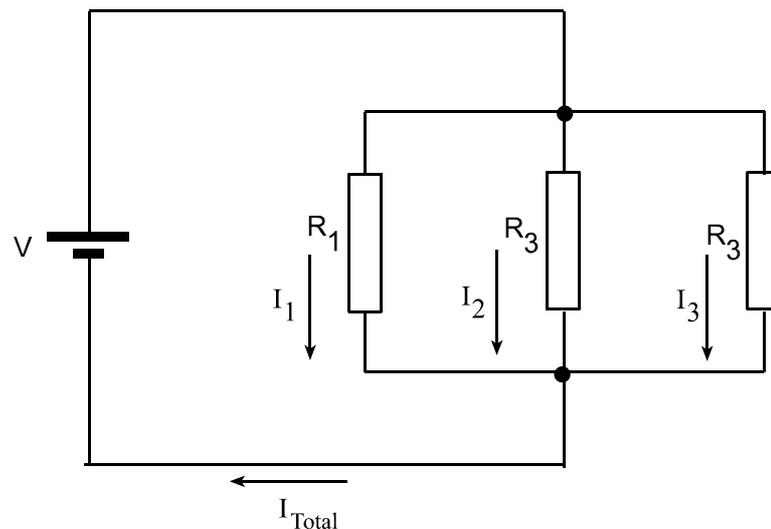
Therefore:

$$R_{\text{Total}} = R_1 + R_2 + R_3$$



### 4.2.3 Resistors in Parallel

Resistors in parallel means that their ends are connected by a conductor as shown in Figure 3-4-2, causing their ends to be at a common potential; that is, the same potential difference is across each of the resistors that are connected in parallel.



**Figure 3-4-2: Resistors in Parallel**

In mathematical form:

$$I_{\text{Total}} = I_1 + I_2 + I_3$$

$$\frac{V}{R_{\text{Total}}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\frac{1}{R_{\text{Total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$



### 4.3 Content

The practicals in this assignment familiarise the student with the parameters of a circuit when it has resistors connected in series or parallel.

### 4.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation	dc Voltmeter & Ammeter (Option C11)	68-110

#### NOTES:

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 4.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

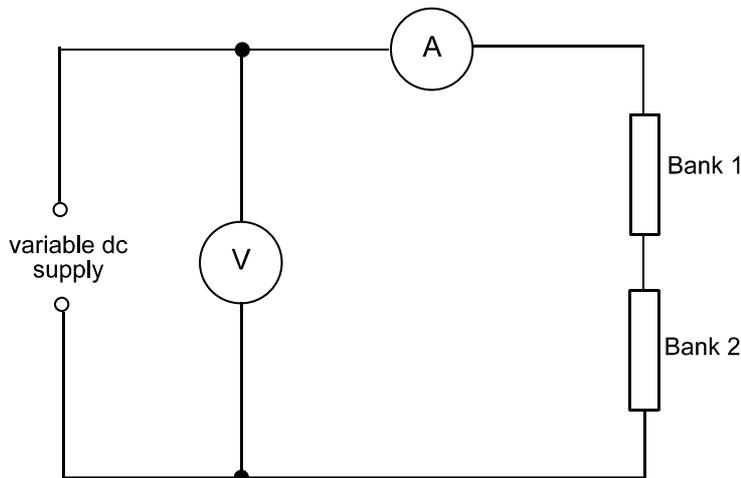
If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



**4.6 Practical 4.1 – Resistors in Series**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-4-4, which equates to the theoretical circuit shown in Figure 3-4-3.



**Figure 3-4-3: Theoretical Circuit**

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 200 mA to be monitored when the 200 mA socket is connected.

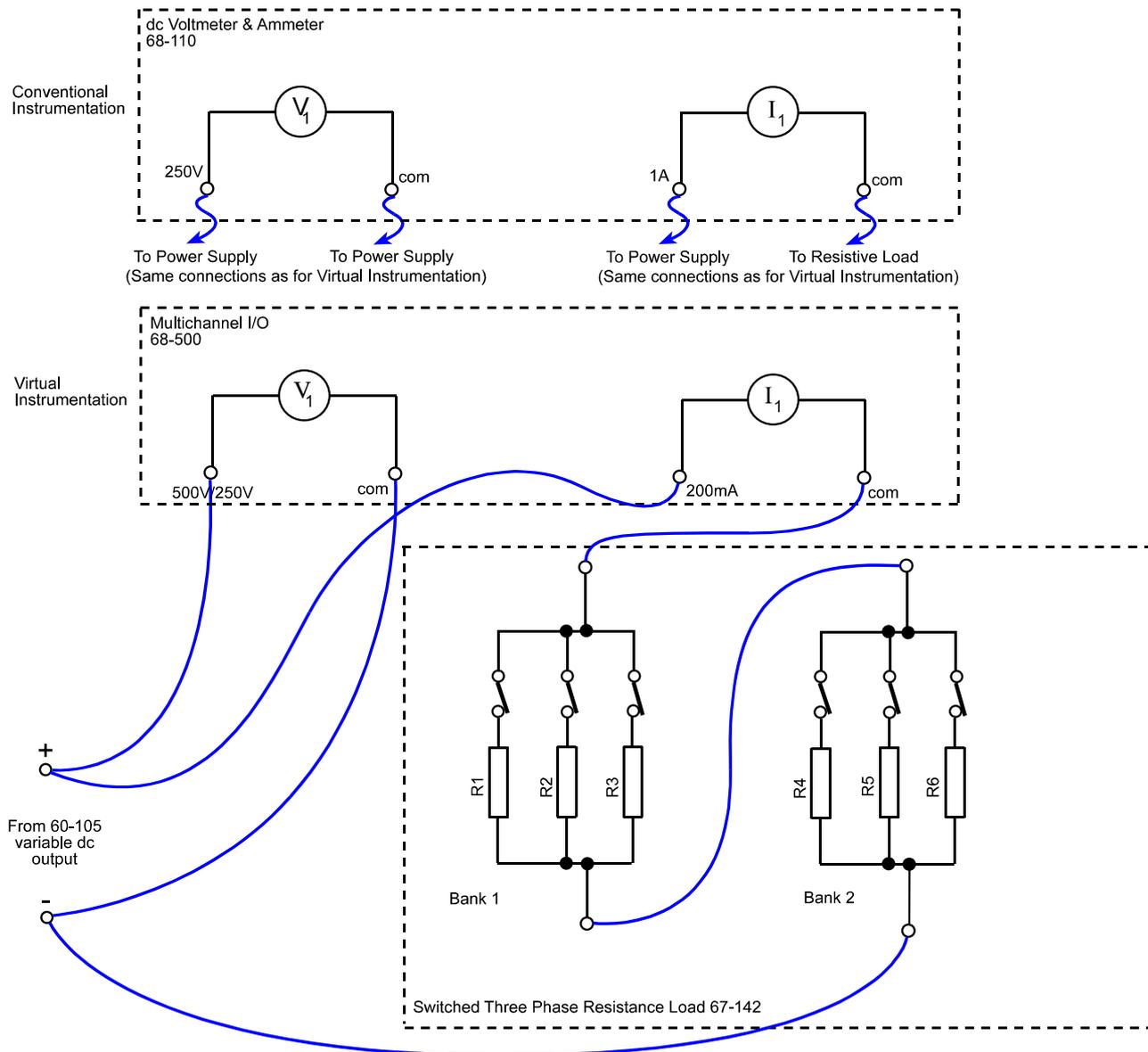
On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on providing a load of.....
- Bank 2 - switches 1 and 2 (upper and middle) set to on, switch 3 (lower) set to off providing a load of.....

Product Version	
230 V	120 V
546 Ω	
640 Ω	

**NOTE:**

Although each bank consists of three resistors in parallel, for the purpose of this practical it is assumed that each bank is a single resistor.



**Figure 3-4-4: Practical 4.1 Circuit Diagram**



On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Set the output voltage to.....  
 by use of the 'variable output voltage' control (as shown by virtual or conventional voltmeter  $V_1$ ).

Measure and record on a copy of the appropriate Practical 4.1, Results Table (230 V or 120 V product version), the current flowing through the circuit as shown on the virtual or conventional ammeter  $I_1$ .

On the Universal Power Supply 60-105, use the 'variable output voltage' control to increase the output voltage to.....

Measure and record on your copy of Practical 4.1, Results Table, the current now flowing in the circuit.

Repeat for current recordings for voltages of.....

Product Version	
230 V	120 V
50 V	
100 V dc	
150 V, 200 V & 220 V dc	

On your copy of Practical 4.1, Results Table, calculate and record the resistance from each voltage and current reading and then calculate the average resistance for the five readings.

*Question 4.1 - The value of  $R_1$  and  $R_2$  connected in series is thus ...ohms?*

Compare this value with the individual values of  $R_1$  and  $R_2$ .

*Question 4.2 - Can you see any connection between them?*

You should find that:

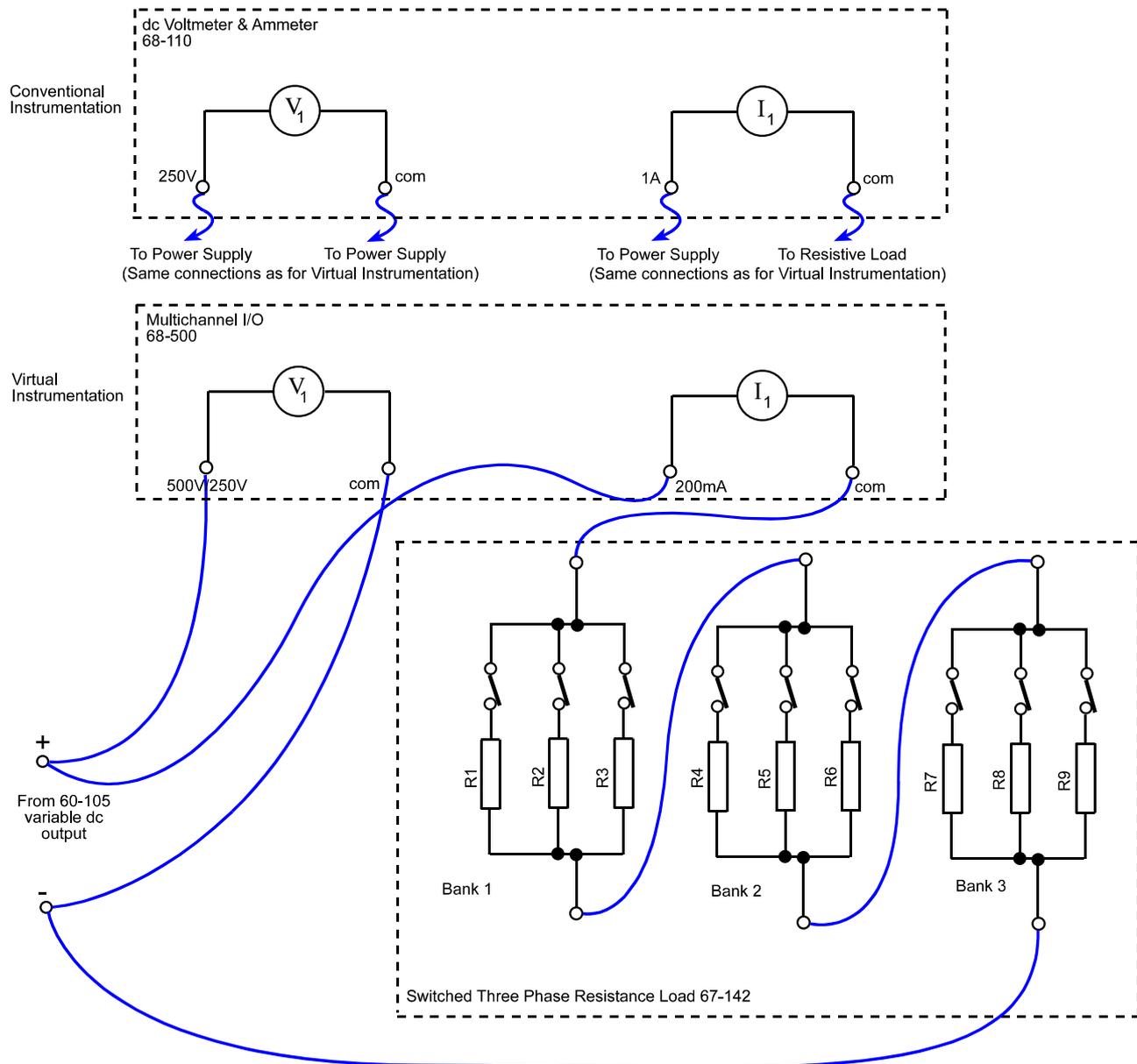
**The total resistance of the two in series is equal to the sum of the individual resistor values.**

$$\text{ie, } R_{\text{Total}} = R_1 + R_2$$

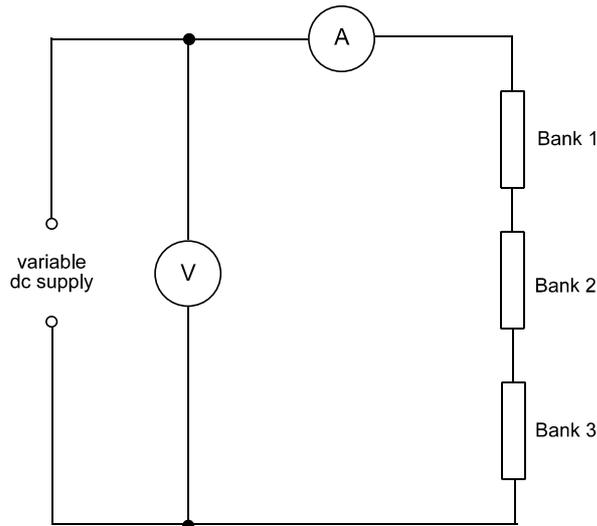
As this holds for two resistors, let us see if it holds for more than two.

Turn the 'variable output voltage' control to 0% on the Universal Power Supply 60-105 and then switch off the '3 phase circuit breaker'.

Reconfigure the series circuit as shown in Figure 3-4-5, which relates to the theoretical circuit shown in Figure 3-4-6.



**Figure 3-4-5: Practical 4.1 Circuit Diagram – Second Configuration**



**Figure 3-4-6: Theoretical Circuit**

Product Version	
230 V	120 V
546 Ω	
640 Ω	
759 Ω	
50 V, 100 V, 150 V, 200 V & 220 V dc	

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on providing a load of.....
- Bank 2 - switches 1 and 2 (upper and middle) set to on, switch 3 (lower) set to off providing a load of.....
- Bank 3 - switches 1 and 3 (upper and lower) set to on, switch 2 (middle) set to off providing a load of.....

Repeat the recording on your copy of Practical 4.1, Results Table of current readings for voltage settings of.....  
 for the new circuit, calculate and record resistance for each voltage setting, and then calculate and record the average value.

**Question 4.3**

*What is the value of resistance in ohms when  $R_1$ ,  $R_2$  and  $R_3$  are connected in series?*

**Question 4.4**

*Does the total resistance follow the same relationship as was found for two resistors?*

**Question 4.5**

*What does the total resistance  $R$  equal in terms of  $R_1$ ,  $R_2$  and  $R_3$ ? ie,  $R = ?$*

Next we will prove this theoretically using Ohm's Law and Kirchhoff's Laws.



With series connection of resistors, as in Figure 3-4-3, the same current must flow through each resistance. Let us call this current  $I$ .

From Ohm's Law, the voltage across  $R_1$ , ( $VR_1$ ), is given by:

$$VR_1 = IR_1 \quad (1)$$

similarly, the voltage across  $R_2$ , ( $VR_2$ ) is given by:

$$VR_2 = IR_2 \quad (2)$$

But by Kirchhoff's Law of voltage (see Assignment 5), the sum of the voltages around a circuit is zero, and with the power supply set to 100 V:

$$VR_1 + VR_2 - 100 = 0$$

$$\therefore VR_1 + VR_2 = 100 \quad (3)$$

If the total circuit resistance is called  $R$

$$\therefore IR = 100 \quad (4)$$

Therefore, combining (1), (2), (3) and (4), we get:

$$IR_1 + IR_2 = IR$$

or  $R_1 + R_2 = R$

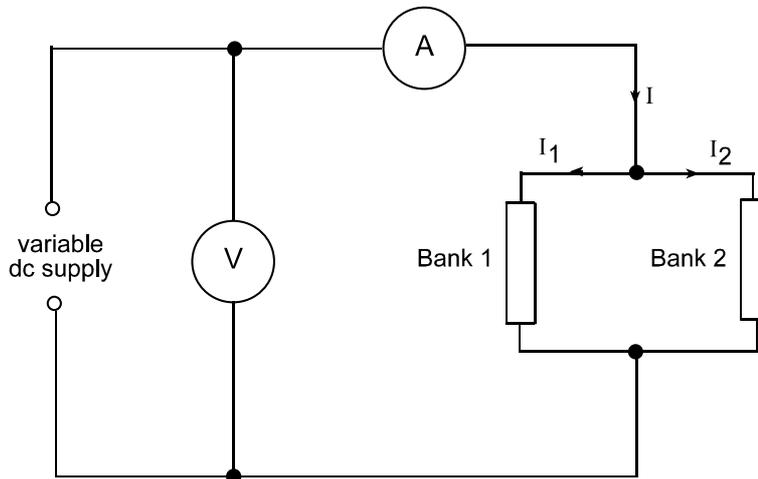
which agrees with the experiment.



**4.7 Practical 4.2 – Resistors in Parallel**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-4-8, which equates to the theoretical circuit shown in Figure 3-4-7.



**Figure 3-4-7: Theoretical Circuit**

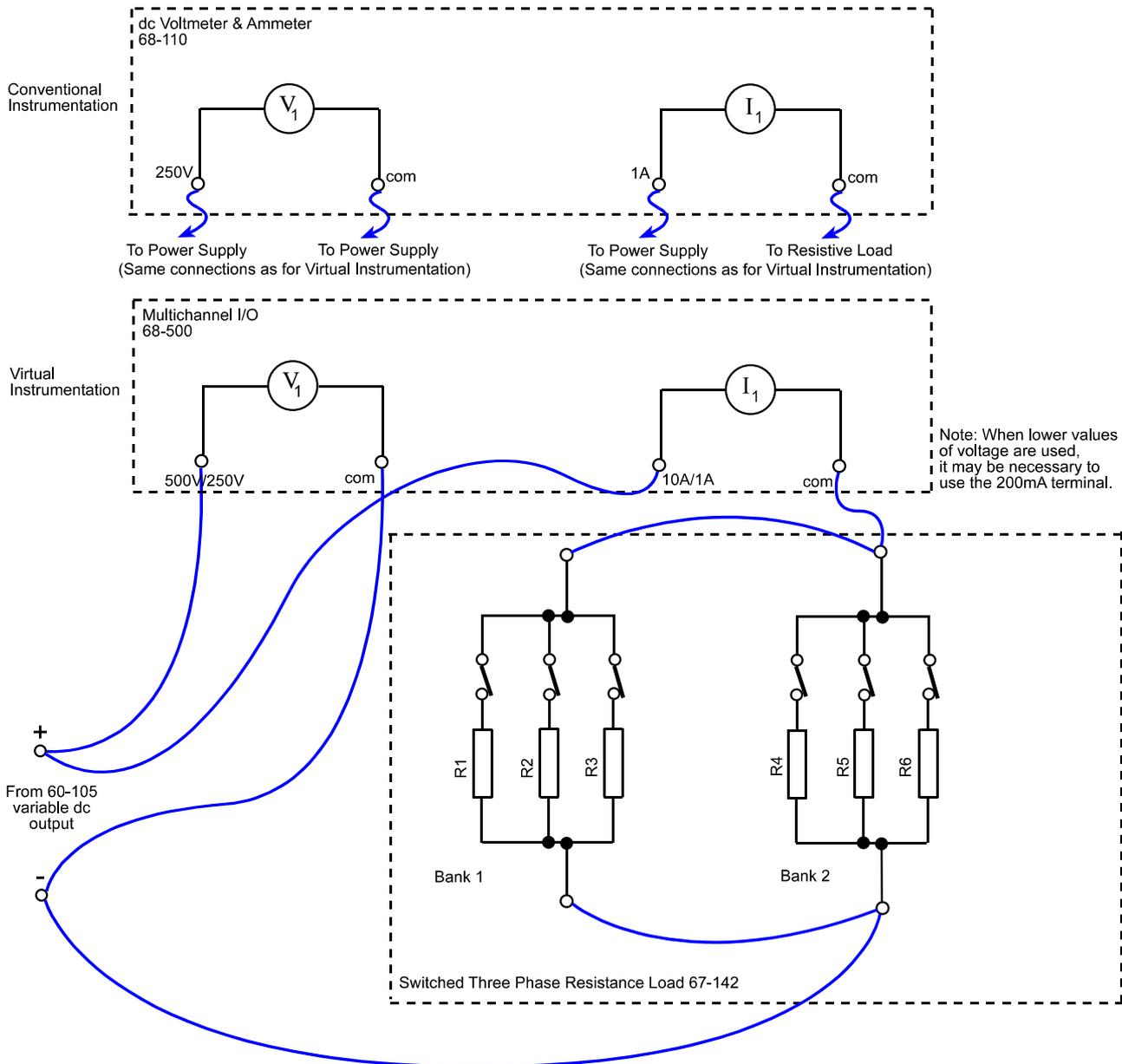
If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on providing a load of.....
- Bank 2 - switches 1 and 2 (upper and middle) set to on, switch 3 (lower) set to off providing a load of.....

Product Version	
230 V	120 V
546 Ω	
640 Ω	

**NOTE:**  
 Although each bank consists of three resistors in parallel, for the purpose of this practical it is assumed that each bank is a single resistor.



**Figure 3-4-8: Practical 4.2 Circuit Diagram**



On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Set the output voltage to.....  
 by use of the 'variable output voltage' control (as shown by virtual or conventional voltmeter  $V_1$ ).

Measure and record on a copy of the appropriate Practical 4.2, Results Table (230 V or 120 V product version), the current flowing through the circuit as shown on the virtual or conventional ammeter  $I_1$ .

On the Universal Power Supply 60-105, use the 'variable output voltage' control to increase the output voltage to.....

Measure and record on your copy of Practical 4.2, Results Table, the current now flowing in the circuit.

Repeat for current recordings for voltages of.....

Product Version	
230 V	120 V
50 V	
100 V dc	
150 V, 200 V & 220 V dc	

On your copy of Practical 4.2, Results Table, calculate and record the resistance from each voltage and current reading and then calculate the average resistance for the five readings.

*Question 4.6 - The value of  $R_1$  and  $R_2$  connected in parallel is thus .....ohms?*

*Question 4.7 - Is this value bigger or smaller than either  $R_1$  or  $R_2$ ?*

The relationship between  $R_1$ ,  $R_2$  and the total combined resistance  $R$  is not obvious, but again can be found simply by using Ohm's Law and, this time, Kirchhoff's Law of current (see Assignment 5).

Examining Figure 3-4-7 we can see that the voltage across both  $R_1$  and  $R_2$  is the same, (say) 100 V; however, the current  $I$  is split between the two resistors as shown.  $I_1$  flows through  $R_1$  and  $I_2$  through  $R_2$ .

Now, by Ohm's Law:

$$R_1 = \frac{100}{I_1} \quad \therefore I_1 = \frac{100}{R_1}$$



and  $R_2 = \frac{100}{I_2} \quad \therefore I_2 = \frac{100}{R_2}$

also  $R = \frac{100}{I} \quad \therefore I = \frac{100}{R}$

But, by Kirchhoff's Law of current:

$$I = I_1 + I_2$$

thus  $\frac{100}{R} = \frac{100}{R_1} + \frac{100}{R_2}$

Hence:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

**This is the relationship for parallel connected resistors.**

Calculate  $\frac{1}{R_1} + \frac{1}{R_2}$ , and then take the reciprocal.

*Question 4.8 - Does the calculated value agree with the measured value for the total resistance?*

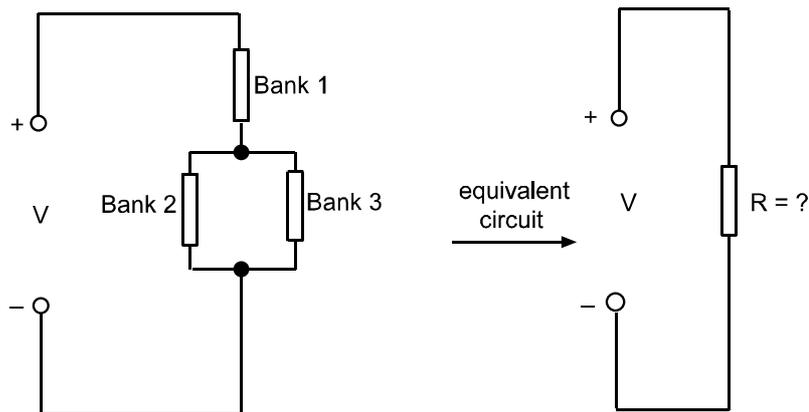
For more than two resistors in parallel, the formula for the total resistance becomes:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \dots\dots\dots + \frac{1}{R_n}$$



**4.7.1 Exercise 4.1**

For a network such as shown in Figure 3-4-9, calculate the total resistance  $R$  of the series-parallel combination (hint: calculate the parallel combination first).



**Figure 3-4-9**

**Question 4.9** *What is the total resistance of  $R$ ?*

With the power supply unit 60-105 switched off, make up the circuit shown in Figure 3-4-9. Wiring connections on the resistive load 67-142 for the parallel combination bank 2 and bank 3 are as shown in fig 3-4-8.

Connect bank 1 between the 'com' socket of I1 and the paralleled resistor banks 2 and 3. Use either virtual or conventional instrumentation to measure voltage and current.

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - switches 1 and 3 (upper and lower) set to on, switch 2 (middle) set to off providing a load of.....
- Bank 2 - switches 1 and 2 (upper and middle) set to on, switch 3 (lower) set to off providing a load of.....
- Bank 3 - all switches set to on providing a load of.....

Make measurements of the current at voltage settings of..... as before, and calculate the average value of resistance. Record all results on a copy of Exercise 4.1 Results Table.

		Product Version	
		230 V	120 V
759 $\Omega$			
640 $\Omega$			
546 $\Omega$			
50 V, 100 V, 150 V, 200 V & 220 V			



Question 4.10                      *The measured resistance was ..... ohms?*

Question 4.11                      *Does this agree with your calculations?*

An alternative way of writing the formula for **two** resistors in parallel is:

$$R = \frac{R_1 \cdot R_2}{R_1 + R_2} \text{ ie. } \frac{\text{product}}{\text{sum}}$$

This form is, perhaps, more convenient to use, as no reciprocals have to be calculated.

The proof for this formula is given below:

$$\begin{aligned} \frac{1}{R} &= \frac{1}{R_1} + \frac{1}{R_2} \\ &= \frac{R_1 + R_2}{R_1 \cdot R_2} \\ R &= \frac{R_1 \cdot R_2}{R_1 + R_2} \end{aligned}$$



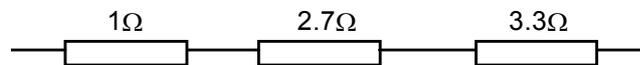
#### 4.8 Practical Aspects

The practical applications of the series and parallel calculations are innumerable. With nearly every circuit built there comes a time where the calculation of resistors in series or parallel is needed.

As an example, a meter shunt of 7 Ω may be needed for a 10 mA full scale deflection (fsd).

7 Ω is not a preferred value, and would have to be made specially. Let us assume that we have a range of 1% tolerance preferred value resistors. How can we make a 7 Ω resistor from these?

We could use resistors in series. There are preferred values of 1Ω, 2.7Ω and 3.3Ω.



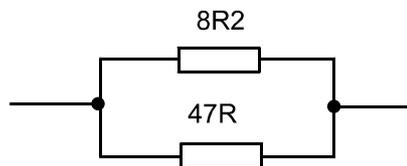
**Figure 3-4-10**

For resistors in series:

$$\begin{aligned} \text{Total resistance} &= R_1 + R_2 + R_3 \\ &= 1 \Omega + 2.7 \Omega + 3.3 \Omega \\ &= 7 \Omega \end{aligned}$$

As each of the resistors is ±1% tolerance, the total tolerance will also be ±1%.

We could use a parallel connection of resistors. A commonly used preferred value just above 7 Ω is 8.2 Ω, also 47 Ω is a preferred value.



**Figure 3-4-11**

For resistors in parallel

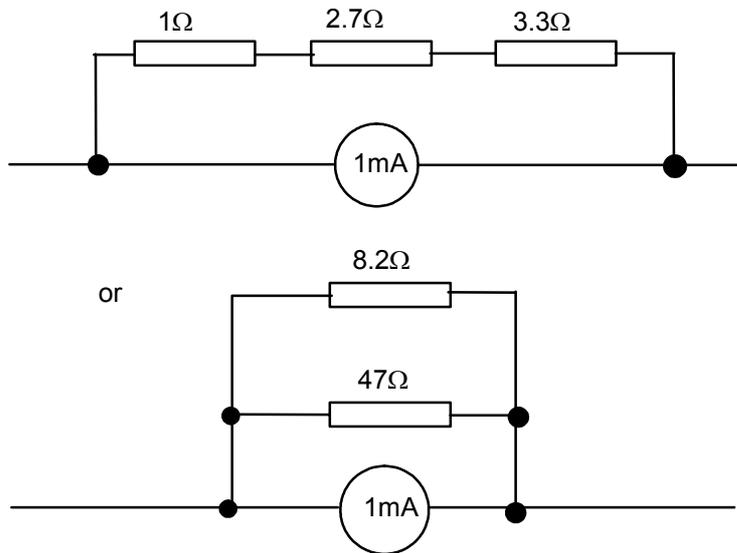
Total resistance

$$\begin{aligned} \frac{R_1 R_2}{R_1 + R_2} &= \frac{8.2 \times 47}{8.2 + 47} \\ &= \frac{385.4}{55.2} = 6.98 \Omega \end{aligned}$$

Which is well within the accuracy of the individual resistors.



Thus the shunt could be assembled either way, as in Figure 3-4-12.



**Figure 3-4-12**



**4.9 Practical 4.1 - Results Tables (230 V Product Version)**

<b>Resistors in Series</b>	<b>Voltage (V)</b>	<b>Current (mA)</b>	<b>Resistance (<math>\Omega</math>)</b>
$R_1 + R_2$ (546 + 640)	50		
	100		
	150		
	200		
	220		
		Average Value	
$R_1 + R_2 + R_3$ (546 + 640 + 759))	50		
	100		
	150		
	200		
	220		
		Average Value	



**4.10 Practical 4.1 - Results Tables (120 V Product Version)**

<b>Resistors in Series</b>	<b>Voltage (V)</b>	<b>Current (mA)</b>	<b>Resistance (<math>\Omega</math>)</b>
$R_1 + R_2$			
		Average Value	
$R_1 + R_2 + R_3$			
		Average Value	



**4.11 Practical 4.2 - Results Tables (230 V Product Version)**

Resistors in Parallel	Voltage (V)	Current (mA)	Resistance ( $\Omega$ )
$R_1/R_2$ (546//640)	50		
	100		
	150		
	200		
	220		
		Average Value	

**4.12 Exercise 4.1 - Results Table (230 V Product Version)**

Resistors Combination	Voltage (V)	Current (mA)	Resistance ( $\Omega$ )
$R_1 + (R_2/R_3)$ 759 + (640/546)	50		
	100		
	150		
	200		
	220		
		Average Value	



**4.13 Practical 4.2 - Results Tables (120 V Product Version)**

<b>Resistors in Parallel</b>	<b>Voltage (V)</b>	<b>Current (mA)</b>	<b>Resistance (<math>\Omega</math>)</b>
$R_1/R_2$			
		Average Value	

**4.14 Exercise 4.1 - Results Table (120 V Product Version)**

<b>Resistors Combination</b>	<b>Voltage (V)</b>	<b>Current (mA)</b>	<b>Resistance (<math>\Omega</math>)</b>
$R_1 + (R_2/R_3)$			
		Average Value	



## **5 Resistor Networks**

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### **5.1 Assignment Information**

#### **5.1.1 Objectives**

When you have completed this assignment you will:

- have investigated what happens when resistors are interconnected in a circuit.
- have applied Kirchhoff's current and voltage laws.

#### **5.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignments 1 to 4.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **5.1.3 Practicals**

Kirchhoff's Current and Voltage Law

#### **5.1.4 Exercise**

Kirchhoff's Voltage Law

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## 5.2 Theory

### 5.2.1 Introduction

In this assignment, the currents and voltages present when several resistors are connected together to form a resistor network are investigated using Kirchhoff's Laws.

Gustav Kirchhoff (1824–87) was a German physicist who proclaimed the following two laws:

**Kirchhoff's Current Law** (First Law): *If several conductors meet at a point, the total current flowing towards that point is equal to the total current flowing away from it; ie, **the algebraic sum of all currents at any junction is zero.***

**Kirchhoff's Voltage Law** (Second Law): *In any closed circuit, the algebraic sum of the products of the current and the resistance of each part of the circuit is equal to the resultant emf in the circuit; ie, **in a closed circuit, the algebraic sum of all the voltages around the circuit is zero.***

Summarising the two laws mathematically we may state:

$$\text{Kirchhoff's Current Law: } \quad \sum I = 0$$

$$\text{Kirchhoff's Voltage Law: } \quad \sum V = 0$$

**NOTE:**

$\Sigma$  is the Greek letter sigma and is used to represent 'algebraic sum of'.

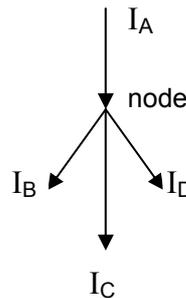
Using these laws, the currents and voltages can be theoretically calculated without having to do measurements.

If we do not know what the voltage or current is going to be at the start of a theoretical calculation, we must assume that it is one particular way round; ie, assume its polarity and take that assumed polarity into account. If our assumption was wrong, the answer will simply come out negative.



### 5.2.2 First Law

Kirchhoff's Current Law (also known as the Junction Rule) applies to a junction (or node) in a circuit; this is a point where current has several paths to flow as shown in Figure 3-5-1.



**Figure 3-5-1**

$I_A$  is the only current flowing into the node. However, there are three paths for current to leave and these currents are represented by  $I_B$ ,  $I_C$ , and  $I_D$ . Once current has entered into the node, it has no place to go except leave (this is known as 'conservation of charge'). The total current flowing into a node must be the same as the total current flowing out of the node. Therefore:

$$I_B + I_C + I_D = I_A$$

Transforming the equation to bring everything to the left-hand side, we get:

$$(I_B + I_C + I_D) - I_A = 0$$

It can be seen that the sum of all current is zero. This is generalised as:

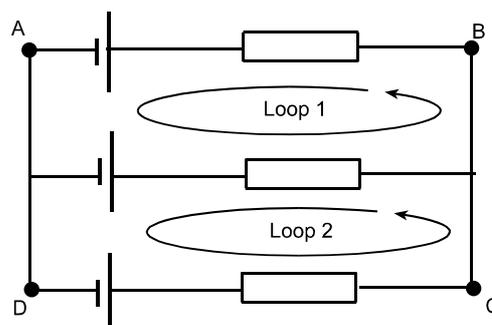
$$\Sigma I = 0$$

### 5.2.3 Second Law

Kirchhoff's Voltage Law (also known as the Loop Rule) applies to a closed loop circuit and states that the total voltage around the loop must be zero. Therefore:

$$\Sigma V = 0$$

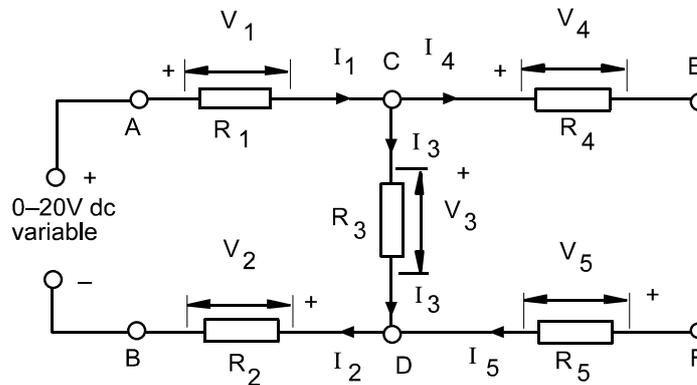
As shown in Figure 3-5-2, the total voltage around loop 1 should sum to zero, as does the total voltage in loop 2. Furthermore, the loop which consists of the outer part of the circuit (path ABCD) should also sum zero.



**Figure 3-5-2**



**5.2.4 Worked Examples**



**Figure 3-5-3**

Referring to Figure 3-5-3:

For loop ACBD

$$\sum V = 0; \quad \text{ie, } V_1 + V_2 + V_3 - V = 0$$

Now

$$V_1 = I_1 R_1; \quad V_2 = I_2 R_2; \quad V_3 = I_3 R_3$$

$\therefore$

$$I_1 R_1 + I_2 R_2 + I_3 R_3 - 20 = 0 \quad (1)$$

For loop CEFD

$$\sum V = 0; \quad \text{ie, } V_4 + V_5 - V_3 = 0$$

Now

$$V_3 = I_3 R_3; \quad V_4 = I_4 R_4; \quad V_5 = I_5 R_5$$

$\therefore$

$$I_4 R_4 + I_5 R_5 - I_3 R_3 = 0 \quad (2)$$

Similarly for loop ACEFDB,

$$I_1 R_1 + I_4 R_4 + I_5 R_5 + I_2 R_2 - 20 = 0,$$

but this equation is redundant, telling us nothing further, since we could obtain it by adding together equations (1) and (2).



For node C:

$$\sum I = 0; \quad \text{ie, } I_1 = I_3 + I_4 \quad (3)$$

For node D:

$$\sum I = 0; \quad \text{ie, } I_2 = I_3 + I_5 \quad (4)$$

A fifth equation is needed to determine the five unknown currents. In this case it is fairly obvious that:

$$I_1 = I_2 \text{ (they are the same current)}$$

and

$$I_4 = I_5 \text{ (similarly)}$$

These equations could however be formally derived by using the current law. At node E,  $\sum I = 0$ . Since  $I_4$  enters node E, the current in the link EF must be  $I_4$  leaving E and entering node F. The same argument applied then to node F gives the result:

$$I_4 = I_5 \quad (5)$$

Equations 1 to 5 enable the currents to be determined. Using (5) we can write  $I_4$  instead of  $I_5$  in equation (4).

$$I_2 = I_3 + I_4 \quad (6)$$

Combining equations (3) and (6) we deduce that:

$$I_1 = I_2 \quad (7)$$

Equations (3), (5) and (6) enable all the currents to be expressed in terms of  $I_3$  and  $I_4$ . Applying this to equations (1) and (2), they become:

$$(I_3 + I_4)(R_1 + R_2) + I_3 R_3 - 20 = 0 \quad (8)$$

$$I_4(R_4 + R_5) - I_3 R_3 = 0 \quad (9)$$

Equation (8) can be rewritten:

$$I_4(R_1 + R_2) + I_3(R_1 + R_2 + R_3) - 20 = 0 \quad (10)$$

Substituting the known resistance values in equation (9) gives:

$$I_4(330 + 680) - I_3(2200) = 0$$

$$\therefore 1010 I_4 - 2200 I_3 = 0 \quad (11)$$



and in equation (10) gives:

$$I_4 (1000+470) + I_3 (1000+470+2200) - 20 = 0$$

$$\therefore 1470 I_4 + 3670 I_3 = 20 \quad (12)$$

From equation (11)

$$I_3 = \frac{1010}{2200} \times I_4$$

Substituting in equation (12)

$$1470 I_4 + \frac{3670 \times 1010}{2200} \times I_4 = 20$$

$$\therefore I_4 = \frac{20}{3155} = 0.00634 \text{ A} = 6.34 \text{ mA.}$$

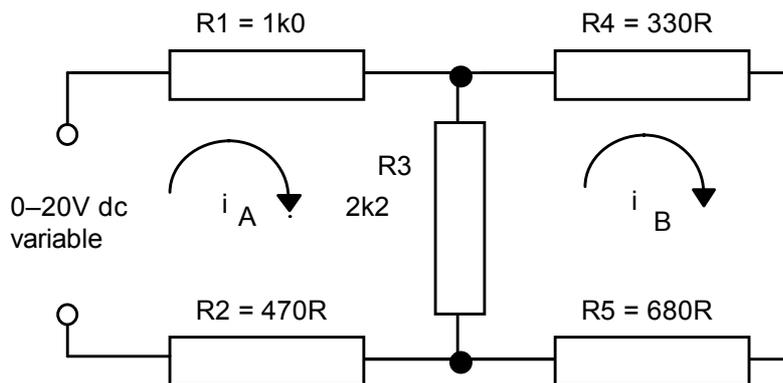
From (11),  $I_3 = 2.91 \text{ mA.}$

From (6),  $I_2 = 2.91 + 6.34 = 9.25 \text{ mA.}$

(5) and (7) complete the determination of the currents. All the answers are positive, so we chose the directions of the arrows correctly.

An alternative method of calculation, which employs Kirchoff's Laws, uses 'loop currents'.

A network can be broken down into closed loops as shown in Figure 3-5-4, each of which is given an arbitrary current ( $i$ ) flowing in it. By convention the currents are drawn flowing clockwise round the loops to mean positive polarity.



**Figure 3-5-4**

$i_A$  and  $i_B$  are the loop currents.

By using Kirchoff's Voltage Law we traverse each closed loop and write the equations for the voltage drops:

ie, 
$$R_1 i_A + R_3 [i_A - i_B] + R_2 i_A - 20 = 0$$

and 
$$R_4 i_B + R_5 i_B + R_3 [i_B - i_A] = 0$$



These can then be written as:

$$[R_1 + R_2 + R_3] i_A - R_3 i_B = 20$$

and

$$-R_3 i_A + [R_3 + R_4 + R_5] i_B = 0$$

These may then be solved for  $i_A$  and  $i_B$  as below:

$$3.67 i_A - 2.2 i_B = 20$$

$$-2.2 i_A + 3.21 i_B = 20 \quad (13)$$

Multiply (13) by  $\frac{3.67}{2.2}$  giving

$$-3.67 i_A + 5.35 i_B = 20$$

$$(1) + (3) \text{ gives: } 3.15 i_B = 20$$

$$i_B = 6.34 \text{ mA}$$

substituting back in (13)

$$-2.2 i_A + 3.21 \times 6.34 = 0$$

$$\therefore i_A = \frac{3.21 \times 6.34}{2.2}$$

$$i_A = 9.25 \text{ mA}$$

$$\therefore i_{2k2} = i_A - i_B = 9.25 - 6.34 \text{ mA}$$

$$i_{2k2} = 2.91 \text{ mA}$$

Comparing these values with the currents obtained using Kirchhoff's Laws with node currents and loop voltages, shows that both methods give the same answers, but the above method, using loop currents, is often faster and more convenient. You will see that only two simultaneous equations are needed to solve the network, rather than five for the first method.

The loop current method is sometimes known as Maxwell's Circulating Current Method.



### 5.3 Content

The practicals in this assignment familiarise the student with Kirchhoff's Laws.

### 5.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB

**or**

Conventional Instrumentation	Two dc Voltmeter & Ammeter (Option C11)	68-110
------------------------------	---	--------

Conventional Instrumentation	Two ac Voltmeter & Ammeter (Option C12)	68-117
------------------------------	---	--------

Ancillary Equipment	Digital Multimeters (3* required for Conventional Instruments. See page 3-5-9)	
	1 required for Virtual Instruments	

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 5.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



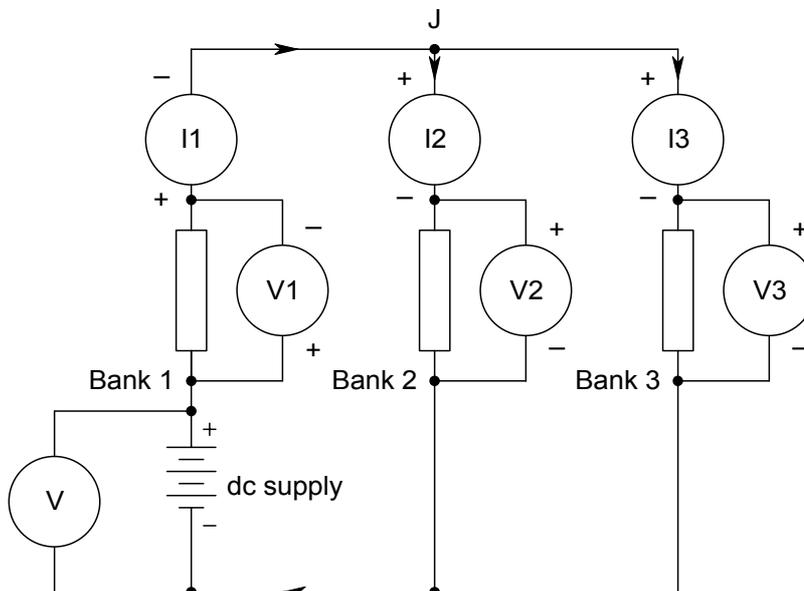
\*If you have Conventional Instrumentation and you have only one Digital Multimeter (DMM) available then for the measurement of V3 and I3 use the 68-110 meter used for V2 and I2 measurement.

Ensure that when doing this that in place of I2 that it is replaced by a link. The DMM can be used for measuring voltages around the circuit.

### Practical 5.1 - Current and Voltage Law

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-5-6, which relates to the theoretical circuit shown in Figure 3-5-5. The power supply unit 60-105 connections should be made via an external voltmeter, which should be set to the appropriate dc range.



**Figure 3-5-5: Theoretical Circuit**

If virtual instrumentation is being used, set the 250 V/500 V range switches for V1, V2 and V3 channels to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switches for I1, I2 and I3 to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' sockets are connected or 200 mA to be monitored when the '200 mA' socket is connected.



Conventional Instrumentation

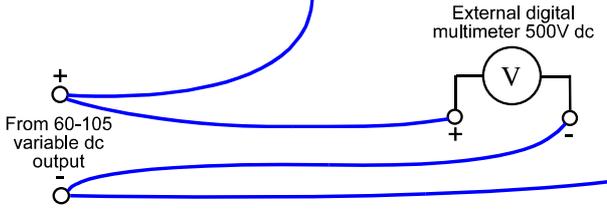
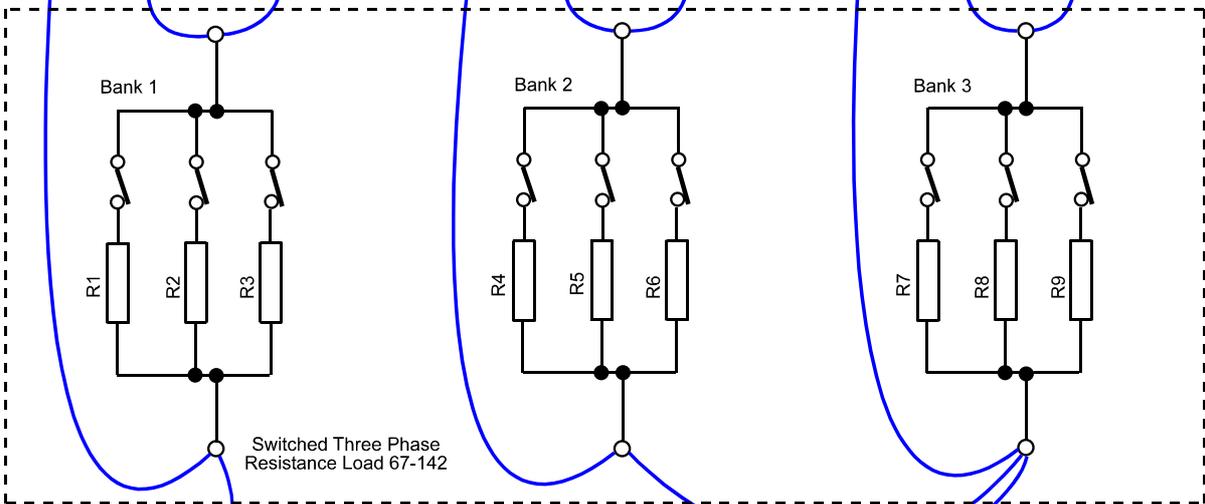
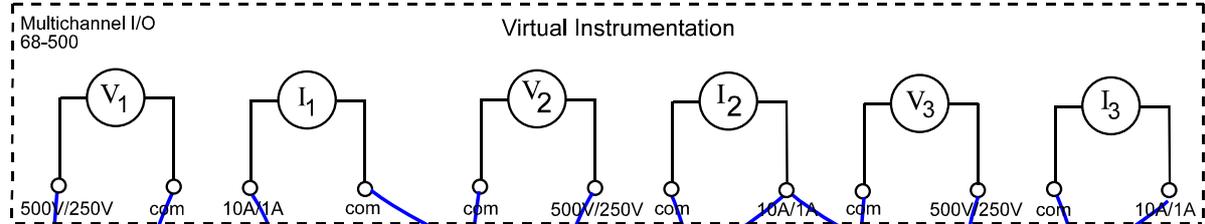
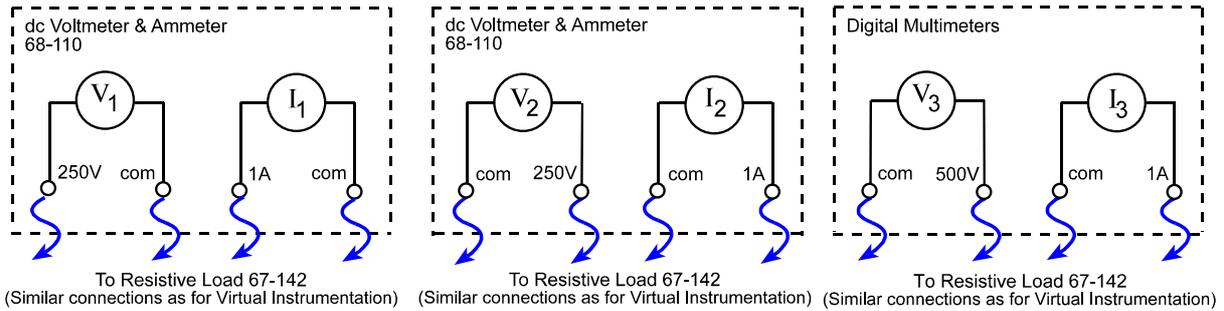


Figure 3-5-6: Practical 5.1 Circuit Diagram



		Product Version	
		230 V	120 V
<p>On the switched three phase resistance load 67-142, set switches as follows:</p> <ul style="list-style-type: none"> <li>• Bank 1 - all switches set to on to provide.....</li> <li>• Bank 2 - all switches set to on to provide.....</li> <li>• Bank 3 - all switches set to on to provide.....</li> </ul>		<p>546 <math>\Omega</math></p> <p>546 <math>\Omega</math></p> <p>546 <math>\Omega</math></p>	
<p>On the Universal Power Supply 60-105 , ensure the '<i>variable output voltage</i>' control is set to 0% then set the '<i>3 phase circuit breaker</i>' to the on position.</p>			
<p>By use of the '<i>variable output voltage</i>' control, set the output voltage to..... as shown on the external voltmeter.</p>		200 V dc	
<p>Measure and record on a copy of the appropriate Practical 5.1, Results Table (230 V or 120 V product version), the current flowing and the three voltages for all three legs of the circuit as shown on virtual or conventional ammeters and voltmeters.</p>			
<p>On the switched three phase resistance load 67-142, set switches as follows:</p> <ul style="list-style-type: none"> <li>• Bank 1 - switches 1 and 3 (upper and lower) set to on and switch 2 (middle) set to off to provide.....</li> <li>• Bank 2 - all switches set to on to provide.....</li> <li>• Bank 3 - all switches set to on to provide.....</li> </ul>		<p>759 <math>\Omega</math></p> <p>546 <math>\Omega</math></p> <p>546 <math>\Omega</math></p>	
<p>Measure and record on your copy of Practical 5.1, Results Table, the current flowing in all three legs of the circuit as shown on virtual or conventional ammeters <math>I_1</math>, <math>I_2</math> and <math>I_3</math>.</p> <p>Repeat the above steps so that current can be measured for the resistance values given on your copy of Practical 5.1, Results Table and record the results.</p>			
<p>To obtain a resistance value of..... set the 67-142 switches as follows:</p> <ul style="list-style-type: none"> <li>• Switches 2 and 3 (middle and lower) set to on and switch 1 (upper) set to off.</li> </ul>		1285 $\Omega$	

Turn the '*variable output voltage*' control to 0% on the Universal Power Supply 60-105 and then switch off the '*3 phase circuit breaker*'.



Examine the results obtained in your copy of Practical 5.1, Results Table, and in particular the currents  $I_1$ ,  $I_2$ , and  $I_3$ . Can you see any relationship between them? Does the sum of  $I_2$  plus  $I_3$  equal  $I_1$ ?

Kirchhoff's Current Law states:

***'The algebraic sum of all currents at any junction is zero'.***

That is the current flowing into the junction  $J = I_1$

The current flowing away from the junction  $J = I_2 + I_3$

Therefore  $I_1 = I_2 + I_3$

Or

$$I_1 - I_2 - I_3 = 0$$

Now apply Kirchhoff's Voltage Law to your results and see if you can verify this.

Kirchhoff's Voltage Law states:

***'In a closed circuit, the algebraic sum of all the voltages around the circuit is zero'.***

Look at the columns  $V_1$ ,  $V_2$  and  $V_3$  in your table. You should notice that there is a relationship between them and the applied voltage.

$$V = V_1 + V_2 + V_3$$

Or

$$V - V_1 - V_2 - V_3 = 0$$

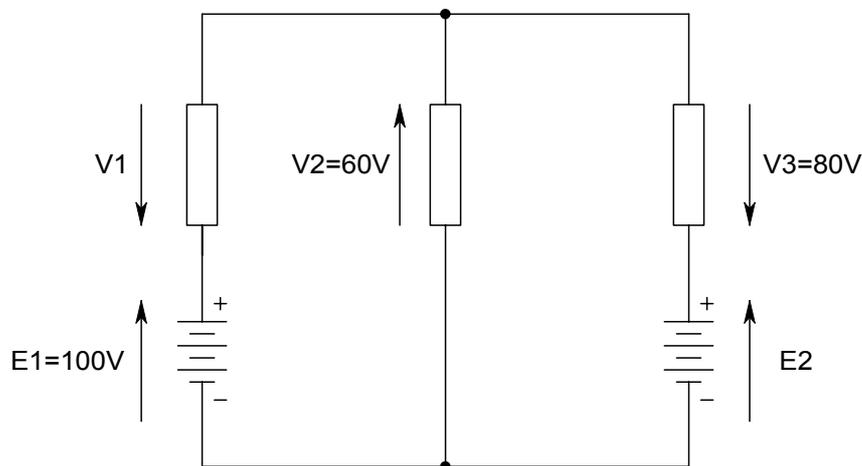


### 5.6 Exercise 5.1.4 - Voltage Law

In this exercise we shall be looking at a circuit that contains more than one voltage source unlike the more simplified circuit of practical 5.1.

The object of this exercise is to fully test the understanding and the application of Kirchhoff's second law.

Examine the circuit of figure 3-5-7 and consider how you would begin to find the values of  $V_1$  and  $E_2$ .



**Figure 3-5-7: Theoretical Circuit**

Remember that to apply the theory the circuit must be divided into circuit loops and voltage equations written for those loops. From these equations the values of  $V_1$  and  $E_2$  can be found.

Start with the left hand loop for  $E_1$  and then right hand loop for  $E_2$ .

You should find that evaluating these equations reveals  $V_1$  is equal to 40 V and  $E_2$  equals 140 V

Use the diagram at the end of the results section to write down your equations and answers.



## 5.7 Practical Aspects

Kirchhoff's Laws of current and voltage are two of the basic 'building blocks' with which the analysis of electrical circuits is constructed. It is obviously essential to know how any particular circuit works, and to be able to predict how it will behave under the conditions of interest. To do this the circuit has to be analysed, and in this analysis network theorems such as Kirchhoff's Laws are indispensable.

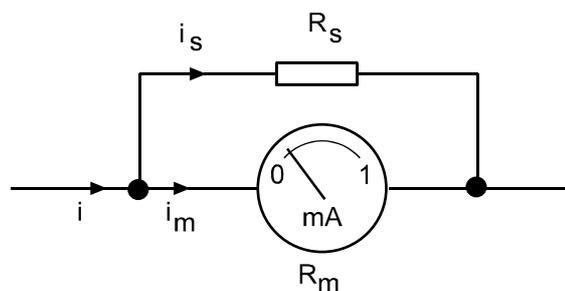
The modified method of analysis, which has been called Maxwell's Circulating Current Method, is a very useful tool in analysis. It usually produces fewer equations to solve simultaneously, and usually simplifies and shortens the calculations considerably. It does not matter which way round you draw the circulating currents provided you call this the positive direction of current and remember that all currents going in the opposite direction are negative, and must be subtracted.

As an example of the application of Kirchhoff's Laws let us take the following case:

We have a dc milliammeter which has a full-scale deflection current of 1 mA. We wish to use this meter to measure currents up to 10 mA.

*Question 5.1*                      *How can this be achieved?*

Let us assume the line we want to monitor is carrying the full 10 mA, and at this value we wish our meter to show full scale deflection, ie, it must be passing 1 mA. We must therefore provide another path for the remainder of the current to flow, as in Figure 3-5-9.



**Figure 3-5-9**



Now  $i = 10 \text{ mA}$

$$I_m = 1 \text{ mA}$$

$\therefore$  by Kirchhoff's current law

$$i_s = 9 \text{ mA}$$

By Kirchhoff's voltage law

$$V_{R_s} - V_m = 0$$

where  $V_{R_s}$  = voltage across  $R_s$

$$V_m = \text{voltage across meter}$$

and

$$R_m = \text{meter resistance}$$

$$\therefore V_{R_s} = V_m$$

$$\therefore i_s R_s = i_m R_m$$

$$\therefore 9 R_m = 1 R_m$$

$$\therefore R_s = \frac{1}{9} R_m$$

A typical value of  $R_m$  for a 1 mA movement may be  $63 \Omega$

$$\therefore R_s = \frac{1}{9} \times 63 \Omega$$

$$\therefore R_s = 7 \Omega$$

Thus if a  $7 \Omega$  resistor is connected in parallel with the meter, the meter may be scaled to read 10 mA full-scale deflection as required.

The parallel resistor is usually called a shunt resistor or just a SHUNT, for short.



Notes



**5.8 Practical 5.1 - Results Tables (230 V Product Version)**

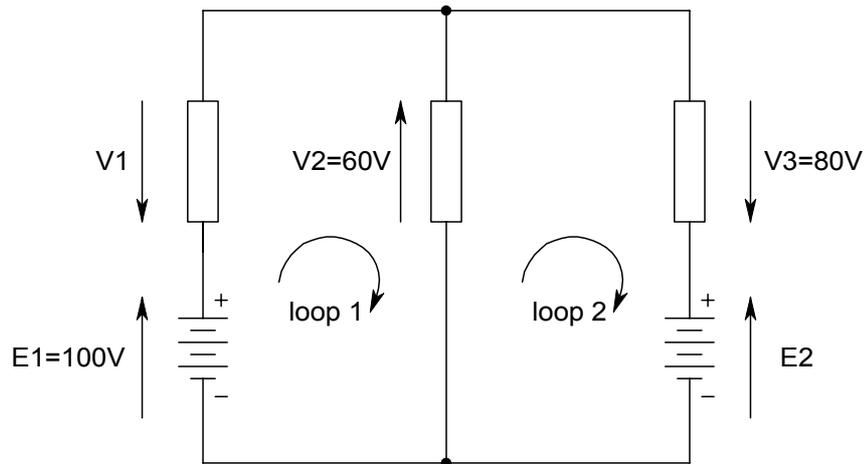
dc supply voltage 200V								
Bank 1 Resistance (ohms)	Bank 1 Resistance (ohms)	Bank 1 Resistance (ohms)	$I_1$	V1	$I_2$	V2	$I_3$	V3
546	546	546						
759	546	546						
759	759	546						
759	759	759						
1285	759	759						
1285	1285	759						
1285	1285	1285						

**5.9 Practical 5.1 - Results Tables (120 V Product Version)**

dc supply voltage 100V								
Bank 1 Resistance (ohms)	Bank 1 Resistance (ohms)	Bank 1 Resistance (ohms)	$I_1$	V1	$I_2$	V2	$I_3$	V3



**5.10 Exercise 5.1.4 - Kirchhoff's Voltage Law**





## **6 Power**

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### **6.1 Assignment Information**

#### **6.1.1 Objectives**

When you have completed this assignment you will:

- have investigated the concepts of electrical power and power transfer.

#### **6.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed Assignments 1 to 5.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **6.1.3 Practicals**

1. Voltage and Current Relationship to Power
2. Power Transfer

**NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.





A resistor is part of an electric circuit, and it will take work to push a charge through the resistor against the opposition offered to the charge. The power used in the resistor (we say 'dissipated by the resistor') is given by the formula above, where  $V$  is the voltage across the resistor, and  $I$  the current through it.

### 6.3 Content

The practicals in this assignment familiarise the student with the concepts of electrical power and power transfer.

### 6.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation	Two dc Voltmeter & Ammeter (Option CI1)	68-110

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 6.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

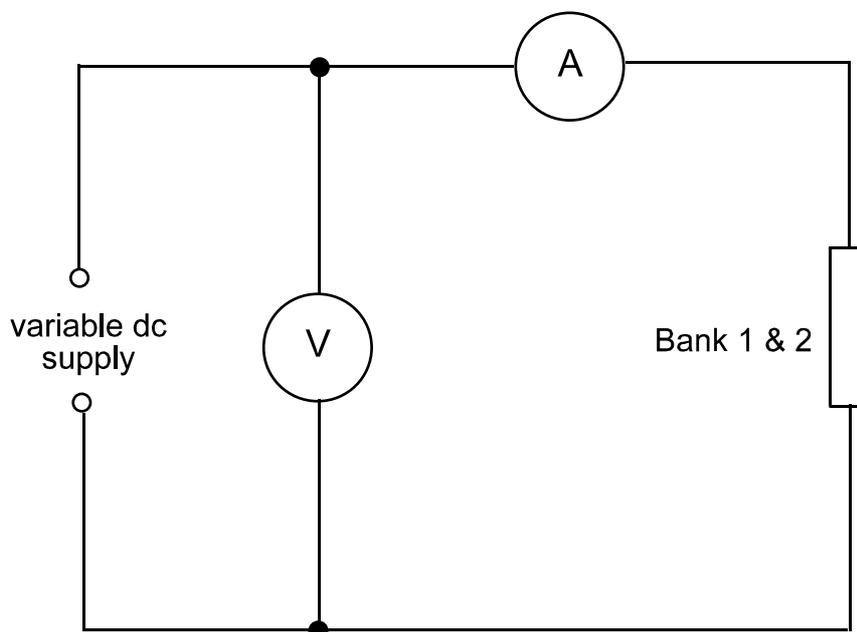
If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 6.6 Practical 6.1 - Voltage and Current Relationship to Power

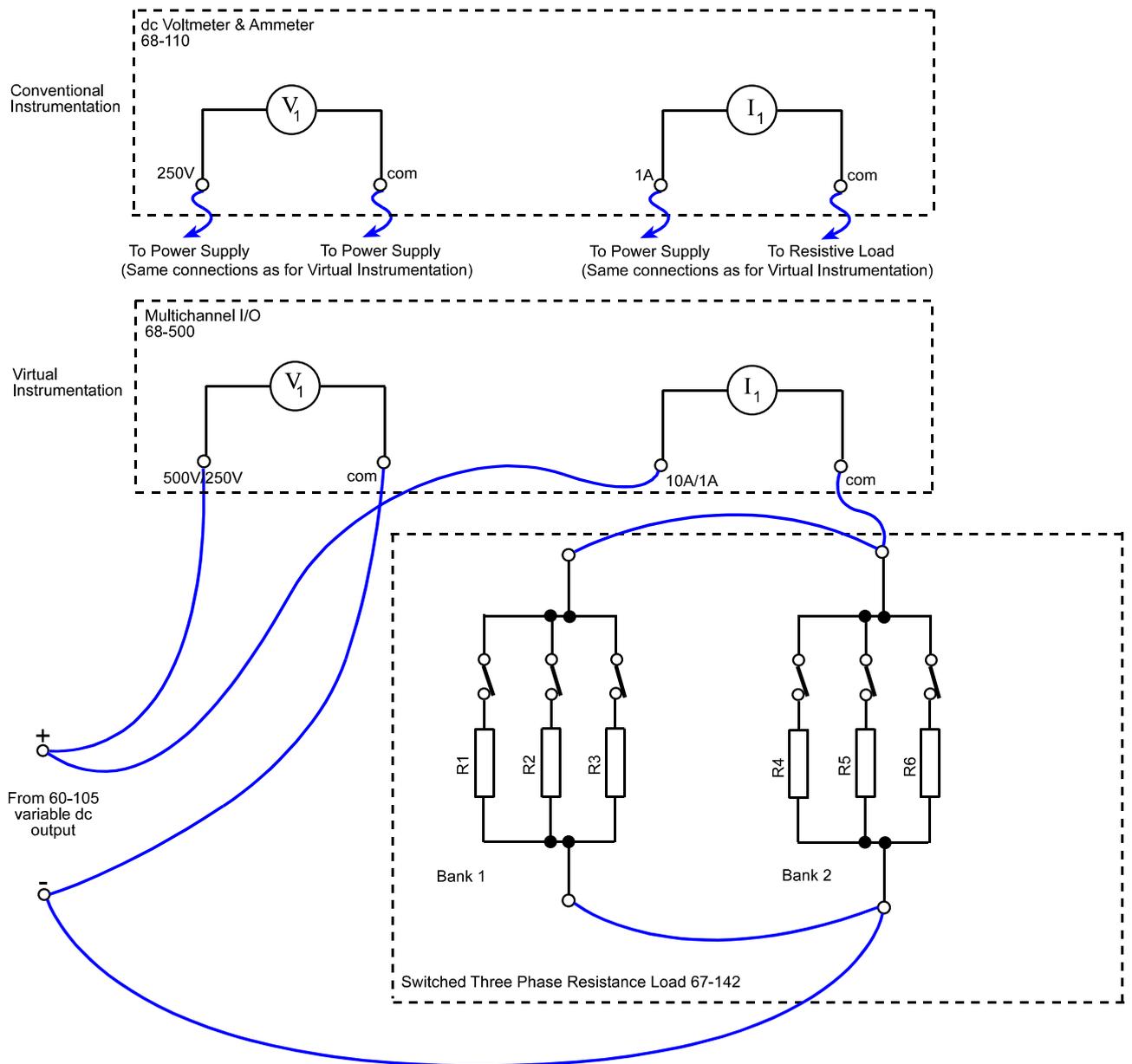
On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-6-2, which relates to the theoretical circuit shown in Figure 3-6-1.



**Figure 3-6-1: Theoretical Circuit**

If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the '200 mA' socket is connected.



**Figure 3-6-2: Practical 6.1 Circuit Diagram**



Product Version	
230 V	120 V
546 Ω	
546 Ω	
50 V dc	
100 V dc	
150 V, 200 V & 220 V dc	

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on to provide.....
- Bank 2 - all switches set to on to provide.....

On the Universal Power Supply 60-105 , ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

By use of the '*variable output voltage*' control, set the output voltage to..... as shown on the virtual or conventional voltmeter V<sub>1</sub>.

Measure and record on a copy of the appropriate Practical 6.1, Results Table (230 V or 120 V product version), the current flowing through the circuit as shown on the virtual or conventional ammeter I<sub>1</sub>.

By use of the '*variable output voltage*' control, increase the output voltage to..... and measure and record on your copy of Practical 6.1, Results Table the current now flowing in the circuit.

Repeat for current readings for voltages of.....

For each voltage setting, calculate power ( $P = VI$ ) and enter the result in your copy of Practical 6.1, Results Table.

### 6.6.1 Exercise 6.1

On a copy of the graph axis given in Exercise 6.1 Graph Axis, located in the Results Tables section at the end of this assignment, plot graphs of voltage against current and then voltage against power using the tabulated in results in your copy of Practical 6.1, Results Table. The same axis should be used for both plots using the different scales shown.



- Question 6.1 *From the results you obtained, can you deduce the law of the curve for power against voltage?*
- Question.6.2 *If you double the applied voltage from 50 V to 100 V, how many times does the power increase?*
- Question 6.3 *If you double the applied voltage from 100 V to 200 V, does the power increase by the same factor as it did from 50 V to 100 V?*
- Question 6.4 *If you tripled the applied voltage, how many times would you expect the power to increase?*

**You should find that power is proportional to the square of the voltage.**

- Question 6.5 *What relationship is there between the power and the current flowing?*

Summarising these results mathematically we can say:

$$\text{Power} \propto (\text{voltage})^2$$

or

$$\text{Power} \propto (\text{current})^2$$

for a resistive circuit such as shown in Figure 3-6-1. This can be obtained from the expression:

$$W = VI$$

and from Ohm's Law as below:

$$W = VI, \text{ but } V = IR$$

$$W = IR \times I \quad \text{thus } W = I^2 R$$

ie;

$$W \propto I^2$$

and

$$W = VI, \text{ but } I = \frac{V}{R}$$

∴

$$W = V \times \frac{V}{R} \quad \therefore W = C$$

ie;

$$W \propto V^2$$

Summarising

$$W = V \times I$$

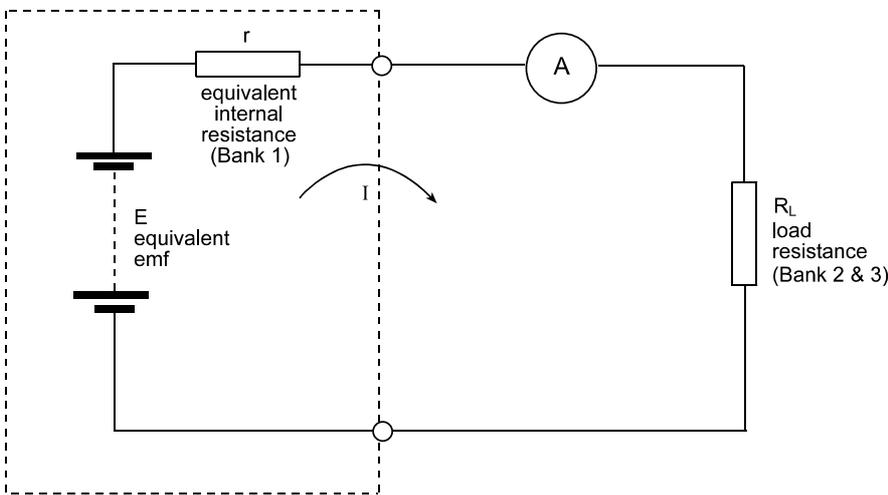
$$W = \frac{V^2}{R}$$

$$W = I^2 R$$



**6.7 Practical 6.2 - Power Transfer**

This practical investigates the power dissipated in a load resistor for a network having an equivalent source emf of  $E$  volt and an equivalent internal resistance of  $r$  ohm. This time we shall keep the emf constant and vary the value of the load resistance. The theoretical circuit for this is shown in Figure 3-6-4.



**Figure 3-6-4: Theoretical Circuit**

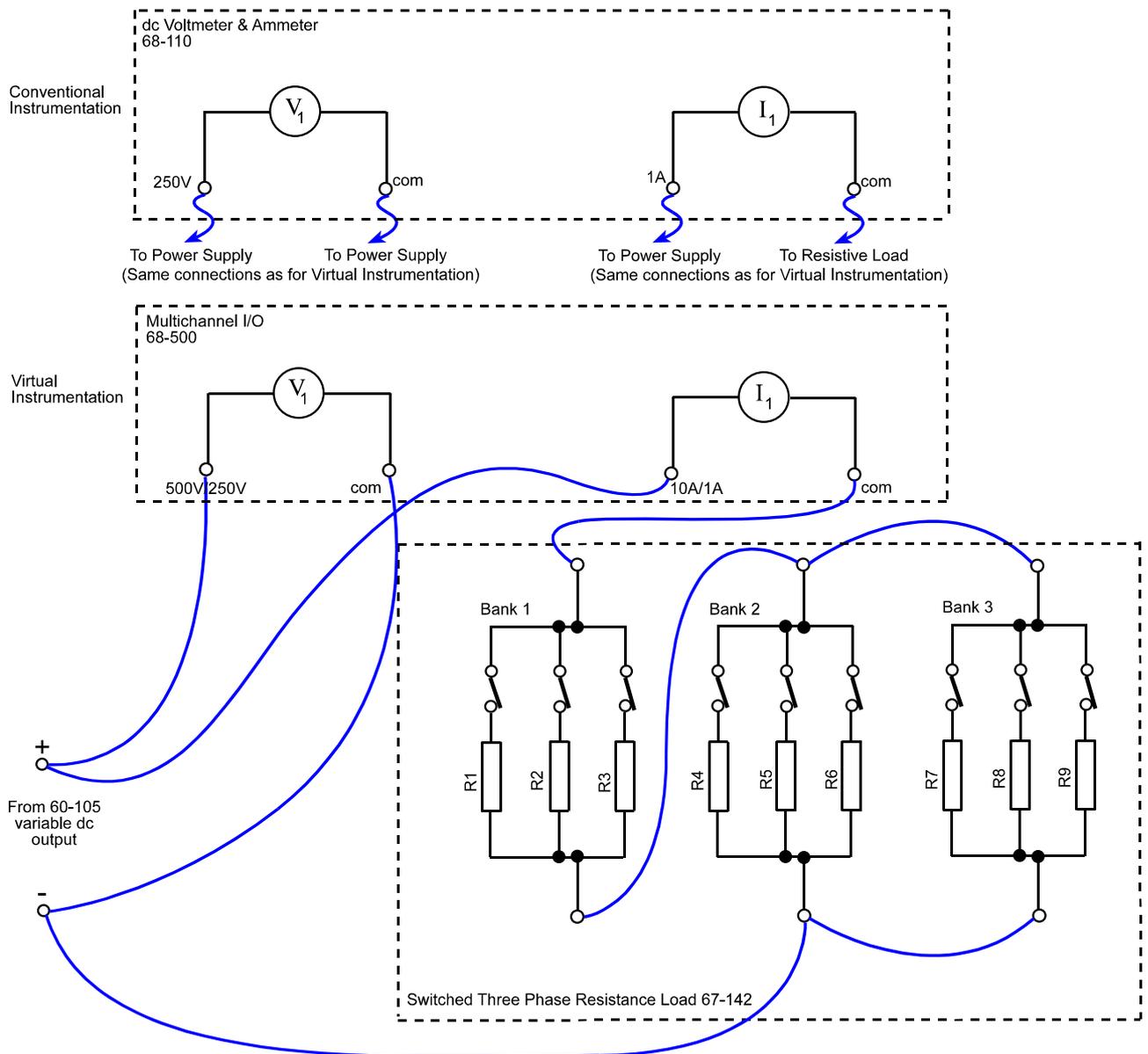
If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the '200 mA' socket is connected.

Let us say that for the purpose of this practical that the equivalent source of emf is.....  
 and the equivalent series resistance of the network is .....

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-6-5, which equates to the theoretical circuit shown in Figure 3-6-4.

Product Version	
230 V	120 V
200 V	
546 Ω	



**Figure 3-6-5: Practical 6.2 Circuit Diagram**



Product Version	
230 V	120 V
546 Ω	
546 Ω	
273 Ω	

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on to provide.....
- Bank 2 and 3 - all switches set to on to provide.....

Banks 2 and 3 are connected in parallel to give a..... resistive load ( $R_L$ ).

On the Universal Power Supply 60-105 , ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

By use of the 'variable output voltage' control, set the output voltage to..... as shown on the virtual or conventional voltmeter  $V_1$ .

200 V dc	
----------	--

Measure and record on a copy of the appropriate Practical 6.2, Results Table (230 V or 120 V product version), the current flowing through the circuit as shown on the virtual or conventional ammeter  $I_1$ .

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on to provide.....
- Bank 2 and 3 - switches 1 and 2 (upper and middle) set to on and switch 3 (lower) set to off .....

Banks 2 and 3 are connected in parallel to give a ..... resistive load ( $R_L$ ).

546 Ω	
640 Ω	
320 Ω	

Measure and record on your copy of Practical 6.2, Results Table, the current flowing through the circuit as shown on the virtual or conventional ammeter  $I_1$ .

Repeat this procedure for ..... resistive loads ( $R_L$ ) as listed in your copy of Practical 6.2, Results Table. For settings to obtain the desired resistance values these are given below.

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 2 - all switches set to on and Bank 3, all switches off for.....
- Bank 2 - switches 2 and 3 (middle and lower) set to on and Bank 3 middle switch set to on and all others set to off for.....

546 Ω, 774 Ω & 958 Ω	
546 Ω	
774 Ω	



- Bank 2 - switches 2 and 3 (middle and lower) set to on and Bank 3 lower switch set to on and all others set to off for.....

958 $\Omega$	
--------------	--

When you have completed your measurements, calculate power for each resistive load ( $P = I^2R$ ).



### 6.7.1 Exercise 6.2

On a copy of the graph axis given in Exercise 6.2 Graph Axis, located in the Results Tables section at the end of this assignment, plot a graph of power against resistive load ( $R_L$ ) using the tabulated results in your copy of Practical 6.2, Results Table.

On the graph, draw a vertical line at  $R_L = r$ .

ie:  $R_L = 546$  ohm (230 V product version)

$R_L =$       ohm (120 V product version)

**Question 6.6**                      *What is the power dissipated in  $R_L$  at  $R_L = 546$  ohms?*

You should find from your graph that the maximum power dissipated in the load is when the load resistance is equal to the equivalent series internal resistance of the source. In this case that is 548 ohms (230 V product version) or .....ohms (120 V product version).

We say that the load and source are matched when the conditions for maximum power transfer are met. To achieve maximum efficiency for a circuit, the source and load should be matched.

When the source and load are matched, the voltage across the load is  $\frac{1}{2} \times$  equivalent source emf.

### 6.8 Practical Aspects

Power will be dissipated whenever a current flows in a resistor. This power is dissipated in the form of heat and will thus tend to heat up the resistor body.

For efficient and correct working this heat must be dispersed from the resistor body, or the temperature of the resistor will rise above permissible limits. Generally, the larger the resistor body is physically, the more power can be dissipated by the resistor without the temperature increasing too much.

Thus the resistor sizes normally used are dependent on the maximum permissible average power dissipation by the resistances in circuit. The Practical Aspects discussed at the end of Assignment 1-3 show the different sizes and types of resistor.

Generally, in electronic circuits, resistor power ratings are fairly low, the most common being:

$$\frac{1}{10} \text{ W}, \frac{1}{8} \text{ W}, \frac{1}{4} \text{ W}, \frac{1}{2} \text{ W}, 1 \text{ W}, 2 \text{ W}, 3 \text{ W}, 5 \text{ W}$$

perhaps the most commonly used of these are:

$$\frac{1}{8} \text{ W}, \frac{1}{4} \text{ W}, \frac{1}{2} \text{ W resistors.}$$

For space and cost reasons, it is usually desirable to use the smallest possible resistor consistent with adequate power dissipation properties.



Thus a resistor  $R_2$  of a transistor bias circuit, which had a value of  $15\text{ k}\Omega$  and was passing a current of  $0.067\text{ mA}$  when  $V_{CC}$  was  $+12\text{ V}$  and  $V_S$  was  $+1\text{ V}$ , would dissipate a power of:

$$\begin{aligned}P_{\text{diss}} &= I^2 R \\ &= (0.067 \times 10^{-3})^2 \times 15 \times 10^3 \text{ Watt} \\ &= 47.25 \mu\text{W}.\end{aligned}$$

Thus virtually any resistor could be used in this position with regard to power dissipation. However not every resistor in circuit would have such a low  $P_{\text{diss}}$  value. It is not unusual for the output stage of an amplifier to have resistors of values in the region of  $100\ \Omega$  passing currents of  $100\text{ mA}$  or more.

$$\begin{aligned}\text{Here } P_{\text{diss}} &= (0.1)^2 \times 100 \\ &= 0.01 \times 100 \\ &= 1\text{ W}\end{aligned}$$

Thus a resistor capable of dissipating at least  $1\text{ watt}$  is necessary.

The power transfer theorem must be used when it is desired to get as much power as possible into a load. A microphone for instance will usually produce only a tiny amount of power which must not be wasted. Even smaller powers are received by radio and television antennas. The connected equipment must in each case be matched in impedance so as to receive the maximum possible power. The load (such as a loudspeaker) on an amplifier must also be matched although, in this case, the source emf can fairly easily be varied, so the matching problem is rather different.



Notes



**6.9 Practical 6.1 - Results Tables (230 V Product Version)**

<b>Voltage (V)</b>	<b>Current I (A)</b>	<b>Power (P=VI) (W)</b>
50		
100		
150		
200		
220		

**6.10 Practical 6.2 - Results Tables (230 V Product Version)**

<b>Load (<math>R_L</math>) (<math>\Omega</math>)</b>	<b>Current I (A)</b>	<b>Power (<math>P=I^2R_L</math>) (W)</b>
273		
320		
546		
774		
958		



**6.11 Practical 6.1 - Results Tables (120 V Product Version)**

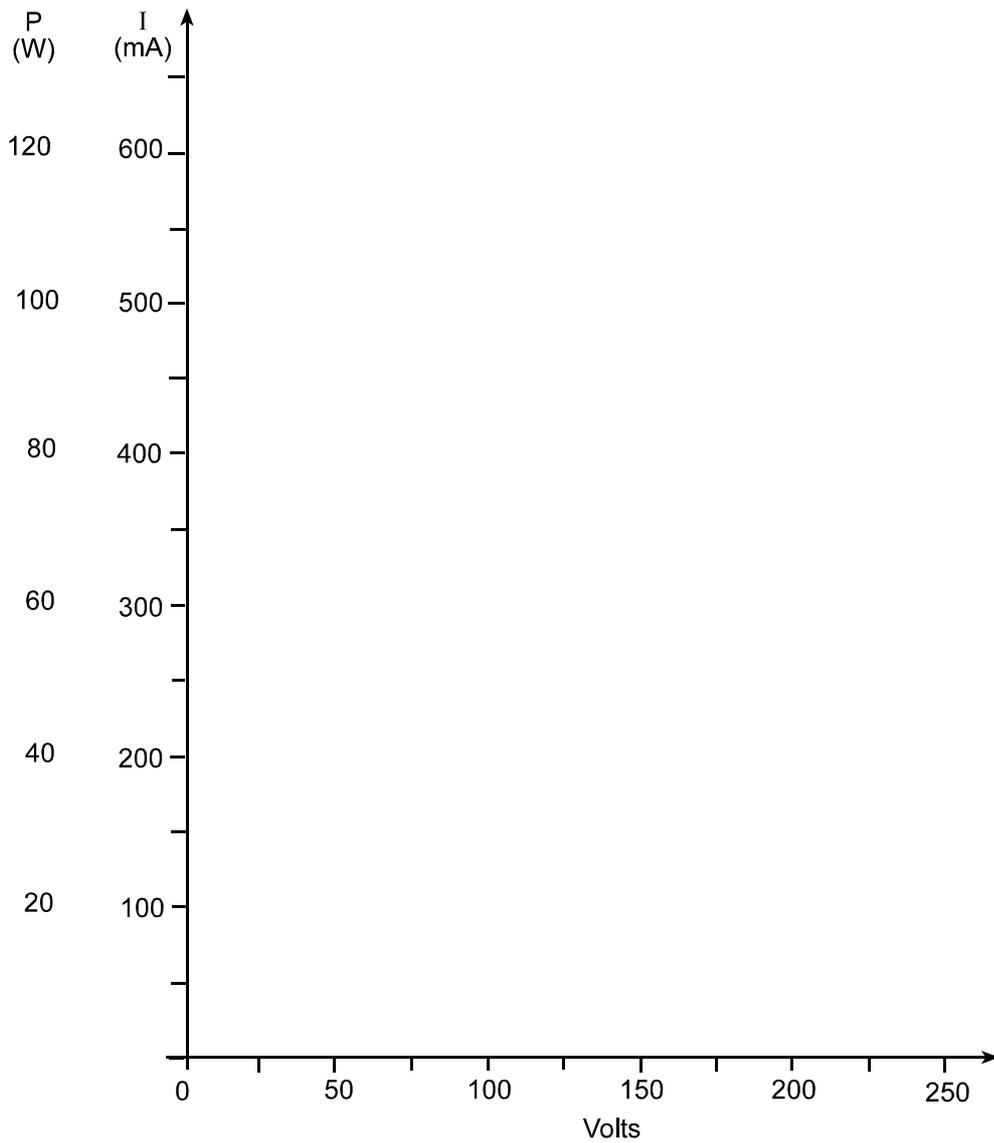
<b>Voltage (V)</b>	<b>Current I (mA)</b>	<b>Power (P=VI) (W)</b>

**6.12 Practical 6.2 - Results Tables (120 V Product Version)**

<b>Load (<math>R_L</math>) (<math>\Omega</math>)</b>	<b>Current I (mA)</b>	<b>Power (<math>P=I^2R_L</math>) (W)</b>

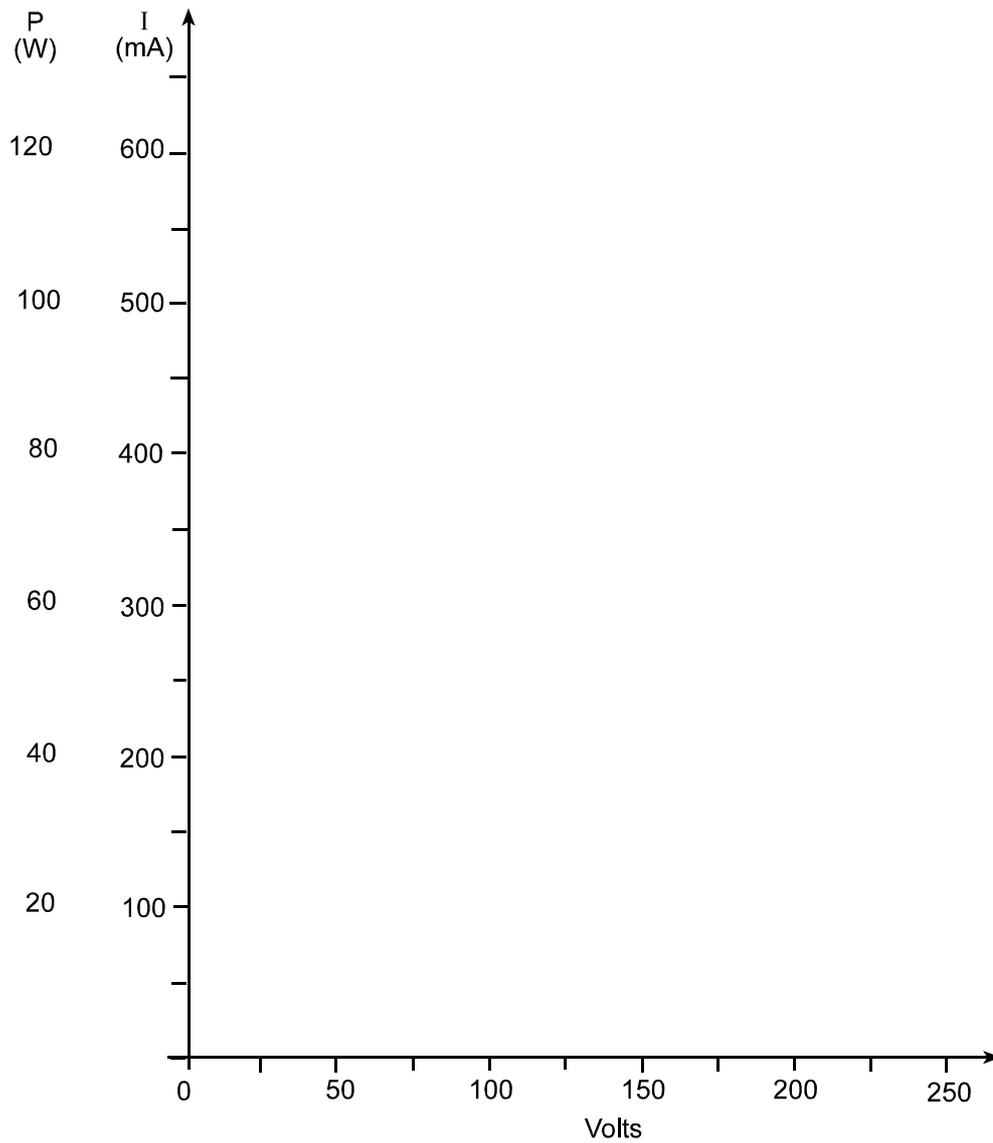


**6.13 Exercise 6.1 - Graph Axis (230 V Product Version)**



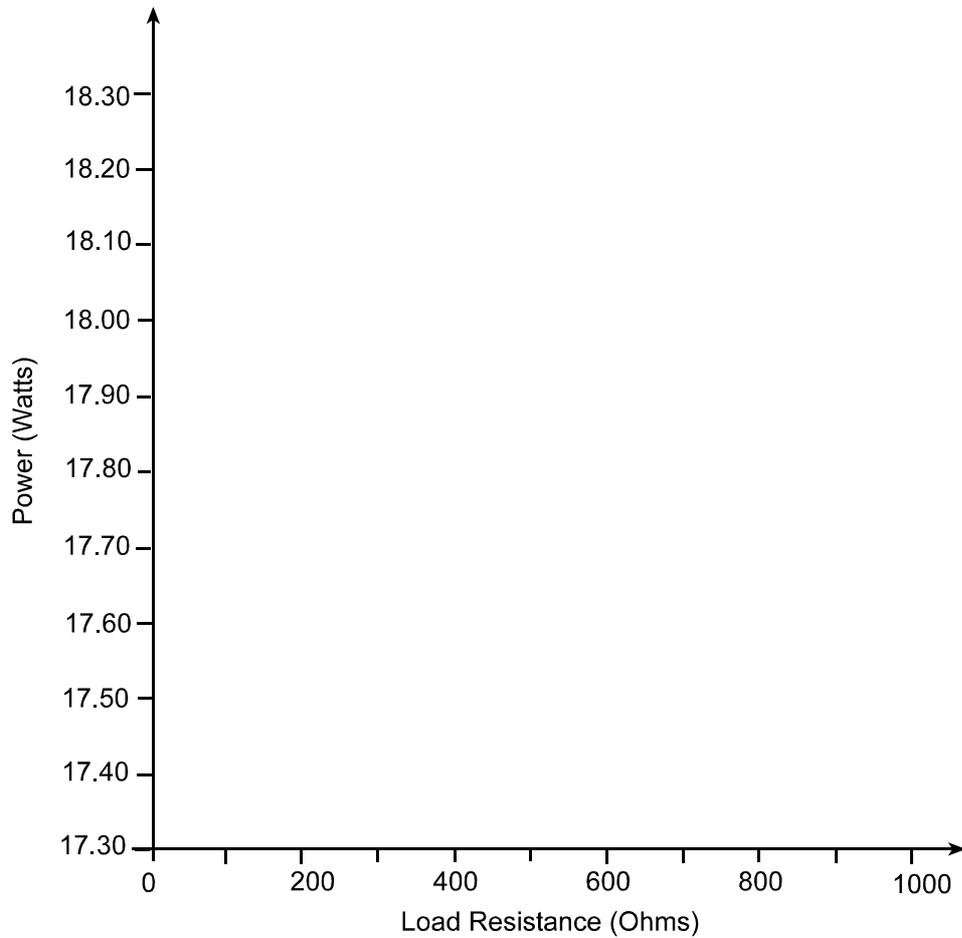


**6.14 Exercise 6.1 - Graph Axis (120 V Product Version)**



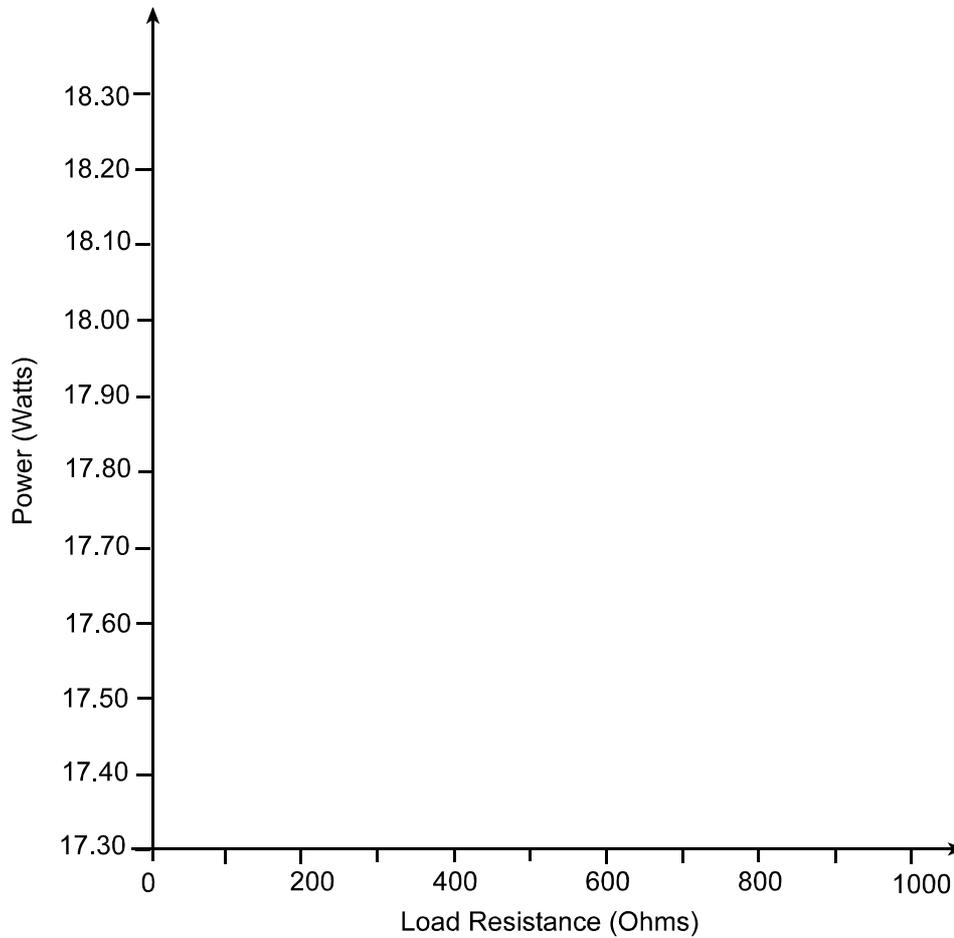


**6.15 Exercise 6.2 - Graph Axis (230 V Product Version)**





**6.16 Exercise 6.2 - Graph Axis (120 V Product Version)**





## **7 ac Theory**

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### **7.1 Assignment Information**

#### **7.1.1 Objectives**

When you have completed this assignment you will:

- know the difference between direct current (dc) and alternating current (ac).
- understand the characteristics of a sine wave.

#### **7.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignments 1 to 6.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **7.1.3 Practicals**

1. ac and dc Comparison,
2. Characteristics of a Sine Wave

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **7.2 Theory**

### **7.2.1 Introduction**

In assignments 1 to 6, we looked at dc circuits in which current flowed from positive to negative. We will now explore another form of current flow which alternates in direction in accordance with the generated supply.

### **7.2.2 Alternating Current**

Firstly it must be considered how alternating current is generated. If a wire loop is rotated between the north and south poles of a magnet as shown in Figure 3-7-1, current flow is induced in the loop in a given direction as the lines of force of the magnetic field are cut. As the coil approaches the south pole, the current begins to flow in the opposite direction from which it was originally moving. It continues to move in this direction until, once again, it approaches the north pole. It is therefore said that electric current is alternating between positive and negative and is called alternating current (ac).

If the swing from positive to negative is plotted on a graph and compared to the time it takes for the coil to turn a complete circle, the result produced would be similar to that shown in Figure 3-7-2.

Initially, the coil is positioned directly in the centre between the poles of the magnet and current flow is zero. As the coil begins to turn, one side moves towards the north pole and becomes positive. Simultaneously, the other side of the coil moves towards the south pole and becomes negative. As there is now a positive and negative charge across the coil, current starts to flow and increases until a peak is reached when the coil is orientated horizontally between north and south. This positive peak is called the 90° point. After this point is passed, the current flow begins to drop but doesn't reach zero again until the coil is positioned between the two magnets. This is called the 180° point.

As the coil continues to turn, the side that was positive moves towards the south pole of the magnet and becomes negative. Simultaneously, the side of the coil that was negative becomes positive. Thus the direction of current flow within the wire is reversed. The current flow continues in this direction until it again reaches a (this time negative) peak at 270°. Finally, as the coil approaches its original position, it swings positive again until the current flow reaches zero.

By plotting current against time, a pattern known as a sinusoidal wave (or sine wave) is produced which has positive and negative peaks at 90° and 270° respectively.

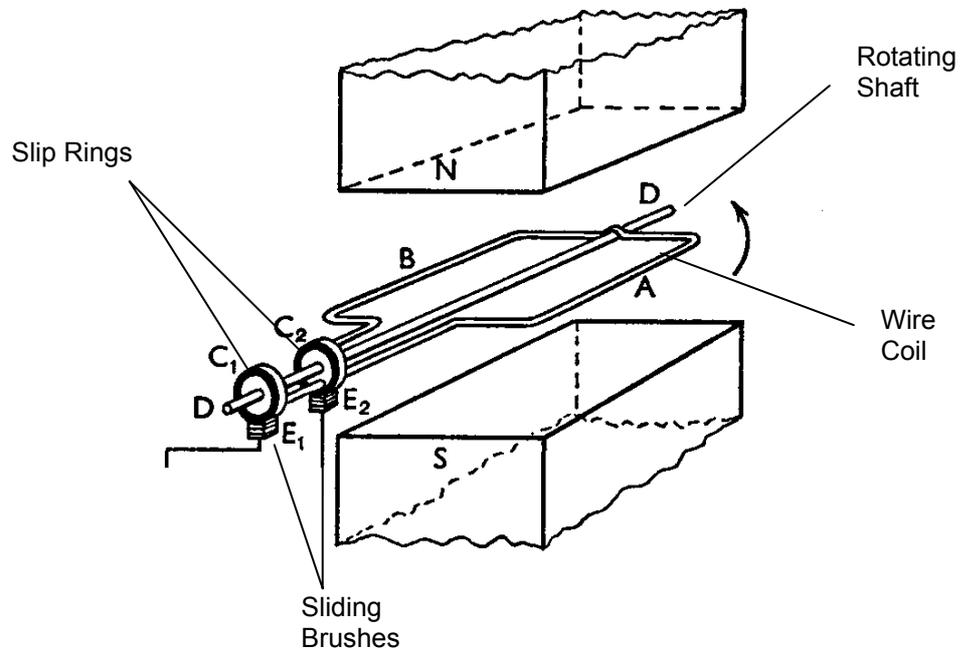


Figure 3-7-1

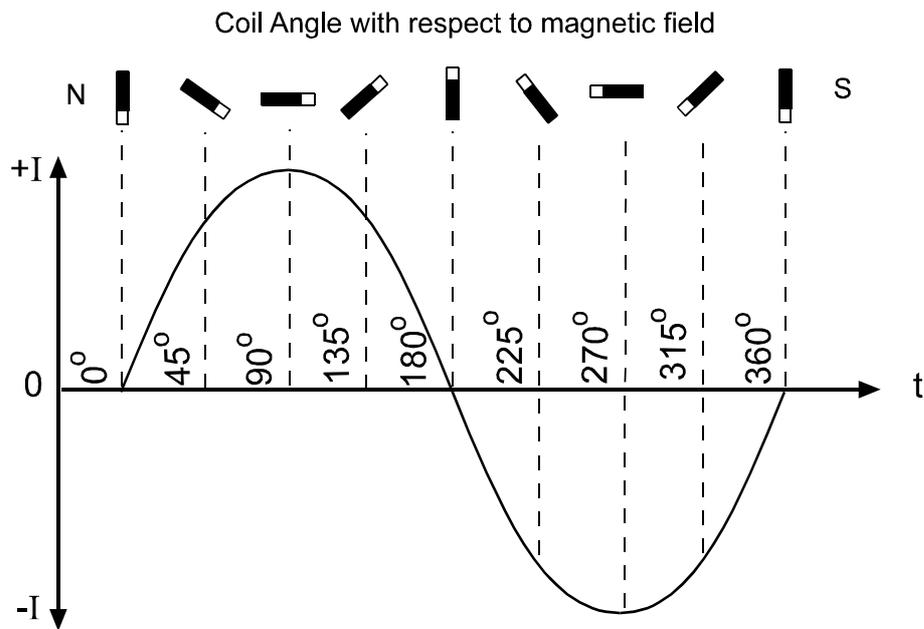


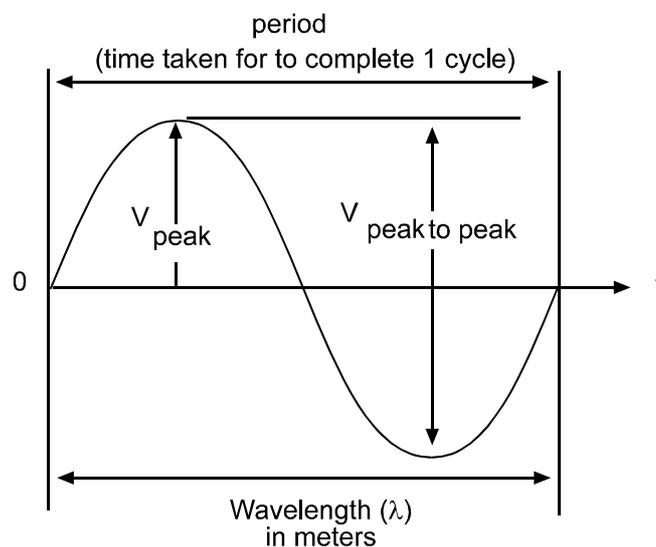
Figure 3-7-2



### 7.2.3 Sine Wave Characteristics

A sine wave has several important characteristics shown in Figure 3-7-3 which are:

- Cycle: one complete revolution from  $0^\circ$  to  $360^\circ$ .
- Wavelength: the distance between the beginning of one cycle and the beginning of the next is called a wavelength. The symbol for wavelength is lambda ( $\lambda$ ).
- Period: the time in which it takes to complete one cycle.
- Frequency: the number of complete sine wave cycles generated in one second. Measured in cycles per second, the unit of frequency is the Hertz (Hz).
- Amplitude: the height of the sine wave and is measured in volts (V). The highest point of any wave is called the Peak Amplitude or Peak Voltage.
- Peak-to-Peak Voltage: the difference in amplitude between the highest positive voltage, and the highest negative voltage. It is equal to twice the Peak Voltage.



One cycle of the sine wave is shown (0 to 360 degrees)

**Figure 3-7-3**



### 7.3 Content

The practicals in this assignment familiarise the student with the concepts of alternating current theory by studying how it differs with direct current and observing the characteristics of a sine wave.

### 7.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation	dc Voltmeter & Ammeter ( Option CI1)	68-110
	Rectifier Voltmeter & Ammeter (Option CI2)	68-117
Ancillary Equipment	Differential Voltage Probe (Required for Conventional Instruments only)	68-150
	Two channel oscilloscope, at least 20 MHz bandwidth	

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 7.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

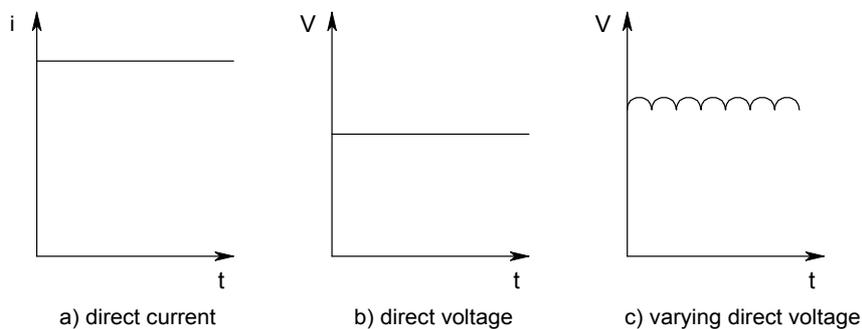
If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 7.6 Practical 7.1 – ac and dc Comparison

A direct current or voltage is generally thought of as unidirectional and not varying with time.

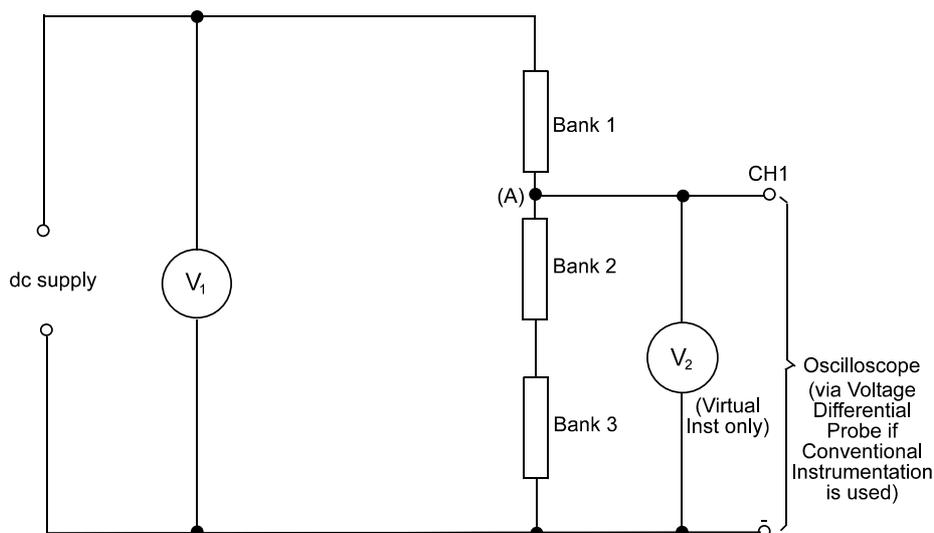
Graphs of direct current and voltage against time are of the form of Figure 3-7-4.



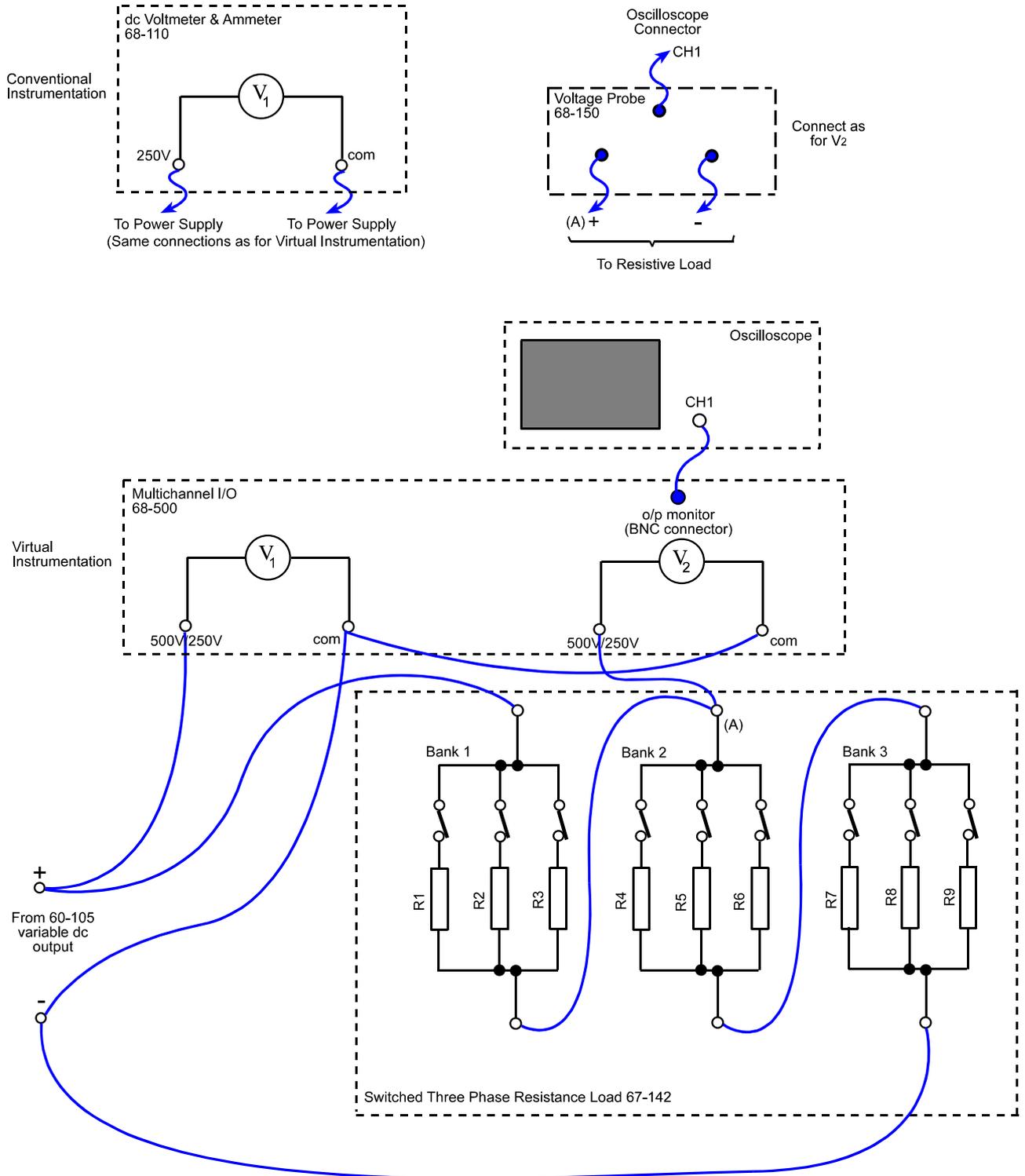
**Figure 3-7-4**

On the Universal Power Supply 60-105, ensure the ‘3 phase circuit breaker’ is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-7-6, which equates to the theoretical circuit shown in Figure 3-7-5.



**Figure 3-7-5: Theoretical Circuit**



**Figure 3-7-6: Practical 7.1 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switches for V1 and V2 channels to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected.

If conventional instrumentation is being used, switch on the differential probe and ensure that the attenuation ratio is set to 1/20.

On the switched three phase resistance load 67-142, set each resistor bank to .....

On the Universal Power Supply 60-105 , ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

By use of the '*variable output voltage*' control, set the output voltage to..... as shown on the virtual or conventional voltmeter.

On the oscilloscope, zero the trace and then set the Y sensitivity to 20 V/cm.

Observe the trace. You should get a graph such as shown in Figure 3-7-4(c) with the voltage level around.....

This trace shows a direct voltage that is varying about a mean value.

On the switched three phase resistance load 67-142, set switches as follows:

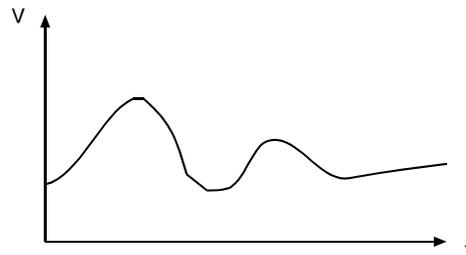
- Bank 1 - all switches set to on to provide.....
- Bank 2 and 3 - switch 1 (upper) set to on, switches 2 and 3 set to off (middle and lower) to provide..... on each of the resistor banks.

**Question 7.1**      *When the load resistance is changed, what does the voltage do, as seen on the oscilloscope?*

**Question 7.2**      *Does it ever cross the zero voltage axis?*

A voltage that is always of the same polarity (ie, one that does not pass through the zero voltage axis), but varies with time may be called a varying direct voltage. Figure 3-7-7 shows such a voltage.

Product Version	
230 V	120 V
546 Ω (all switches on)	
100 V dc	
66 V	
546 Ω 950 Ω	



**Figure 3-7-7**

It is possible for a voltage to vary so that a reversal of polarity occurs. In such cases the term *alternating* voltage is used.

On the Universal Power Supply 60-105, switch off the '3 phase circuit breaker' and connect the circuit shown in Figure 3-7-6 to the **variable ac** output of the power supply unit. Connect the minus (–) supply lead to the 'N' socket and the plus (+) supply lead to the L1 socket.

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Using the 'variable output voltage' control, set the output voltage to..... as shown on the virtual or conventional voltmeter. Remember to change the instrumentation to read ac instead of dc.

Switch the oscilloscope timebase to 5 ms/cm.

**7.6.1 Exercise 7.1**

Draw the waveform you see on a copy of the graphical representation of an oscilloscope screen given in the Results Tables section at the end of this assignment.

**Question 7.3**                      *What is the time period between two successive points of repetition of the waveform?*

**Question 7.4**                      *The period of the waveform is (note value) ..... milliseconds?*

**Question 7.5**                      *If the period of the waveform is as found above, how many complete variations (cycles) does the voltage make each second?*

Product Version	
230 V	120 V
100 V ac	



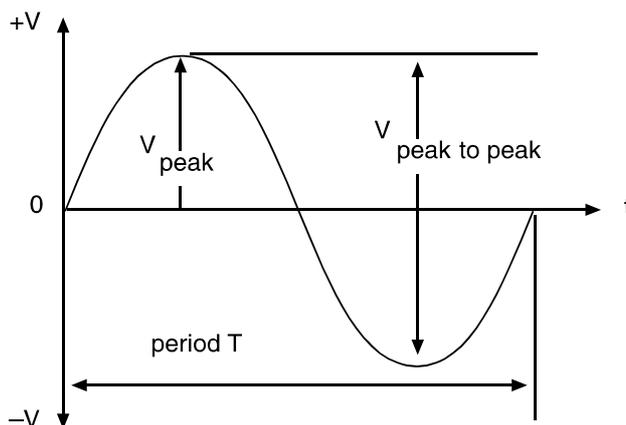
The number of complete variations, known as a 'cycle' made each second is called the *frequency* of the waveform. Frequency is measured in cycles per second, or more correctly, hertz (symbol Hz) after the German physicist Heinrich Hertz (1857–94).

$$1 \text{ cycle/second (c/s)} = 1 \text{ hertz (Hz)}$$

*Question 7.6      The frequency of the waveform examined was .....Hz?*

*Question 7.7      What is the relationship between the period and the frequency of a waveform?*

Measure the peak voltage of the waveform (refer to Figure 3-7-8).



**Figure 3-7-8**

*Question 7.8      The peak-to-peak voltage was ..... volts?*

*Question 7.9      The peak voltage was ..... volts?*

*Question 7.10     What is the relationship between the peak and the peak-to-peak voltages?*

You should find that the period  $T$  and the frequency  $f$  are reciprocals of one another:

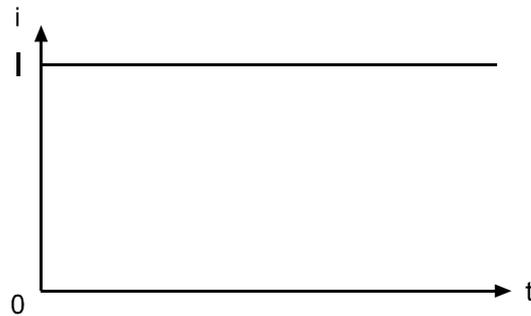
$$T = \frac{1}{f} \text{ and } f = \frac{1}{T}$$

and that  $V_{\text{pk-to-pk}} = 2 \times V_{\text{pk}}$ .

Let us now investigate the power producing properties of some waveforms.



First of all let us consider the direct current waveform of Figure 3-7-9,  $i = I$  (constant).



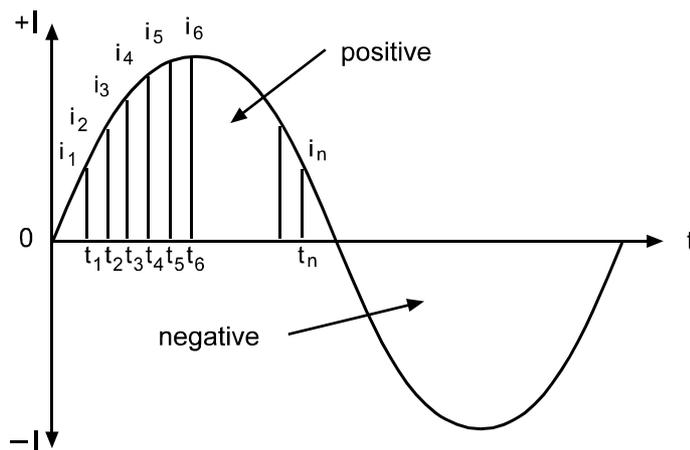
**Figure 3-7-9**

Suppose the current is passed through a resistor of value  $R$  ohms.

At all times the current value is  $I$  amperes and the resistor value is  $R$  ohms, thus the power dissipated in the resistor will be:

$$\text{Power} = I^2 R \text{ watts}$$

Suppose now that a current with the waveform shown in Figure 3-7-10 is passed through the resistor.



**Figure 3-7-10**

At time  $t_1$  the power will be  $i_1^2 R$  watts

At time  $t_2$  the power will be  $i_2^2 R$  watts



At time  $t_3$  the power will be  $i_3^2 R$  watts

At time  $t_n$  the power will be  $i_n^2 R$  watts

∴ The average power produced will be:

$$= \frac{i_1^2 R + i_2^2 R + i_3^2 R + \dots i_n^2 R}{n} \text{ watts}$$

This is the average power produced in the positive half-cycle shown in Figure 3-7-10. The power produced in the negative half-cycle will be the same because the currents, although negative, will have positive squares,

$$\text{ie, } (-i_1)^2 R = i_1^2 R$$

Thus there will be an effective power value of current for the ac waveform. The effective value  $I$  is that value of direct current which produces the same power as the average power produced by the ac.

$$\begin{aligned} \text{i.e where } I^2 R &= \frac{I_1^2 R + I_2^2 R + I_3^2 R + \dots I_n^2 R}{n} \\ \therefore I^2 &= \frac{I_1^2 + I_2^2 + I_3^2 + \dots I_n^2}{n} \\ \therefore I &= \sqrt{\frac{I_1^2 + I_2^2 + I_3^2 + \dots I_n^2}{n}} \end{aligned}$$

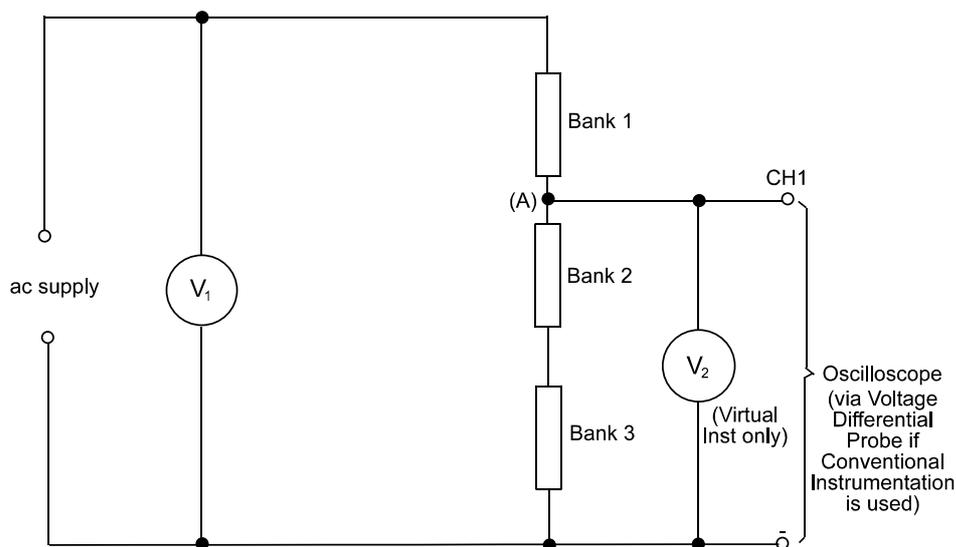
***The effective value of current is found from the root of the mean of the squares of the currents in the ac waveform, and is thus termed the ROOT MEAN SQUARE value, or the rms value of the ac waveform.***



**7.7 Practical 7.2 – Characteristics of a Sine Wave**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-7-12, which equates to the theoretical circuit shown in Figure 3-7-11. Note, if you are continuing from completing practical 7.1 then the connections have been made.



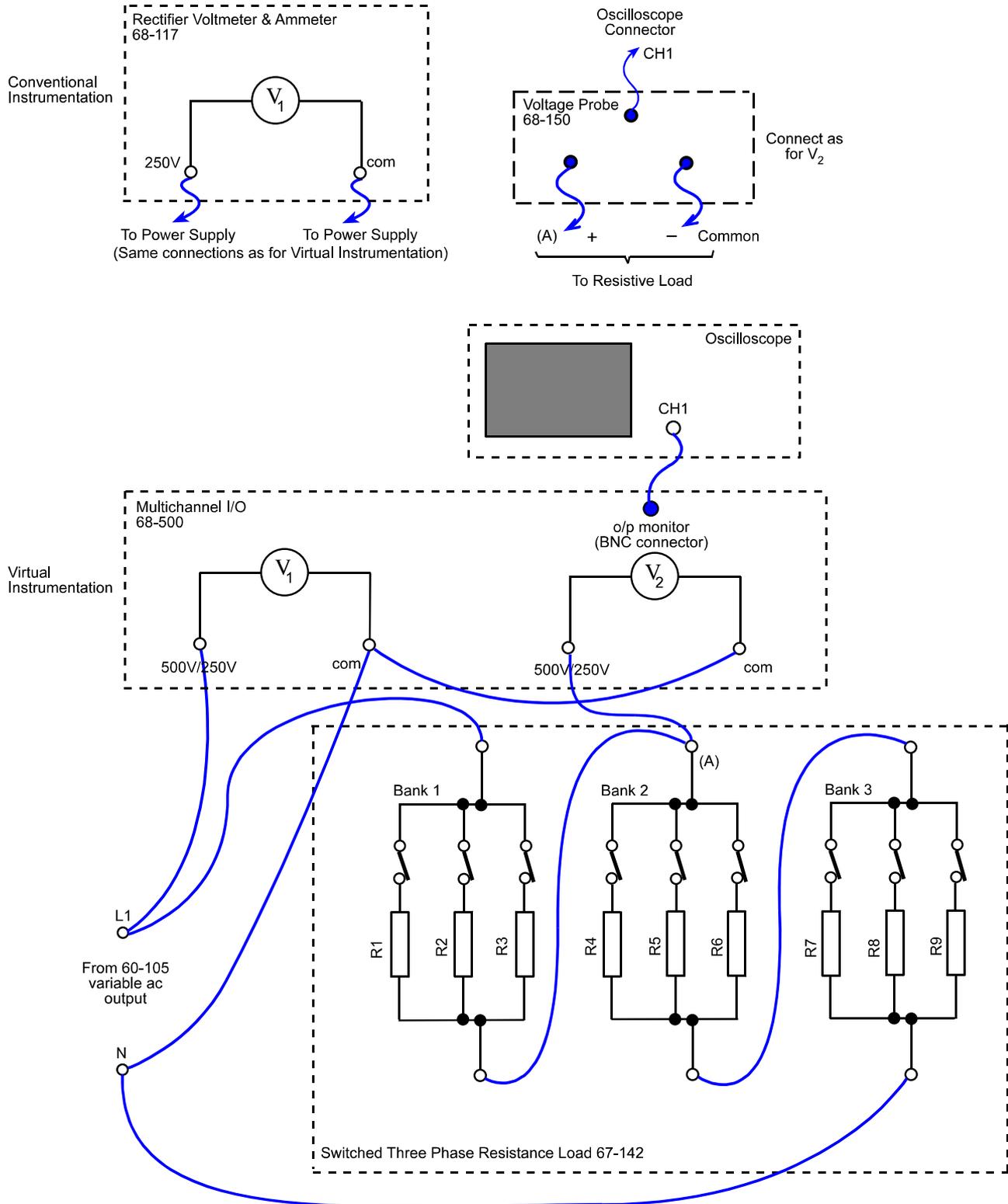
**Figure 3-7-11: Theoretical Circuit**

If virtual instrumentation is being used, set the 250 V/500 V range switches for V1 and V2 channels to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected.

If conventional instrumentation is being used, switch on the differential probe and ensure that the attenuation ratio is set to 1/20.

On the switched three phase resistance load 67-142, set each resistor bank to.....

Product Version	
230 V	120 V
546 Ω (all switches on)	



**Figure 3-7-12: Practical 7.2 Circuit Diagram**



Product Version	
230 V	120 V
100 V ac	

On the Universal Power Supply 60-105 , ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

By use of the '*variable output voltage*' control, set the output voltage to..... as shown on the virtual or conventional voltmeter.

On the oscilloscope, zero the trace and then set the Y sensitivity to 20 V/cm.

Observe the trace on the oscilloscope and record the peak-to-peak voltage on a copy of the appropriate Practical 7.2 Results Table 1 (230 V or 120 V product version) at the end of this assignment.

Calculate the peak-to-peak current and record on your copy of Practical 7.2 Results Table 1.

*Question 7.11                      What is the effective value of the alternating current?*

*Question 7.12                      What is the peak value of the alternating voltage?*

*Question 7.13                      What is the peak value of the alternating current?*

Calculate the relationships between the rms values and the peak values for current and voltage.

The ratio:  $\frac{\text{peak value}}{\text{rms value}}$  is called the *Peak Factor* of the waveform.

*Question 7.14                      What is the peak factor of the current waveform?*

*Question 7.15                      What is the peak factor of the voltage waveform?*

### **7.7.1 Exercise 7.2**

The waveforms you have been examining are approximately of the shape called sinusoidal. This is because the amplitude or value of the waveform at any time is related to the sine of that time. It is possible to construct a sine wave, as shown in Figure 3-7-13 as follows:

Draw a circle with a conveniently sized radius (say one inch). Mark off radii in the circle every 30°. To the right of the circle mark off a vertical axis and a horizontal scale in degrees.

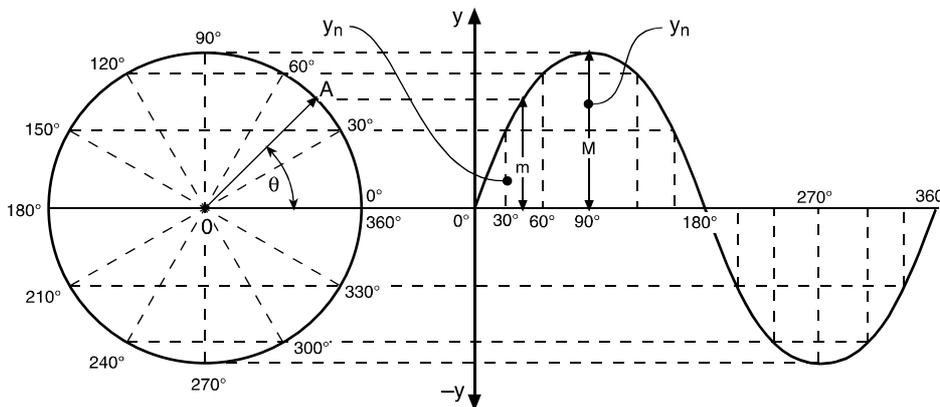


From the points where the radii meet the circle, project horizontal lines to meet the vertical lines drawn from corresponding points on the horizontal scale.

The resultant waveform when these points are joined is a sine wave.

If the rotating vector  $OA$  rotates at an angular speed of  $\omega$  radians per second then, as there are  $2\pi$  radians per revolution, the vector will make:

$$\frac{\omega}{2\pi} \text{ revolutions per second.}$$



**Figure 3-7-13**

Each complete revolution traces out one cycle of sine wave, therefore there will be:

$$\frac{\omega}{2\pi} \text{ cycles per second}$$

Thus the sine wave traced out will have a frequency of:

$$f = \frac{\omega}{2\pi} \text{ Hz}$$

$$\therefore \underline{\omega = 2\pi f}$$

Draw such a sine wave, and mark off the horizontal scale in  $20^\circ$  intervals, ie,  $20^\circ, 40^\circ, 60^\circ, 80^\circ, \dots, 160^\circ, 180^\circ$  to meet your waveform.

Draw vertical lines at the mid-ordinates of these intervals, ie, at  $10^\circ, 30^\circ, 50^\circ, \dots, 150^\circ, 170^\circ$ .



Calling the peak value of the sine wave unity (ie, the radius of the circle  $r = 1$ ), graduate the vertical axis between  $-1$  and  $+1$ .

On a copy of the appropriate Practical 7.2 Results Table 2 (230 V or 120 V product version) at the end of this assignment, enter the values of the mid-ordinates for the angles given in the table.

Calculate:

$$y_{10}^2 + y_{30}^2 + y_{50}^2 + y_{70}^2 + \dots y_{170}^2$$

In the above, the number of mid-ordinates is 9.

$\therefore$  Calculate:

$$\frac{y_{10}^2 + y_{30}^2 + y_{50}^2 + y_{70}^2 + \dots y_{170}^2}{9}$$

Square root this to find:

$$\sqrt{\frac{y_{10}^2 + y_{30}^2 + y_{50}^2 + y_{70}^2 + \dots y_{170}^2}{9}}$$

This will give you the rms value of a sine wave whose peak value is unity.

**Question 7.16**      *How does this compare with the peak factor that you calculated earlier?*

Multiply the rms value above by the peak value of the alternating voltage used before.

Do the same for the alternating current.

You should have found that the peak factor for a pure sine wave is given by:

$$\begin{aligned} \text{Peak factor} &= \sqrt{2} \\ &= 1.414 \end{aligned}$$

Also the rms value of a sine wave with unity peak value should be:

$$\text{rms} = \frac{1}{\sqrt{2}}$$



Thus we can say:

$$\text{For a sine wave } V_{\text{rms}} = 0.707V_{\text{peak}}$$

If a source of triangle and/or square waves is available, repeat the experiment to find the rms values of those waveforms. Construct graphically triangle and square waves and verify your experimental results.

### **7.8 Practical Aspects**

The way in which the value of an ac voltage or current is specified depends on the circumstances in which the value is being used. For instance, if a capacitor with a given voltage rating is to be used in an ac circuit, then the maximum, or peak value of the ac waveform must be used to determine whether the capacitor is working within its rating.

Conversely, if a resistor is to be used in an ac circuit, then the rms value of the waveform should be used to determine the power rating needed for the resistor.

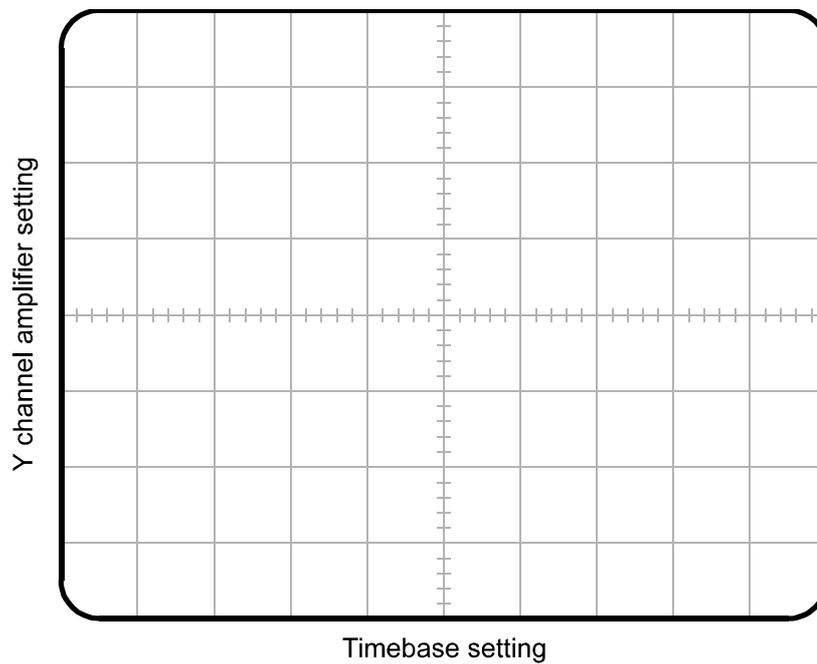
When an ac waveform is rectified and measured by a moving-coil meter the deflection of the needle is proportional to the average value of the waveform. The average value is the normal average taken over a positive or negative half cycle.

For a sinusoidal waveform the average value is  $0.636V_{\text{peak}}$ .

The calibration on the face of rectifying moving coil meters, and indeed on most ac meters, is given in terms of the rms value, and its accuracy is dependent on the fixed ratio between the average and rms values of a sinusoidal waveform. Thus if any wave with a shape other than sinusoidal is measured with an ac meter the indicated value will be incorrect, as this ratio will be different for different waveforms.



**7.9 Practical 7.1 - Oscilloscope Screen Graticule Representation  
(230 & 120 V Product Versions)**





**7.10 Practical 7.2 - Results Tables (230 V Product Version)**

Table 1

<b>ac Voltage, peak-to-peak (pk-pk V)</b>	<b>ac Current peak-to-peak (pk-pk mA)</b>

Table 2

<b>angle</b>	<b><math>y_n</math></b>	<b><math>y_n^2</math></b>
10		
30		
50		
70		
90	1.0	
110		
130		
150		
170		



**7.11 Practical 7.2 - Results Tables (120 V Product Version)**

Table 1

<b>ac Voltage, peak-to-peak (pk-pk V)</b>	<b>ac Current peak-to-peak (pk-pk mA)</b>

Table 2

<b>angle</b>	<b><math>y_n</math></b>	<b><math>y_n^2</math></b>
10		
30		
50		
70		
90	1.0	
110		
130		
150		
170		



Notes



## **8 Resistive Circuit at ac**

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### **8.1 Assignment Information**

#### **8.1.1 Objectives**

When you have completed this assignment you will:

- have investigated a resistive circuit at ac.

#### **8.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignment 1, Familiarisation.
- you should have completed Assignment 7.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **8.1.3 Practicals**

1. Current and Voltage Phase Relationship

**NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **8.2 Theory**

### **8.2.1 Introduction**

In previous assignments, we looked at how a resistor behaves in a dc circuit in which current flowed from positive to negative. We will now see how a resistor behaves in an ac circuit when current flow alternates in direction in accordance with the generated supply.



### 8.3 Content

The practical in this assignment familiarises the student with the concepts of alternating current theory as it is applied to a resistive load.

### 8.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit Software Pack	68-500 68-912-USB
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**or**

Conventional Instrumentation	Rectifier Voltmeter & Ammeter (Option CI2)	68-117
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Ancillary Equipment	Differential Voltage Probe 2 off (Required for Conventional Instruments only) Two channel oscilloscope 20 MHz bandwidth minimum	68-150
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#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 8.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

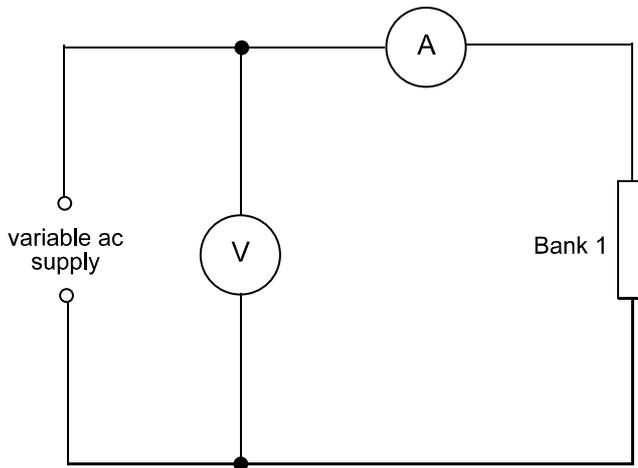
If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



**8.6 Practical 8.1 - Current and Voltage Phase Relationship**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-8-2, which relates to the theoretical circuit shown in Figure 3-8-1.



**Figure 3-8-1: Theoretical Circuit**

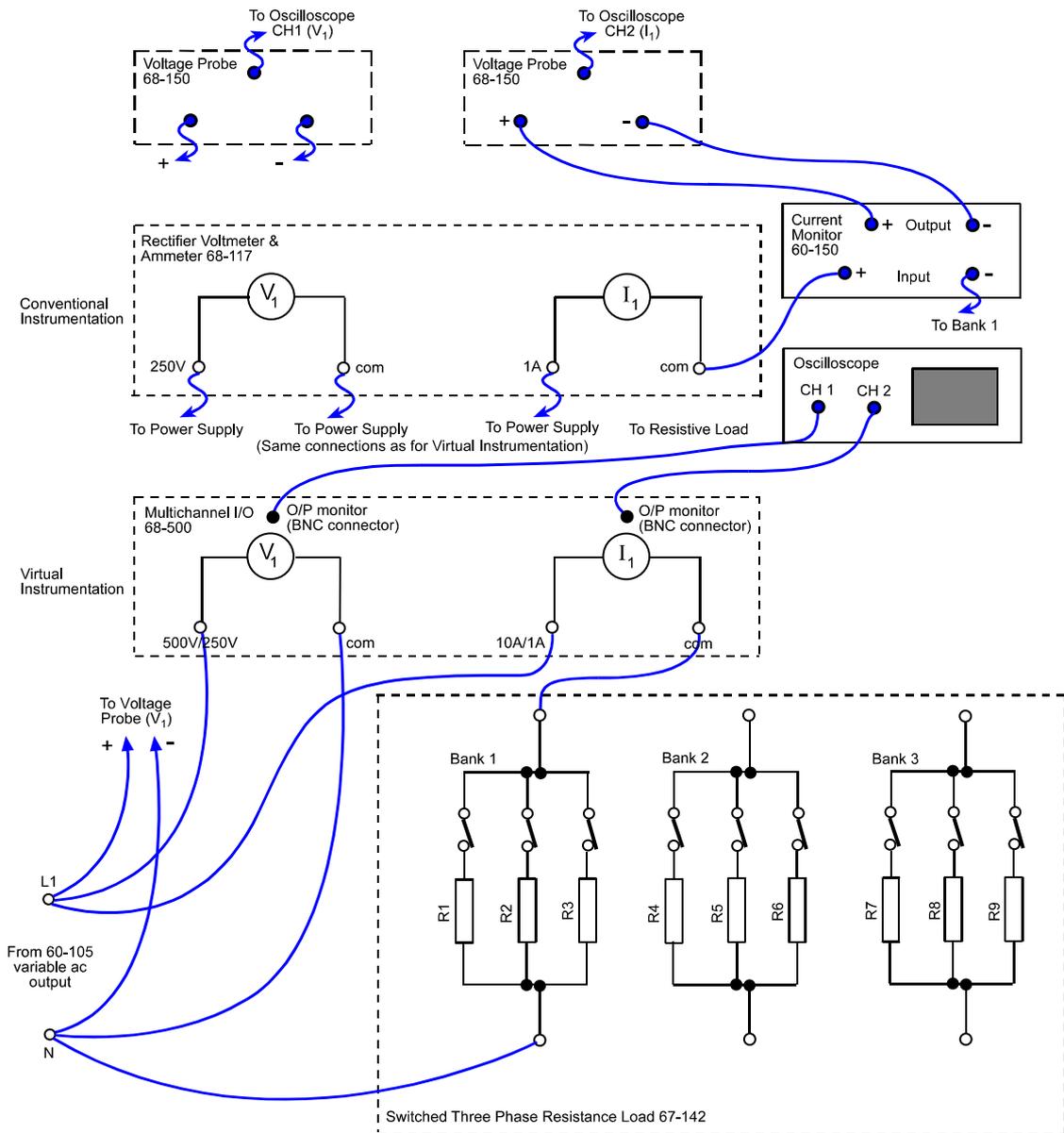
If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

For Conventional instrumentation set the voltage probe V1 to 1/200 and the current probe I1 to 1/20.

On the switched three phase resistance load 67-142, set switches as follows:

- Bank 1 - all switches set to on to provide.....

Product Version	
230 V	120 V
546 Ω	



**Note:** The Differential Probes and Current Monitor 68-150 are required for Conventional Instruments only

**Figure 3-8-2: Practical 8.1 Circuit Diagram**



Product Version	
230 V	120 V
200 V	100 V

On the oscilloscope, set the time base to 2 mS/div and the 'trigger' to 'line' or CH1 if line is not available.

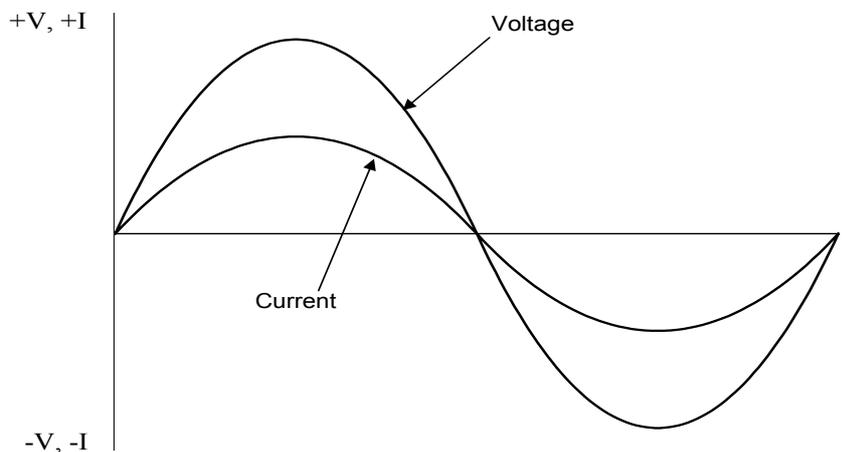
On the Universal Power Supply 60-105 , ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Increase the '*variable output voltage*' slowly whilst observing voltage and current as shown on the oscilloscope display up to a voltage V1 of.....

Your oscilloscope display should be similar to figure 3-8-3.

*Question 8.1 Do the waveforms keep in step with each other as you vary the supply voltage?*

You should find that when current is zero, the voltage is zero. By Ohm's Law, the current is proportional to the voltage, so that if ac is applied to a resistor, the current and voltage waveforms will be the same shape. See Figure 3-8-3.



**Figure 3-8-3**

The two waveforms will have their zeros at the same time, and their maximum and minimum values at the same time; they are said to be in phase with one another.

**In a resistor, the current and voltage are said to be *in phase*.**



### **8.7 Practical Aspects**

Resistors are used at ac in similar ways to the dc applications of earlier assignments. There is no phase shift introduced by a true resistance, and the ratio of voltage to current in a resistance is constant with frequency, so the behaviour with ac is no different from its behaviour with dc.

**NOTE:**

When calculating power dissipation at ac, rms values of voltage and current must be used.



Notes



## **9 Capacitive Circuit at ac**

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### **9.1 Assignment Information**

#### **9.1.1 Objectives**

When you have completed this assignment you will:

- know the phase relationship between current and voltage in a capacitive circuit at ac.
- know the meaning of capacitive reactance.
- know how to calibrate capacitors.
- know the effects of connecting capacitors in series or parallel.

#### **9.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignment 1, Familiarisation.
- you should have completed Assignment 7.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **9.1.3 Practicals**

1. Current and Voltage Phase Relationship
2. Reactance in Capacitive Circuit
3. Calibration of Capacitors
4. Capacitors in Series
5. Capacitors in Parallel

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## 9.2 Theory

### 9.2.1 Introduction

Prior to considering a capacitive circuit at ac, it is helpful to review basic capacitor theory.

### 9.2.2 General

A capacitor is an electrical device designed to store an electrical charge. Normally, it consists of two parallel plates separated by an insulating layer called the dielectric.

The capacitance of a capacitor is affected by the area of the plates, the distance between the plates, and the ability of the dielectric to support electrostatic forces.

- Larger plates provide greater capacity to store electric charge. Therefore, as the area of the plates increases, capacitance increases.
- The value of the capacitor is inversely proportional to the spacing between the plates.
- Dielectric materials are rated on their ability to support electrostatic forces and are given a number called the dielectric constant ( $k$ ). The higher the dielectric constant, the greater the ability of the dielectric to support electrostatic forces. Therefore, as the dielectric constant increases, capacitance increases.

### 9.2.3 Unit of Capacitance

The unit of capacitance is the farad (F), named after the English scientist Michael Faraday (1791–1867). Common ranges of values for capacitors are:

- Microfarad ( $\mu\text{F}$ ) = value  $\times 10^{-6}$  F
- Nanofarad (nF) = value  $\times 10^{-9}$  F
- Picofarad (pF) = value  $\times 10^{-12}$  F

### 9.2.4 Charge on a Capacitor

The amount of charge on a capacitor is given by:

$$Q = VC$$

where:

$Q$  = electrical charge in coulombs

$C$  = value of capacitance in farads

$V$  = voltage across the plates of the capacitor



### 9.2.5 RC Time Constant

When a capacitor is connected in series with a resistor and a dc voltage is connected across the circuit, it will take some time for the capacitor to charge up to value of the applied voltage. Similarly, when the supply voltage is removed, it will take some time for the capacitor to discharge to zero. Both charging and discharging of the capacitor is not at a steady rate. As shown in Figure 3-9-1, initially the rate is rapid but slows considerably as full charge or discharge is approached. To enable the charging or discharging times to be calculated, a time constant is used as follows:

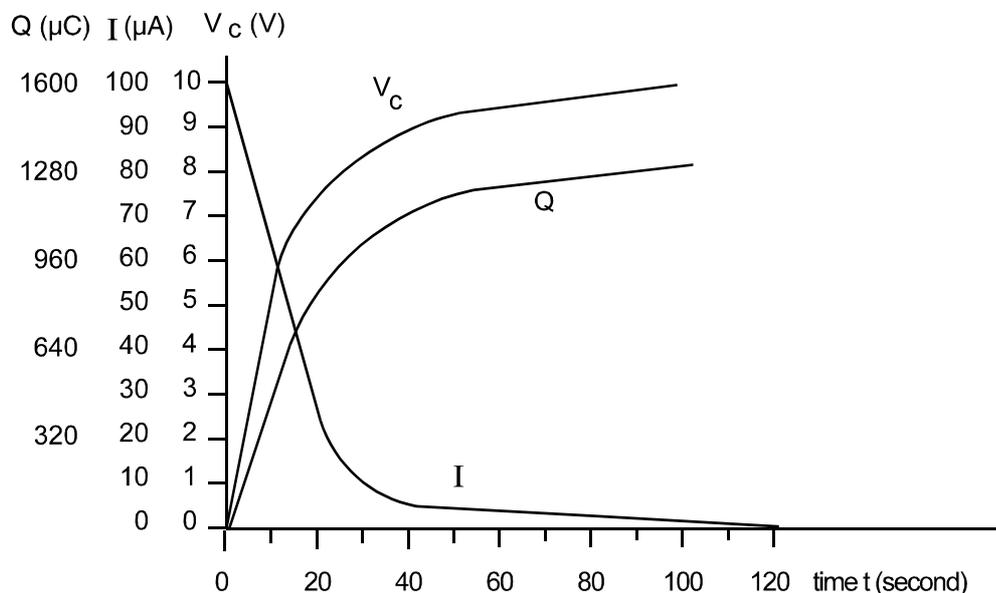
$$T = RC$$

where:

- T = time constant in seconds and is equal to 63.2% of the distance to maximum voltage level.
- R = resistance in ohms
- C = capacitance in farads.

To calculate the time required to achieve full charge or discharge of a capacitor:

Multiply the time constant (T) by 5



**Figure 3-9-1: Typical Charging Curves**



### **9.2.6 Value of Capacitor**

When you know the common area between plates of a capacitor and the distance between them in meters, you can calculate the value of capacitance using:

$$C = kA/s$$

where:

C = value of capacitance in farads, F

k = dielectric constant of plates separating material

A = common area between the plates in m<sup>2</sup>

s = spacing the plates in inches.

**Caution:**

When a capacitor is fully charged, it has been shown that it takes some time for it to be discharged after the charging supply has been removed. Care should be taken when handling capacitors in a charged condition and an appropriate discharge circuit should be used to ensure the item is fully discharged. In the 67-212 Three Phase Capacitive Load, discharge resistors are fitted to avoid the presence of high voltages when the capacitors are not in use.



### 9.3 Content

The practicals in this assignment familiarise the student with the concepts of alternating current theory as it is applied to a capacitive circuit.

### 9.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- Switched Three Phase Capacitive Load 67-212
- System Frame 91-200
- Standard Set of Patch Leads 68-800:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation (Option 60-070-CI2)	Rectifier Voltmeter & Ammeter	68-117
	Electrodynamic Wattmeter	68-204
Ancillary Equipment	Differential Voltage/Current Probe (2 off) (Required for Conventional Instruments only)	68-150
	Two channel oscilloscope with 20MHz bandwidth.	

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 9.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 9.6 Practical 9.1 – Current and Voltage Phase Relationship

As already stated, the relationship between charge, voltage and capacitance is:

$$Q = VC$$

Also,

$$Q = It,$$

where I is current and t is time. Combining these equations, we can say that if a capacitor of C farad is charged from 0 volts to V volts in t seconds, then:

$$I = \frac{V}{t} \times C \text{ coulombs/second}$$

That is to say,

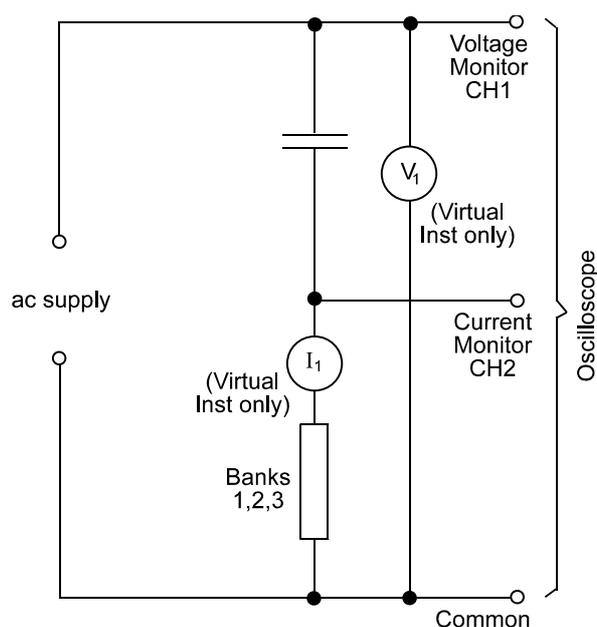
$$\text{charging current} = \text{rate of increase of voltage} \times \text{capacitance}$$

Let us see what happens when a sinusoidal alternating voltage is applied to a capacitor.

#### 9.6.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-9-3, which relates to the theoretical circuit shown in Figure 3-9-2..



**Figure 3-9-2: Theoretical Circuit**

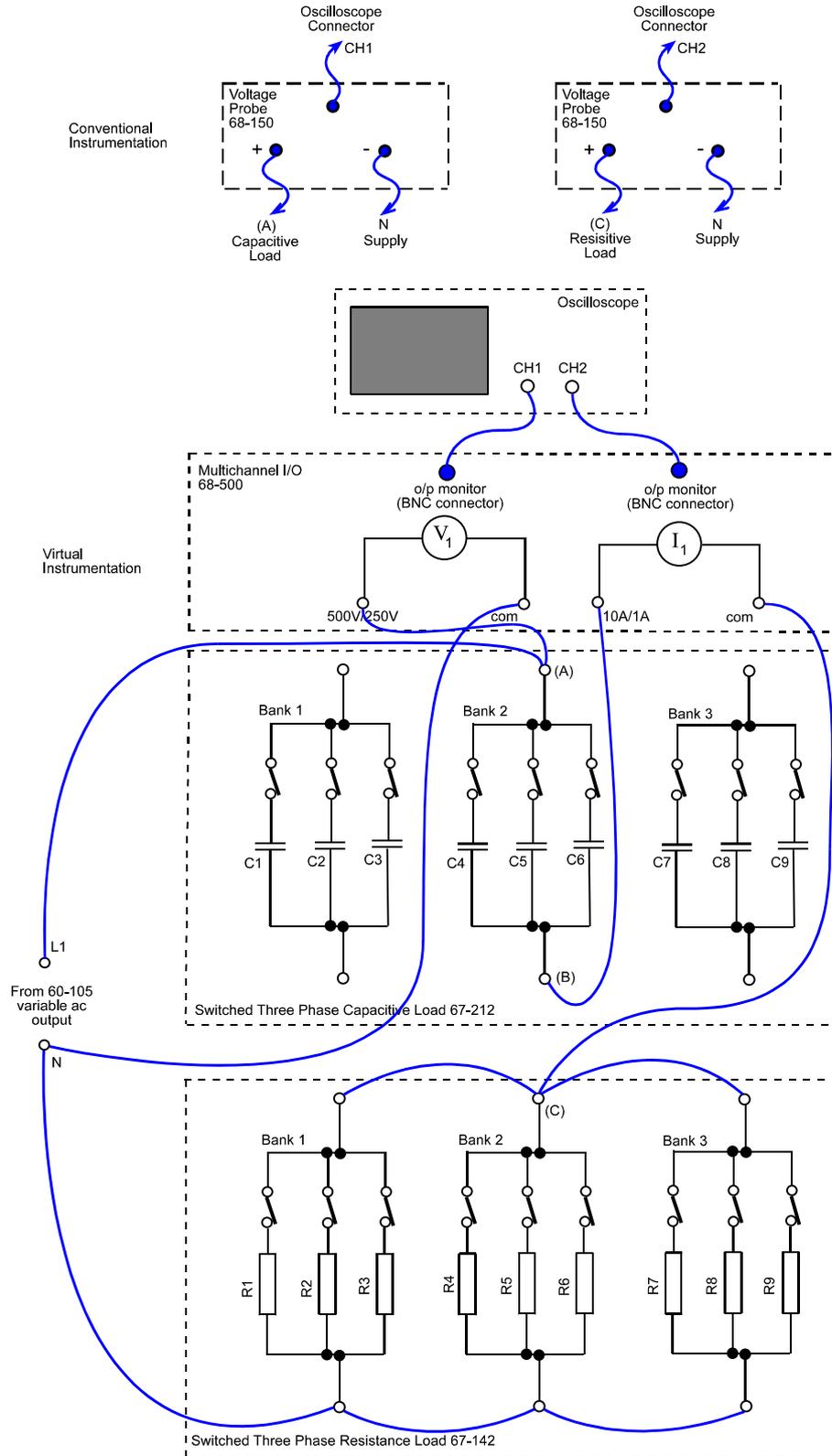


Figure 3-9-3: Practical 9.1 Circuit Diagram



If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 channel to '250 V' on Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or currents of up to 200 mA to be monitored when the 200 mA socket is connected.

If conventional instrumentation is being used, switch on the differential probe and ensure that the attenuation ratio is set to 1/200.

On the switched three phase resistance load 67-142, set all switches to on to give a resistance of.....

On the switched three phase capacitive load 67-212, ensure banks 1 and 3 switches are set to off, and bank 2 switch 2 (middle) is set to on and switches 1 and 3 (upper and lower) are set to off to give a capacitance of ...

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

With the 'variable output voltage' control set voltmeter V1 to indicate..... as shown on the virtual or conventional instrumentation.

Product Version	
230 V	120 V
182 Ω	
2 μF.	
150 V ac	

Set the oscilloscope as follows:

- CH1 (Y1) channel - 200 V/cm
- CH2 (Y2) channel - 100 mV/cm
- Timebase - 5 ms/cm

On the oscilloscope, set both traces at the central X axis with no input connected then observe the two waveforms.

The trace on channel 1 is the supply voltage waveform and on channel two the capacitor current.

Note that the current waveform may not be of a typical sine wave shape due to distortion in the supply voltage waveform.



### 9.6.2 Exercise 9.1

Draw the waveforms you see on a copy of the oscilloscope screen graticule representation given in Practical 9.1, Results Table at the end of this assignment.

- Question 9.1*                      *Where on the waveforms is the rate of change of voltage a positive maximum?*
- Question 9.2*                      *Where on the waveforms is the rate of change of voltage zero?*
- Question 9.3*                      *Where on the waveform is the rate of change of voltage a negative maximum?*
- Question 9.4*                      *Using the same notation as in Assignment 7, Figure 3-7-13 (ie, 360° in one cycle), how many degrees are the two waveforms apart?*
- Question 9.5*                      *What proportion of a cycle is that?*
- Question 9.6*                      *Remembering that the time increases towards the right, which of the two waveforms reaches its positive maximum first?*

As the current waveform reaches its positive peak value 90° before the voltage waveform reaches that value, we say that:

***The current in a capacitive circuit leads the voltage by 90°.***

Often the 90° is referred to as  $\frac{\pi}{2}$

As there are  $2\pi$  radians in 360°, then 90° is  $\frac{\pi}{2}$  radians.

Mathematically, if the voltage waveform is denoted by the formula:

$$v = V_{\max} \sin \omega t$$

then as  $i = C \times$  rate of change of voltage

$$i = C \frac{dv}{dt} = CV_{\max} \times \frac{d}{dt}(\sin \omega t)$$

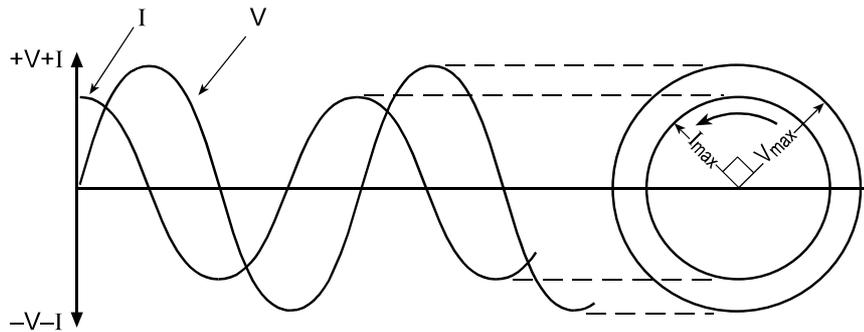
$$\therefore i = CV_{\max} \omega \cos \omega t$$

Thus if  $v$  is sinusoidal,  $i$  will be cosinusoidal, ie, the same shape, but leading by 90°.



This is because  $\cos \omega t = \sin (\omega t + 90^\circ)$

Assignment 7, Figure 3-7-13 shows how a sine wave can be plotted by taking projections from a rotating vector.

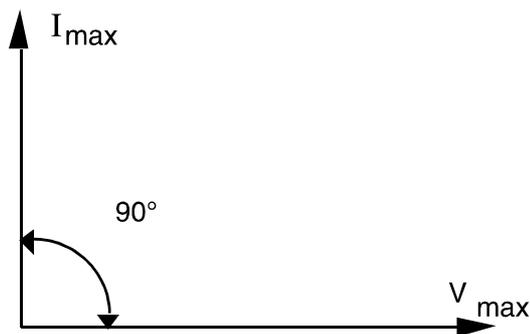


**Figure 3-9-4**

If we were to plot the voltage and current waveforms in the capacitor by that method we would require two vectors. Both vectors would rotate while keeping a constant  $90^\circ$  angle between them, as shown in Figure 3-9-5.

As we go on we shall find it useful to think in terms of these vectors, but rather confusing if they are always rotating. Usually it is the relationships between them that are important, as for instance the  $90^\circ$  angle between those in Figure 3-9-5.

These relationships can be studied conveniently in a diagram where the vectors are shown at rest. The vectors are then said to be represented by 'phasors' and the diagram is a 'phasor diagram'. Figure 3-9-5 is a phasor diagram corresponding to Figure 3-9-5.



**Figure 3-9-5**

The voltage phasor is taken as the reference and is drawn horizontally pointing to the right (3 o'clock). The current phasor leads the voltage phasor by  $90^\circ$  and is thus drawn  $90^\circ$  counter-clockwise from the reference.

When an alternating voltage is applied across a capacitor an alternating current flows. Yet when a dc voltage is applied, after an initial flow of charging current, no dc current flows. This behaviour is different from that of a resistance. Nevertheless, if an ac voltage and an ac current can exist, the ratio between them is likely to be of interest, and the ratio is therefore given a different name.

In an ac circuit the ratio of voltage to current is called 'impedance' and is denoted by Z.



Thus in an ac circuit  $Z = \frac{V}{I}$ .

Note that impedance may be taken as the ratio of two phasors, and therefore has both magnitude and phase.

$$\text{Magnitude} = |Z| = \frac{V_{\max}}{I_{\max}}$$

Phase of the impedance is the angle between the phasors. The impedance of a capacitor has a phase of  $-90^\circ$  or  $-\frac{\pi}{2}$  radians.

Impedances of  $\pm 90^\circ$  phase angle have special properties and are given the special name '*reactance*'.

For further information on phasors, see Appendix B.1.

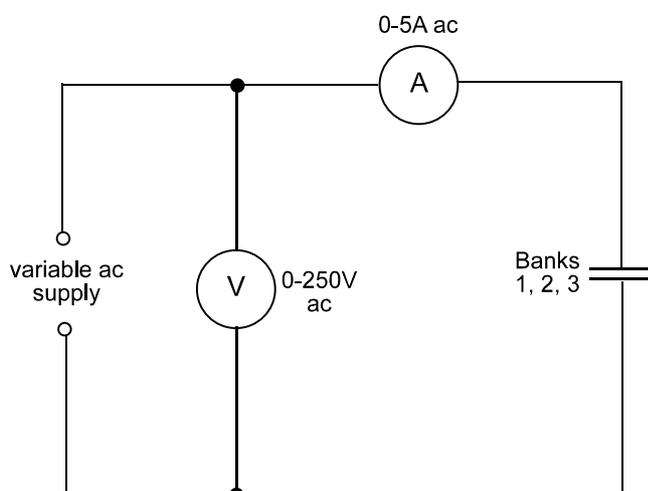
### 9.7 Practical 9.2 - Reactance in Capacitive Circuit

In a capacitor, a sinusoidal current and voltage are always  $90^\circ$  out of phase with one another, so that the phase of the impedance is constant. The magnitude varies, however, in a manner which we shall now discover.

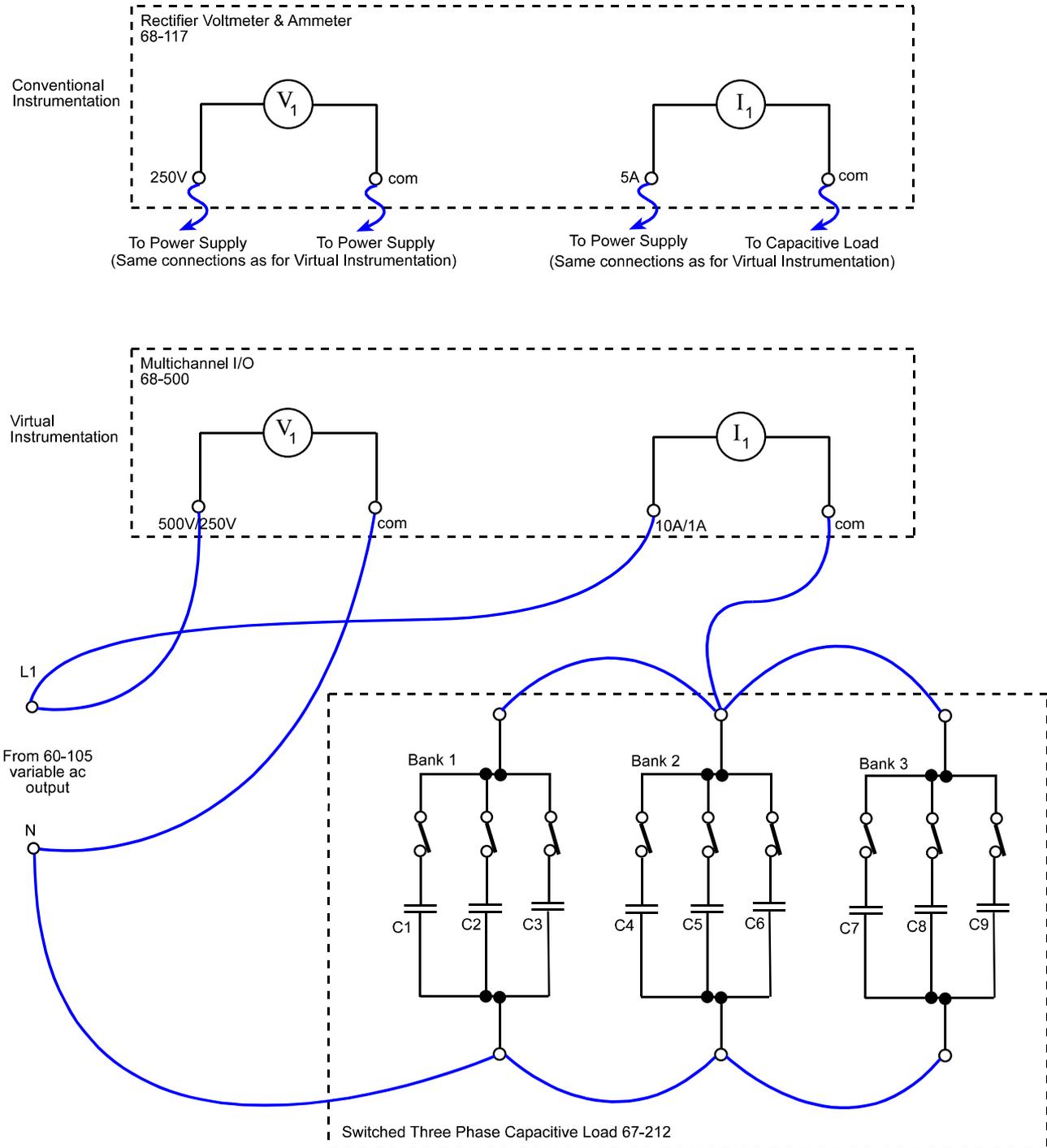
#### 9.7.1 Procedure

On the Universal Power Supply 60-105, ensure the '*3 phase circuit breaker*' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-9-7, which relates to the theoretical circuit shown in Figure 3-9-6.



**Figure 3-9-6**



**Figure 3-9-7: Practical 9.2 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase capacitive load 67-212, set all the banks of switches to the on position so that the capacitance in circuit is.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter indicates..... as shown on the virtual or conventional instrumentation.

Measure and record on a copy of the appropriate Practical 9.2, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for a supply voltage of .....

Repeat this procedure for voltages of ..... recording all results on your copy of Practical 9.2, Results Table.

Product Version	
230 V	120 V
21 $\mu$ F	
50 V ac	
50 V ac	
100 V, 150 V and 200 V	

**9.7.2 Exercise 3.2**

From the results in your copy of Practical 9.2, Results Table, calculate the ratio of rms voltage to rms current.

*Question 9.7 Is there any relationship between rms voltage and rms current?*

We can define the magnitude of the impedance Z as the ratio of the rms voltage to rms current.

(For the remainder of the assignment 'the magnitude of the impedance' will be abbreviated to 'impedance').

*Question 9.8 What is the average value of the impedance?*



*Question 9.9*                      *Thus we can say that the impedance of the capacitor is ..... ohms at a frequency of 50 Hz.*

We know that the impedance of a pure capacitor at dc is infinite, and we have now found the impedance of the capacitor at 50 Hz.

*Question 9.10*                      *Are they the same?*

It would seem reasonable to assume that the impedance of a capacitor is proportional in some way to the frequency of the voltage across it.

**9.7.3 Frequency Effect**

Increasing the frequency of the supply voltage would decrease the opposition offered by the capacitor. This occurs because the number of electrons which the capacitor is capable of handling at a given voltage will change plates more often. As a result, more electrons will pass a given point in a given time (greater current flow). The opposition which a capacitor offers to ac is therefore inversely proportional to frequency and to capacitance. This opposition is called capacitive reactance.

The input voltage is sinusoidal, so we can represent it mathematically as:

$$v = V_{\max} \sin \omega t$$

and that:

$$i = CV_{\max} \omega \sin \left( \omega t + \frac{\pi}{2} \right)$$

Thus, when  $i = I_{\max}$

ie when  $\sin \left( \omega t + \frac{\pi}{2} \right) = 1$

$$I_{\max} = CV_{\max} \omega$$

$$\therefore \frac{V_{\max}}{I_{\max}} = \frac{1}{\omega C}$$

Now, for a sine wave we know:

$$\frac{V_{\max}}{V_{\text{rms}}} = 1.414 \qquad \therefore V_{\max} = 1.414V_{\text{rms}}$$

and 
$$\frac{I_{\max}}{I_{\text{rms}}} = 1.414 \qquad \therefore I_{\max} = 1.414I_{\text{rms}}$$



$$\text{Thus } \frac{V_{\max}}{I_{\max}} = \frac{V_{\text{rms}}}{I_{\text{rms}}}$$

$$\text{Therefore } \frac{V_{\text{rms}}}{I_{\text{rms}}} = \frac{1}{\omega C}$$

$$\therefore Z_c = \frac{1}{\omega C}$$

Therefore, as  $\omega = 2\pi f$

$$Z_c = \frac{1}{2\pi f C}$$

Thus the impedance of a capacitor is inversely proportional to both the frequency and the capacitance.

The impedance of a capacitor is normally termed *capacitive reactance*, and is given the symbol  $X_c$ .

In comparing your experimental impedance values with this calculated value, bear in mind that the capacitor has a  $\pm 20\%$  tolerance, and that any errors in measuring the voltage, the current and the frequency may increase further the discrepancy between experimental and calculated values. Your results should, however, show the correct form of the impedance-frequency relationship quite well.



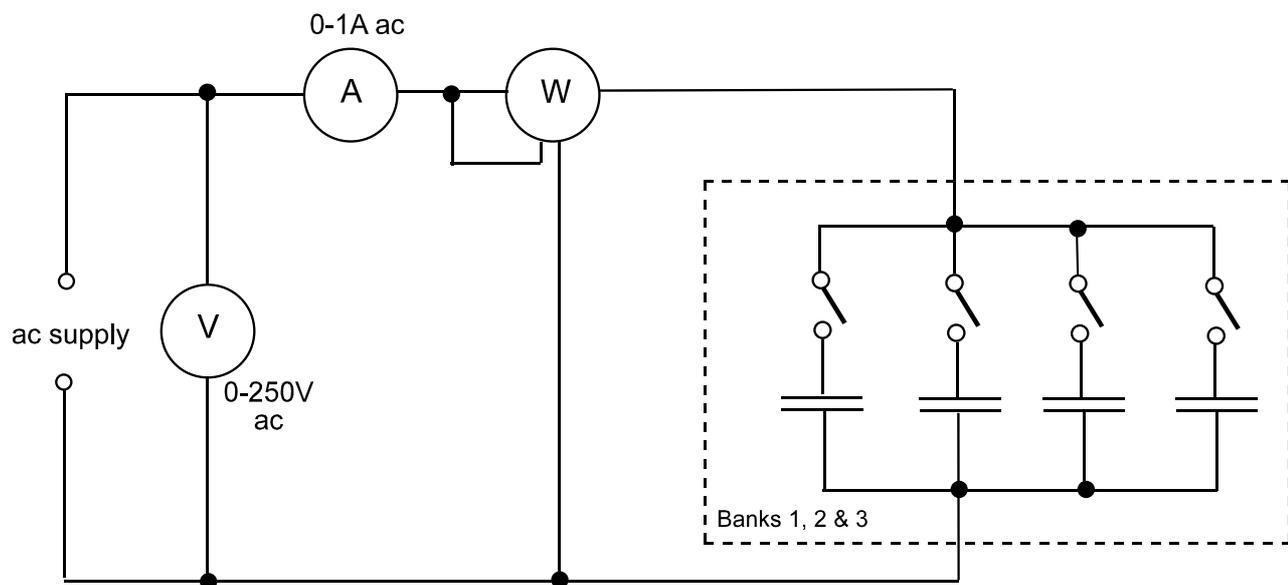
### 9.8 Practical 9.3 – Calibration of Capacitor

The resistance and other losses associated with capacitors are usually small enough to be neglected. It is therefore not necessary to measure the power loss except to confirm this. However, the capacitance of each capacitor may differ from its nominal value. It must therefore be calibrated for future reference.

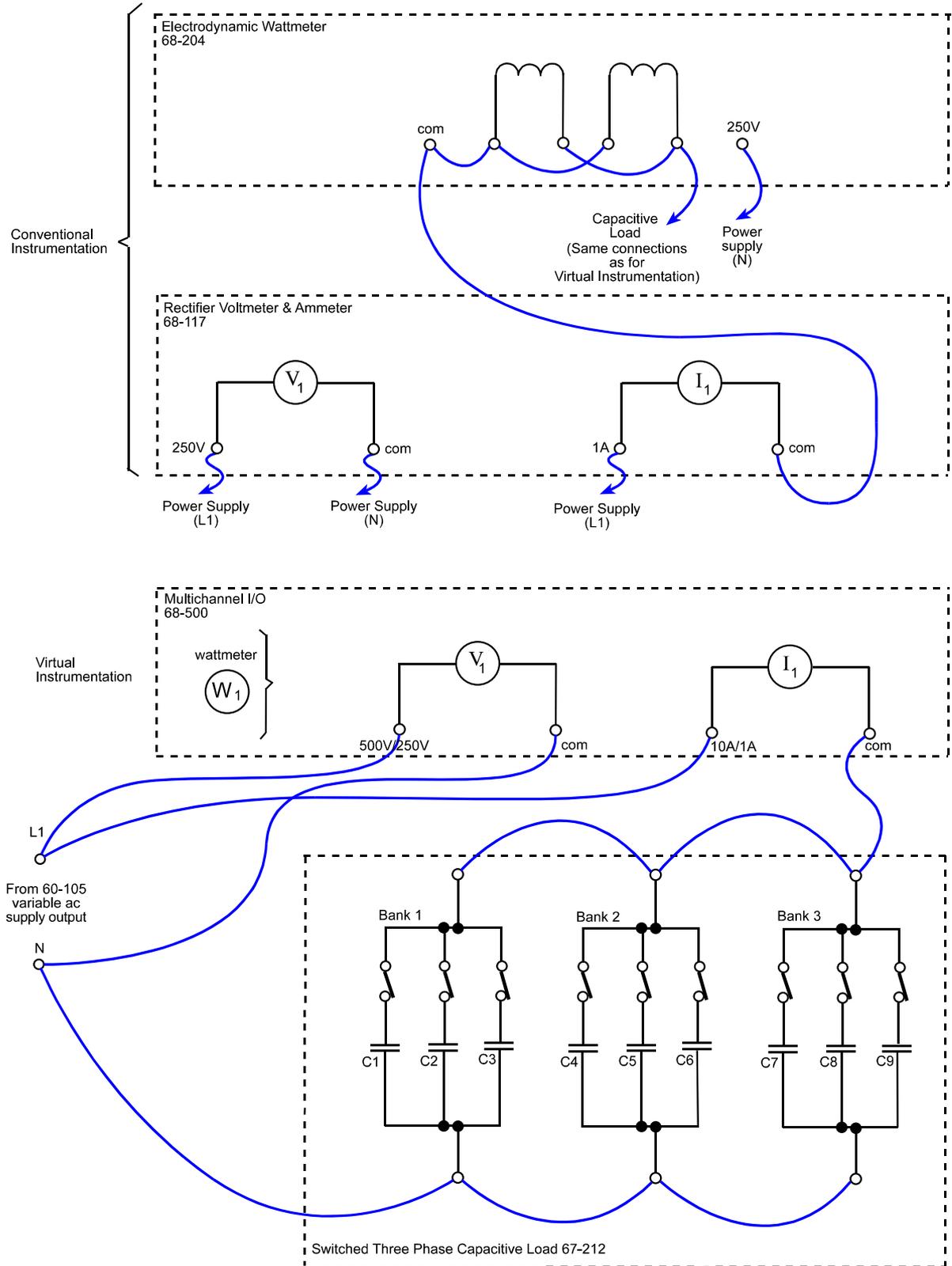
#### 9.8.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-9-9, which equates to the theoretical circuit shown in Figure 3-9-8.



**Figure 3-9-8: Theoretical Circuit**



**Figure 3-9-9: Practical 9.3 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase capacitive load 67-212, ensure banks 2 and 3 switches are set to off, and bank 1, switch 1 and 2 (upper and middle) are switched on and switches 3 (lower) is set to off to give a capacitance of.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 9.3, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for a capacitance of .....

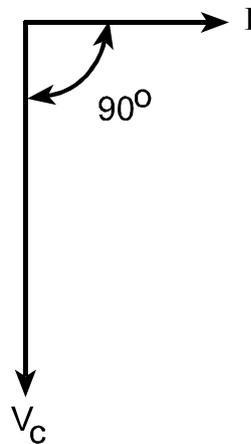
Repeat this procedure for capacitance values of .....  
 While the last capacitor to be tested is still passing current, observe the wattmeter. Do not be surprised if the reading is very small.

On the Universal Power Supply 60-105, set the '*variable output voltage*' control to 0% then set the '*3 phase circuit breaker*' to the off position.

**9.8.2 Analysis of Results**

As the resistive component of the capacitor's impedance is negligible, the whole of the applied voltage is assumed to appear across the capacitor's reactance. Also, the current in a capacitance leads the applied voltage by 90°, as shown in the phasor diagram Figure 3-9-10.

Product Version	
230 V	120 V
3 $\mu F$	
200 V ac	
3 $\mu F$	
6, 9 and 12 $\mu F$ .	



**Figure 3-9-10**

From the measured voltage and current, we can calculate the capacitive reactance ( $X_C$ ):

$$\begin{aligned} X_C &= \frac{V}{I} \\ &= \frac{1}{2\pi fC} \end{aligned}$$

where  $f$  is the supply frequency.

The capacitance  $C$  can therefore be calculated as:

$$C = \frac{1}{2\pi fX_C}$$

### **9.8.3 Exercise 9.3**

Calculate  $X_C$  and  $C$  for each nominal value of capacitor and record the results in your copy of Practical 9.3, Results Table.

On a copy of the graph axis given in the Results Tables section for Practical 9.3 at the end of the assignment, plot a graph of measured values of capacitance against nominal values using the tabulated results in your copy of Practical 9.3, Results Table.

#### **NOTE:**

The power absorbed by an ideal capacitor is always zero. In practise, the capacitors in this equipment are (in accordance with usual practice) provided with parallel-connected resistors to discharge the capacitors when not in use. Each resistor will, under the conditions of the practical, absorb about 1W, which is not measurable with any certainty by means of the wattmeter provided.



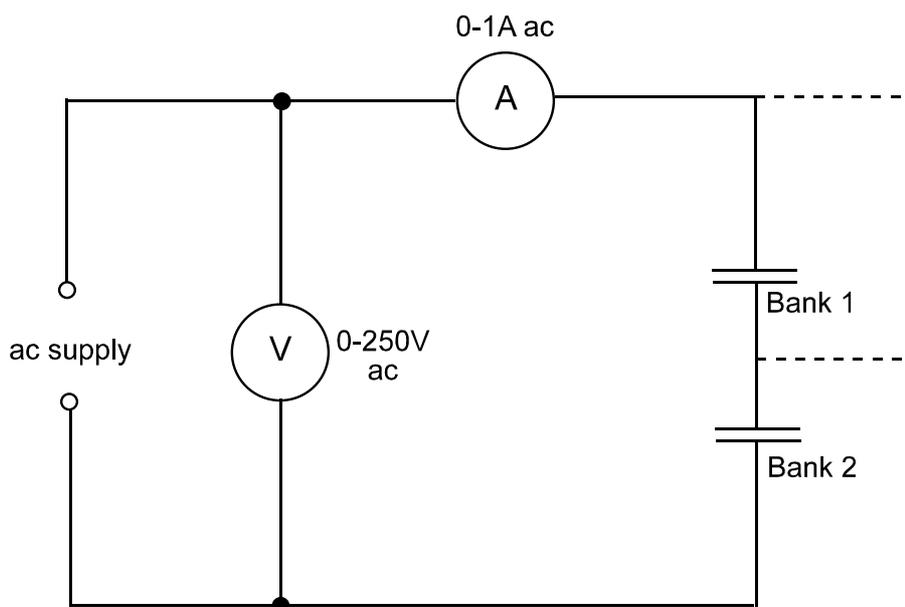
### 9.9 Practical 9.4 – Capacitors in Series

Using the calibration of capacitors procedure given in Practical 9.3, it is possible to show the effect of connecting capacitors in series.

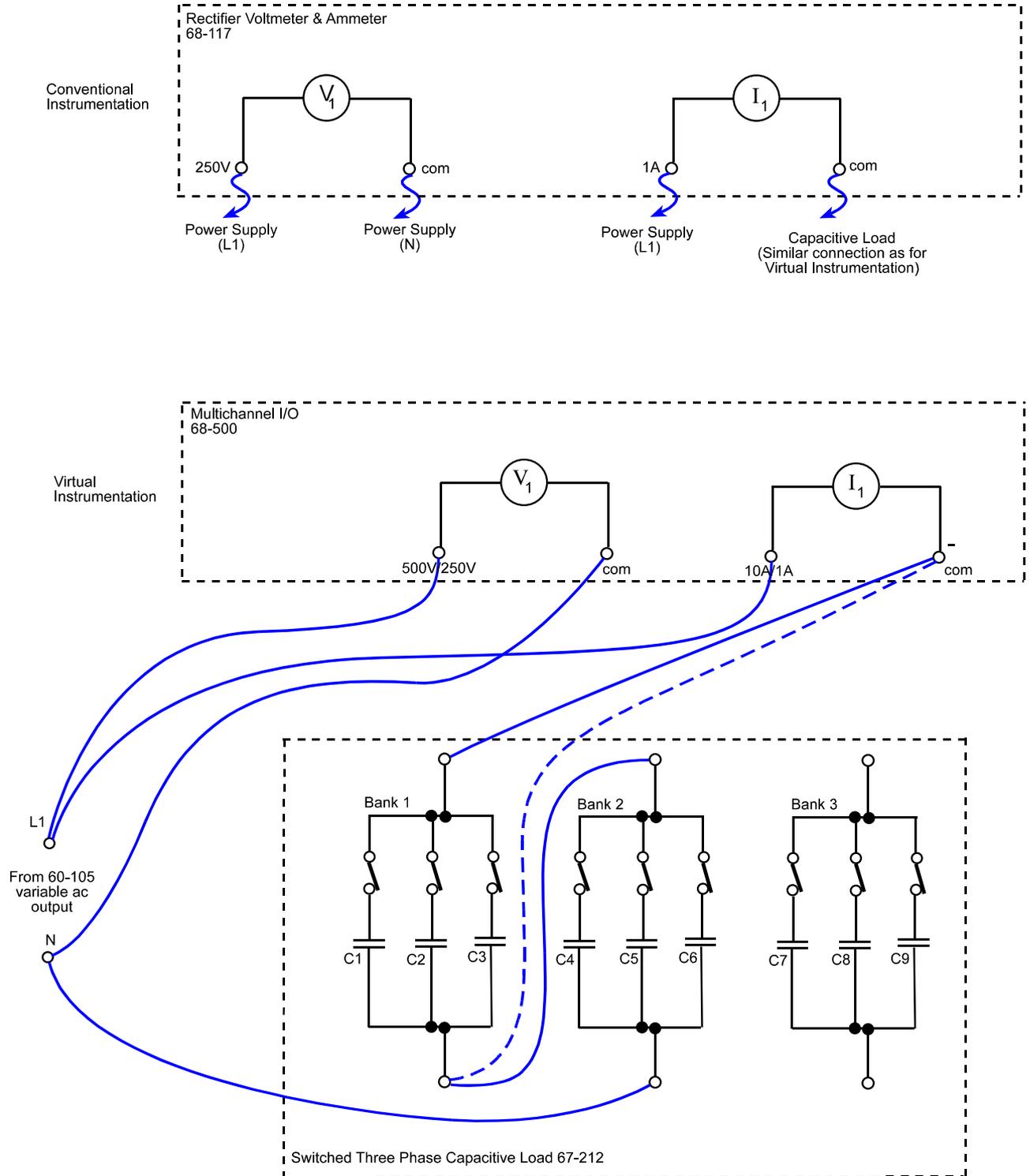
#### 9.9.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-9-12, which relates to the theoretical circuit shown in Figure 3-9-11.



**Figure 3-9-11 Theoretical Circuit**



**Figure 3-9-12: Practical 9.4 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase capacitive load 67-212, set banks 1 and 2 switches to on to give a capacitance of ..... across each bank, and set bank 3 switches to off.

Connect a shorting link (connecting lead) across bank 1 as shown by the dotted line in Figure 3-9-12.

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 9.4, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for a capacitance of.....

Disconnect the supply.

Remove the shorting link so that bank 1 is in series with bank 2.

Repeat the procedure for capacitors in series and record the result in your copy of Practical 9.4, Results Table.

On the Universal Power Supply 60-105, set the '*variable output voltage*' control to 0% then set the '*3 phase circuit breaker*' to the off position.

Product Version	
230 V	120 V
7 $\mu$ F	
200 V ac	
7 $\mu$ F	



### 9.9.2 Exercise 9.4

For a single capacitor bank (7  $\mu\text{F}$ ), use the measured voltage and current to calculate the capacitive reactances ( $X_C$ ) and enter the result into your copy of Practical 9.4, Results Table:

$$\begin{aligned}X_C &= \frac{V}{I} \\ &= \frac{1}{2\pi fC}\end{aligned}$$

where  $f$  is the supply frequency.

For two capacitor banks in series, use Ohm's Law to calculate the circuit's total capacitive reactance and enter the result your copy of Practical 9.4, Results Table.

$$X_{C\text{Total}} = X_{C1} + X_{C2}$$

For each combination of capacitors, calculate its value using the following formula and enter the results your copy of Practical 9.4, Results Table.

$$C = \frac{1}{2\pi fX_C}$$

- Question 9.11**      *Is the capacitance of two capacitors connected in series lesser or greater than that of a single capacitor?*
- Question 9.12**      *Can you state a formula for calculating directly the theoretical value of capacitors in series?*



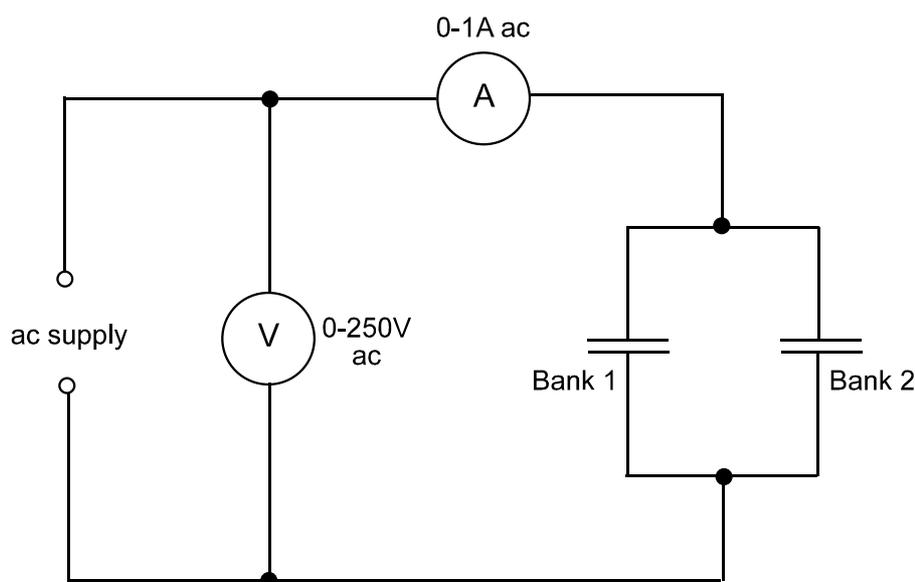
### 9.10 Practical 9.5 – Capacitors in Parallel

Using the calibration of capacitors procedure given in Practical 9.3, it is possible to show the effect of connecting capacitors in parallel.

#### 9.10.1 Procedure

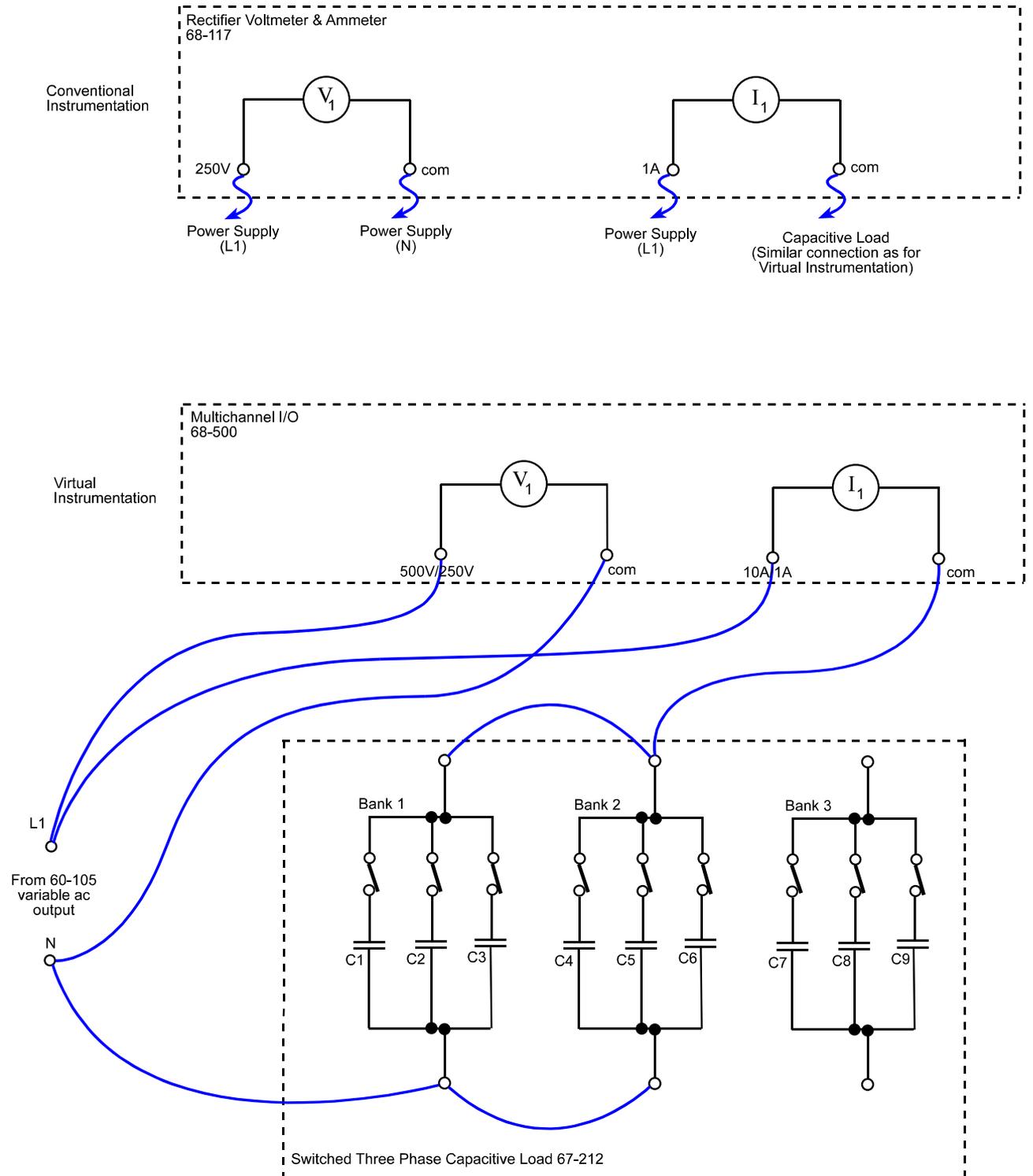
On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-9-14, which equates to the theoretical circuit shown in Figure 3-9-13.



**Figure 3-9-13**

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.



**Figure 3-9-14: Practical 9.4 Circuit Diagram**



Product Version	
230 V	120 V
7 $\mu F$	
200 V ac	
7 $\mu F$	
7 $\mu F$	

On the switched three phase capacitive load 67-212, set bank 1 switches to on to give a capacitance of ..... and banks 2 and 3 switches to off.

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Rotate the 'variable output voltage' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 9.5, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for a capacitance of.....

On the switched three phase capacitive load 67-212, set bank 2 switches to on to give a capacitance of .....; bank 1 switches should remain in the on position and bank 3 switches in the off position.

Repeat the procedure for capacitors in parallel and record the result in your copy of Practical 9.5, Results Table.

Disconnect the supply.

### 9.10.2 Exercise 9.5

For a single capacitor bank (7  $\mu F$ ), use the measured voltage and current to calculate the capacitive reactances ( $X_C$ ) and enter the result in your copy of Practical 9.5, Results Table:

$$X_C = \frac{V}{I}$$

$$= \frac{1}{2\pi fC}$$

where  $f$  is the supply frequency.



For two capacitor banks in parallel, use Ohm's Law to calculate the circuit's total capacitive reactance and enter the result in your copy of Practical 9.5, Results Table.

$$X_{C_{\text{Total}}} = \frac{1}{X_{C_1}} + \frac{1}{X_{C_2}}$$

For each combination of capacitors, calculate its value using the following formula and enter the results in your copy of Practical 9.5, Results Table.

$$C = \frac{1}{2\pi f X_C}$$

*Question 9.13*      *Is the capacitance of two capacitors connected in parallel lesser or greater than that of a single capacitor?*

*Question 9.14*      *Can you state a formula for calculating directly the theoretical value of capacitors in parallel?*

## **9.11 Practical Aspects**

### **9.11.1 Practical 9.1**

Due to the form of construction, wound capacitors of any type possess appreciable inductance, thus do not act as pure capacitors. The effects of this inductance are greater at high frequencies and thus the wound form of capacitor is inferior at high frequencies.

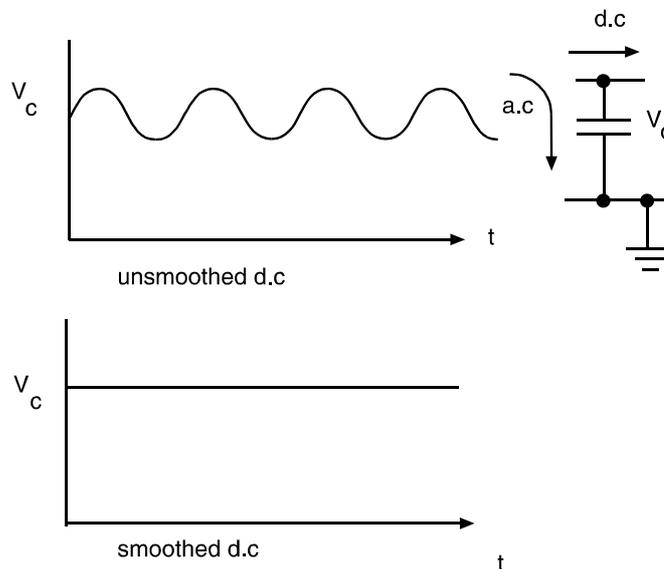
Mica capacitors, ceramic tubular and disc capacitors, and air dielectric capacitors are ideal for high frequency work.

Capacitors normally have a stated maximum voltage rating above which they cannot be used safely. When used at ac the peak or crest value of the voltage must be used to determine whether the capacitor is within rating.

### **9.11.2 Practical 9.2**

Capacitors show infinite impedance to dc but their impedance is finite to ac and decreases as the frequency of the ac increases. Therefore one of their uses is in coupling between circuits or parts of circuits, where it is necessary to block dc transmission but to allow ac signals to pass.

Large value electrolytic capacitors are often used in 'smoothing' circuits in which a dc voltage which has an ac ripple voltage superimposed upon it is applied to the capacitor. The capacitor has no effect on the dc component of the waveform, as its impedance to dc is infinite, but bypasses to earth the ac. This is shown in Figure 3-9-15.



**Figure 3-9-15**

### 9.11.3 Practical 9.3

The capacitors were calibrated by calculating the reactance  $X_c$  from the measured readings of  $V/I$ . The capacitance was then calculated from:

$$C = \frac{1}{2\pi f X_c}$$

The losses were assumed negligible, so that the reactance  $X_c$  was taken to be equal in magnitude to  $V/I$ .

Although the assumptions stated above are true enough for the purposes of this load unit, it should be realised that there are special cases in electrical engineering where even the small resistive component of a capacitor needs to be taken into account. In such cases, highly accurate instruments are used, usually to measure the phase angle  $\phi$ , from which the power dissipation  $W = VI \cos \phi$  and the resistive component of the capacitor can be calculated.

### 9.11.4 Practicals 9.4/5

There are many practical applications for series and parallel capacitors in electronic circuits. The parallel combination of capacitors is perhaps the more common. However, the series combination is still very useful in some circumstances.

Either combination may be used to achieve a special value of capacitance when only preferred values are available.



eg, we wish to obtain  $0.123 \mu\text{F}$

we could use one  $0.100 \mu\text{F}$

one  $0.022 \mu\text{F}$

one  $0.001 \mu\text{F}$

in parallel, giving  $0.123 \mu\text{F}$

or we could use a series combination of

one  $0.15 \mu\text{F}$

one  $0.68 \mu\text{F}$

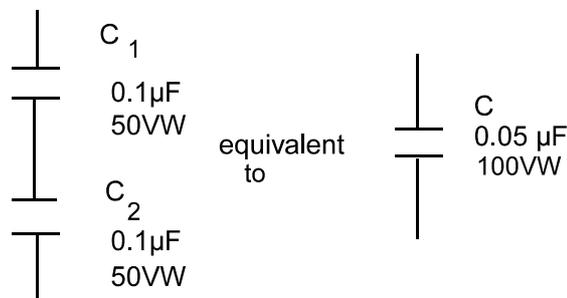
giving  $\frac{0.15 \times 0.68}{0.15 + 0.68}$

$$= \frac{0.102}{0.83}$$

$$= 0.123 \mu\text{F}$$

Another application of series connection of capacitors is when no capacitors of sufficient voltage rating are available for a particular job.

Say a capacitor of  $0.05 \mu\text{F}$  at  $100 \text{ V}$  working is needed, and only capacitors with a  $50 \text{ V}$  working rating are available. Connecting two  $0.1 \mu\text{F}$  capacitors in series will produce the  $0.05 \mu\text{F}$  required, and the combination will have a  $100 \text{ V}$  working rating. This is shown in Figure 3-9-16.



**Figure 3-9-16**



However, remember that the charge on the series capacitor is the same (neglecting leakage), ie for capacitors  $C_1$  and  $C_2$  connected in series

$$C_1V_1 = C_2V_2$$

Thus if  $C_1$  and  $C_2$  are equal, as in Figure 3-9-16, the voltage across each will be the same, but if the capacitances are not equal then the voltages will not be equal.

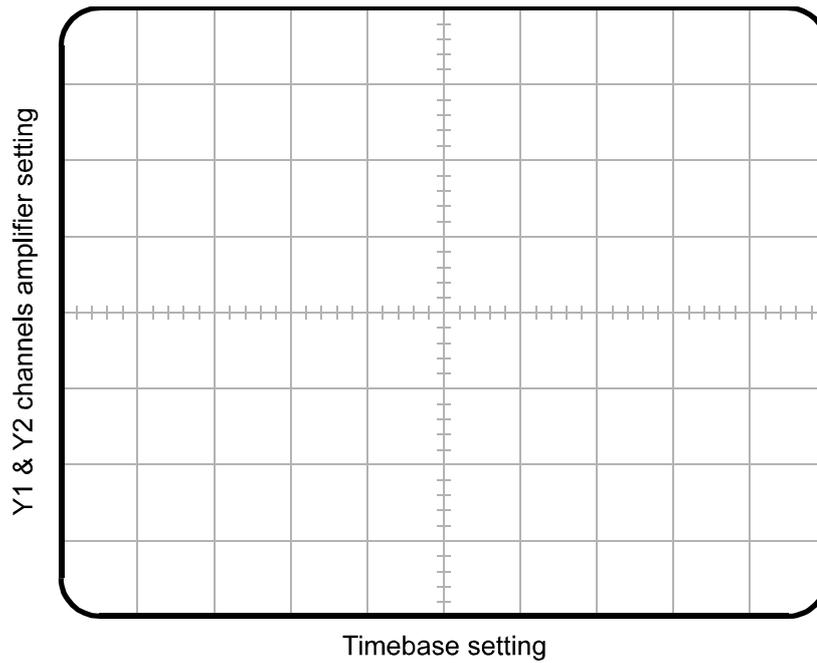
For example, if a  $0.15 \mu\text{F}$  capacitor and a  $0.075 \mu\text{F}$  capacitor had been chosen for the application above, their total capacitance when connected in series would be the required  $0.05 \mu\text{F}$ , but:

$$\begin{aligned}C_1V_1 &= C_2V_2 \\ \therefore 0.15V_1 &= 0.075V_2 \\ \therefore \frac{V_1}{V_2} &= \frac{0.075}{0.15} = 0.5 \\ \therefore V_1 &= 0.5V_2 \\ \text{but if } V_1 + V_2 &= 100\text{V} \\ \text{then } V_1 &= 33.3\text{V} \\ &V_2 = 66.6\text{V}\end{aligned}$$

and, as only 50 V working capacitors are available, the  $0.075 \mu\text{F}$  capacitor would be exceeding its ratings, and may fail.



**9.12 Practical 9.1 - Oscilloscope Screen Graticule Representation  
(230 & 120 V Product Version)**





Notes



**9.13 Practical 9.2 - Results Table (230 V Product Version)**

<b>rms voltage</b>	<b>rms current (mA)</b>	<b><u>rms voltage</u> rms current</b>
50		
100		
150		
200		



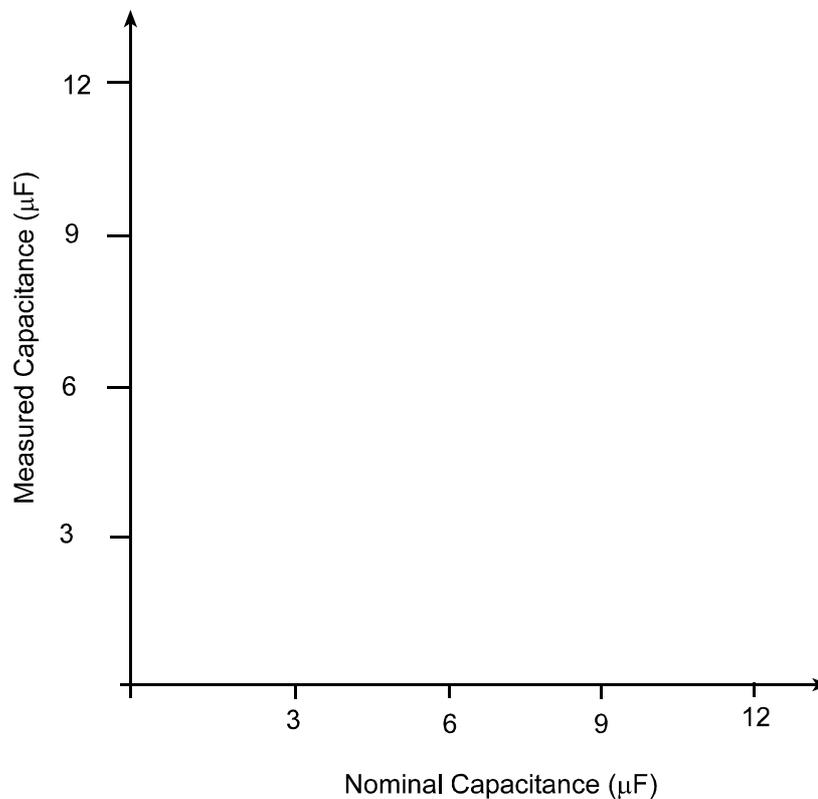
**9.14 Practical 9.2 - Results Table (120 V Product Version)**

<b>rms voltage</b>	<b>rms current (mA)</b>	<b><u>rms voltage</u> rms current</b>



**9.15 Practical 9.3 - Results Tables and Graphs (230 V Product Version)**

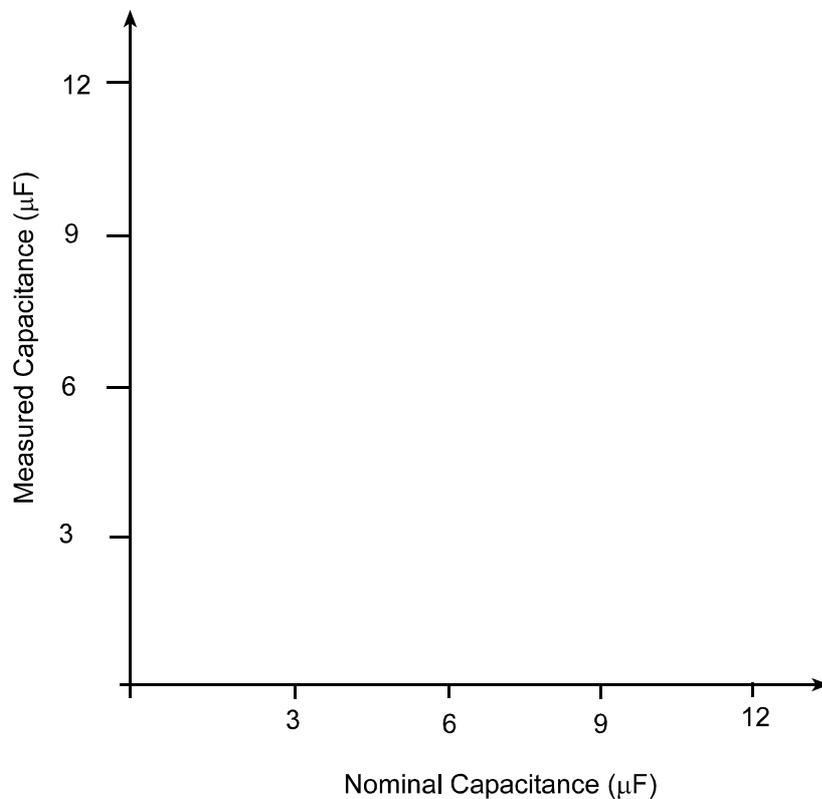
Nominal		Measured		Calculated	
Voltage (V)	Capacitance ( $\mu\text{F}$ )	Voltage (V)	Current (mA)	$X_C = V/I$ ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )
200	3				
200	6				
200	9				
200	12				





**9.16 Practical 9.3 - Results Tables and Graphs (120 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Capacitance ( $\mu\text{F}$ )	Voltage (V)	Current (mA)	$X_C = V/I$ ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )





**9.17 Practical 9.4 - Results Table (230 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Capacitance ( $\mu\text{F}$ )	Voltage (V)	Current (mA)	$X_C = V/I$ ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )
200	7				
200	7 + 7				



**9.18 Practical 9.4 - Results Table (120 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Capacitance ( $\mu\text{F}$ )	Voltage (V)	Current (mA)	$X_C = V/I$ ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )



**9.19 Practical 9.5 - Results Table (230 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Capacitance ( $\mu\text{F}$ )	Voltage (V)	Current (mA)	$X_C = V/I$ ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )
200	7				
200	7 + 7				



**9.20 Practical 9.5 - Results Table (120 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Capacitance ( $\mu\text{F}$ )	Voltage (V)	Current (mA)	$X_C = V/I$ ( $\Omega$ )	Capacitance ( $\mu\text{F}$ )



## **10 Inductive Circuit at ac**

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### **10.1 Assignment Information**

#### **10.1.1 Objectives**

When you have completed this assignment you will:

- know the phase relationship between current and voltage in an inductive circuit at ac.
- know the meaning of inductive reactance.

#### **10.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignment 1, Familiarisation.
- you should have completed Assignment 7.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **10.1.3 Practicals**

1. Current and Voltage Phase Relationship
2. Reactance in Inductive Circuit
3. Calibration of Inductors
4. Inductors in Series
5. Inductors in Parallel

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **10.2 Theory**

### **10.2.1 Introduction**

Prior to considering an inductive circuit at ac, it is helpful to briefly review basic inductor theory.

### **10.2.2 General**

An inductor is a passive electronic component that stores energy in the form of a magnetic field. In its simplest form, an inductor consists of a wire loop or coil which is said to exhibit the properties of self-inductance or simply inductance.

### **10.2.3 Inductance**

Inductance (self-inductance) is the property of a circuit whereby a change in current causes a change in voltage:

$$V_L = L \frac{\delta I}{\delta t}$$

where:

$V_L$  = the induced voltage in volts.

$L$  = the value of self-inductance in henries, H

$\frac{\delta I}{\delta t}$  = the rate of change in current in amperes per second

Inductance is directly proportional to the number of turns in the coil. Other factors affecting inductance include the radius of the coil and the type of material around which a coil is wound.

For a given coil radius and number of turns, air cores result in the least inductance. Dielectric materials such as wood, glass and plastic are essentially the same as air for the purpose of inductor winding. Ferromagnetic substances such as iron increase the inductance obtainable with a coil having a given number of turns. In some cases, this increase is in the order of thousands of times. The shape of the coil is also significant. Toroidal (doughnut-shaped) cores provide more inductance, for a given core material and number of turns, than solenoidal (rod-shaped) cores.

### **10.2.4 Unit of Inductance**

The unit of inductance is the henry (H), named after the English chemist William Henry (1774–1836). One henry is the amount of inductance required to generate one volt of induced voltage when the current is changing at the rate of one ampere per second.

Common ranges of values for inductors are:

microhenry ( $\mu\text{H}$ ) = value  $\times 10^{-6}$  H

millihenry (mH) = value  $\times 10^{-3}$  H



### **10.2.5 Laws that Govern Inductance**

The following laws effect inductance:

Faraday's Law for a Straight Wire - The amount of induced voltage is proportional to the rate of change of flux lines cutting a conductor; ie, the faster the rate of change of flux, the larger the amount of induced voltage.

Faraday's Law for a Coil of Wire - The amount of induced voltage is proportional to the rate of change of flux and the number of turns of wire; ie, increasing the number of turns or rate of change of flux increases the amount of induced voltage.

Lenz's Law - The voltage induced in a conductor will oppose the change in voltage that is causing the flux change. This is, when an increasing voltage is applied to a conductor, the resulting increase in flux lines will induce a voltage that opposes the increase.

### **10.2.6 Mutual Inductance**

Mutual inductance is the electrical property of circuits that enable a current flowing in one conductor (or coil) to induce a current in a nearby conductor (or coil). A good example of a component that makes use of this effect is the transformer. The formula which governs mutual inductance is:

$$M = k\sqrt{L_1L_2}$$

where:

M = mutual inductance in henries

k = coefficient of coupling between two inductances

L<sub>1</sub> and L<sub>2</sub> = values of the two inductances

### **10.2.7 L/R Time Constant**

When an inductor is connected in series with a resistor and a dc voltage is connected across the circuit, it will take some time for current flow to be come maximum. The current build up is gradual because of the counter emf generated by the self-inductance of the coil. Similarly, when the supply voltage is removed, it will take some time for current to decay because, again, the change of current is opposed by self-inductance. As shown in Figure 3-10-1, initially the rate of current increase is rapid but slows down considerably as full current flow is approached. To enable current flow to be calculated, a time constant is used as follows:

$$T = \frac{L}{R}$$

where:

T = time constant in seconds and is equal to 63.2% of the time to reach maximum current flow.

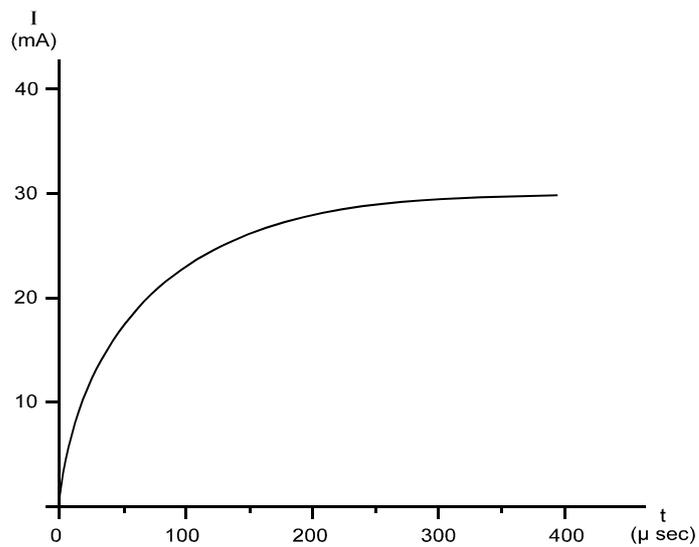
L = inductance in henries

R = resistance in ohms



To calculate the time required to achieve full current flow or decay:

Multiply the time constant (T) by 5



**Figure 3-10-1: Typical Current Flow Curve**



**10.3 Content**

The practicals in Assignment 10 familiarise the student with the concepts of alternating current theory as it is applied to an inductive circuit.

**10.4 Equipment Required**

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- Switched Three Phase Inductive Load 67-312
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit Software Pack	68-500 68-912-USB
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**or**

Conventional Instrumentation (Option 60-070-CI2)	Rectifier Voltmeter & Ammeter Electrodynamic Wattmeter	68-117 68-204
Ancillary Equipment	Differential Voltage/Current Probe (2 off) (For use with conventional Instruments only)	68-150

Two channel oscilloscope at least 20 MHz bandwidth.

**NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

**10.5 Preliminary Set-up**

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel® Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 10.6 Practical 10.1 - Current and Voltage

It is known that the relationship between induced emf, current and inductance in a system is:

$$e = L \frac{\delta i}{\delta t}$$

where:

$e$  = induced emf

$L$  = inductance

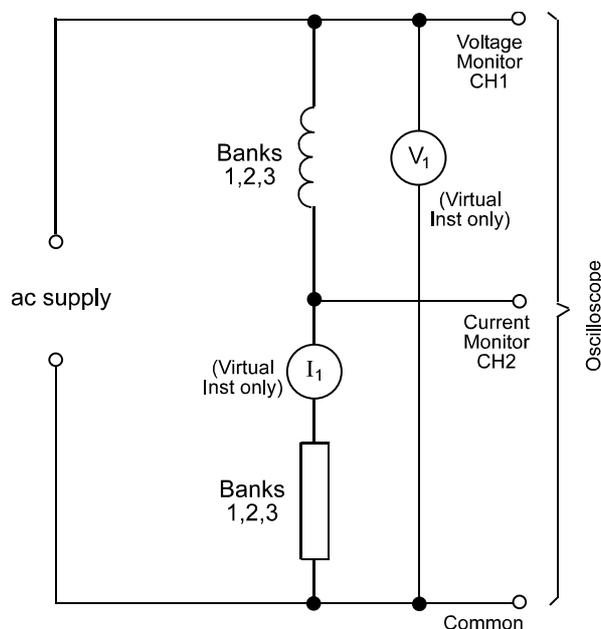
$\frac{\delta i}{\delta t}$  = rate of change of current

We will now examine what happens when a sinusoidal alternating voltage is applied to an inductor.

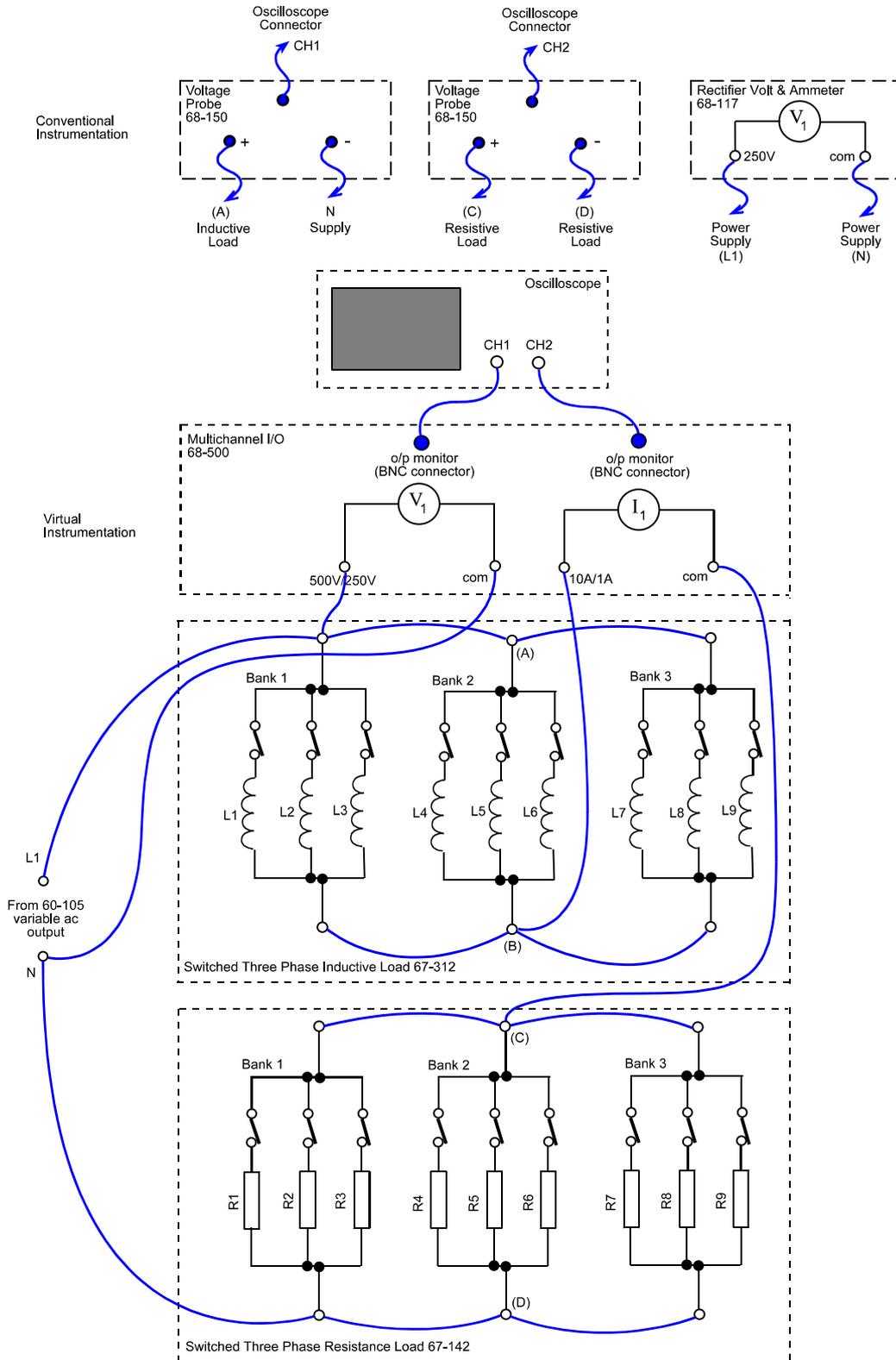
#### 10.6.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-10-3, which relates to the theoretical circuit shown in Figure 3-10-2.



**Figure 3-10-2: Theoretical Circuit**



**Figure 3-10-3: Practical 10.1 Circuit Diagram**



Product Version	
230 V	120 V
182 $\Omega$	
560 mH	
100 V ac	

If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 channel to '250 V' on Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or currents of up to 200 mA to be monitored when the 200 mA socket is connected.

If conventional instrumentation is being used, switch on the differential probe and ensure that the attenuation ratio is set to 1/20.

On the switched three phase resistance load 67-142, set all switches to on to give a resistance of.....

On the switched three phase inductive load 67-312, set all switches to on to give an inductance of.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter indicates.....

Set the oscilloscope as follows:

- CH1 (Y1) channel - 1 V/cm
- CH2 (Y2) channel - 500 mV/cm
- Timebase - 5 ms/cm

On the oscilloscope, zero both traces and then observe the two waveforms.



**10.6.2 Exercise 10.1**

Draw the waveforms you see on a copy of the oscilloscope screen graticule representation given in Practical 10.1, Results Table at the end of this assignment.

- Question 10.1*            *Where on the waveform is the rate of change of current a positive maximum?*
- Question 10.2*            *Where on the waveform is the rate of change of current zero?*
- Question 10.3*            *Where on the waveform is the rate of change of current a negative maximum?*
- Question 10.4*            *How far apart, in degrees, are the voltage and current waveforms?*
- Question 10.5*            *Which waveform is leading?*
- Question 10.6*            *Is this the same as for a capacitive circuit?*

If the current waveform is denoted by:

$$i = I_{\max} \sin \omega t$$

then as             $e = \frac{\delta i}{\delta t}$

then             $e = -LI_{\max} \omega \cos \omega t$

Here we must be careful. We have found the induced emf, and included the minus sign as a reminder that it opposes the change of current. But when we look at ac applied to a resistor or dc applied to it, we look at the *applied* voltage.

In the same way, with the inductance, we must look at the applied voltage if we are to be consistent. Since the sum of the voltages around the circuit is zero (Kirchhoff's Law), this applied emf is equal and opposite to the induced emf; ie,

$$\text{applied emf} = +L \frac{\delta i}{\delta t}$$

$$LI_{\max} \omega \cos \omega t$$

So we can say that a positive applied emf produces a positive current which induces an opposing (negative) emf in the inductor.

This was the voltage you were looking at experimentally, as should be evident by a look at Figure 3-10-4, in which the polarity of the emfs is indicated by arrows in the direction of action.

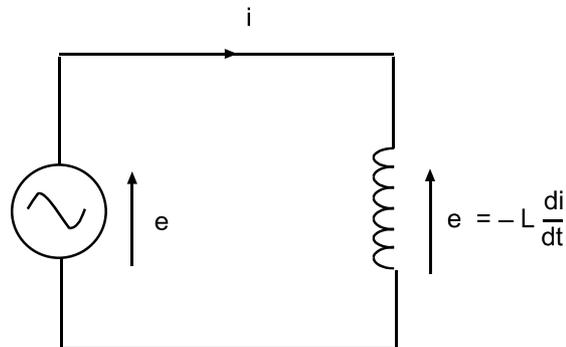


Figure 3-10-4

The results show that the voltage waveform is the same as that of the current, but leads it by  $90^\circ$ , since  $\cos \omega t = \sin(\omega t + 90^\circ)$ .

Thus the voltage in an inductive circuit leads the current by  $90^\circ$ .

To remember which waveform leads which in either a capacitive or an inductive circuit, the following mnemonic is useful.

CIVIL

ie, in a capacitive circuit (C) the current (I) leads the voltage (V)

CIV

in an inductive circuit (L) the voltage (V) leads the current (I)

VIL

The phasor representation of voltage and current is given in Figure 3-10-5.

Here the current is taken as the reference and the voltage leads it by  $90^\circ$ .

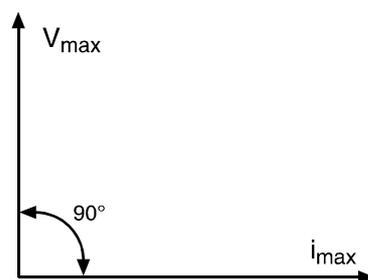


Figure 3-10-5

For further information on phasors, see Appendix B.1.



### 10.7 Practical 10.2 – Reactance in Inductive Circuit

As shown in Assignment 9, impedance,  $Z$ , is given by:

$$Z = \frac{V_{\text{rms}}}{I_{\text{rms}}}$$

and, for a capacitor, its impedance is termed capacitive reactance,  $X_C$ .

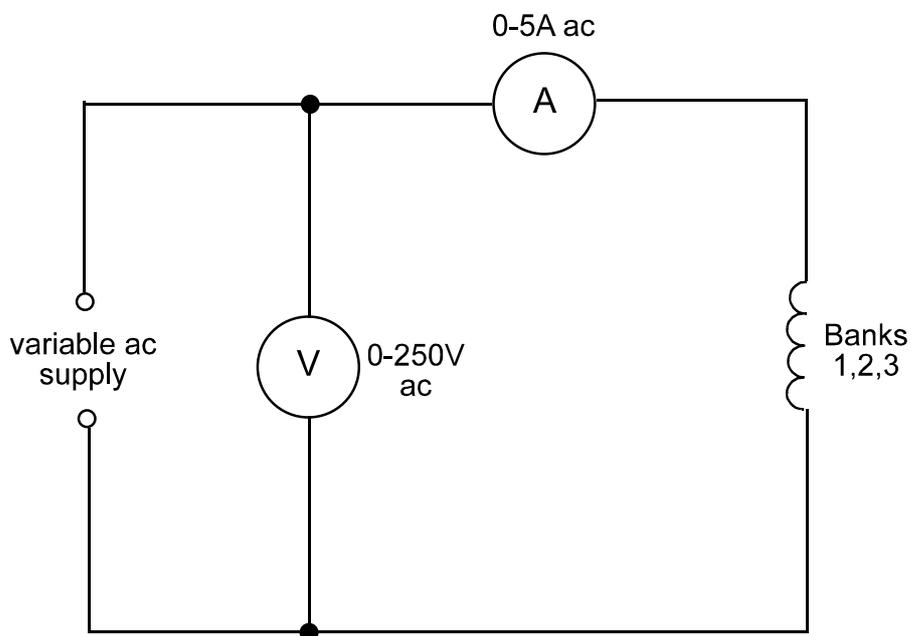
Similarly, we can determine the *inductive reactance* of an inductor.

Inductive reactance is given the symbol  $X_L$ .

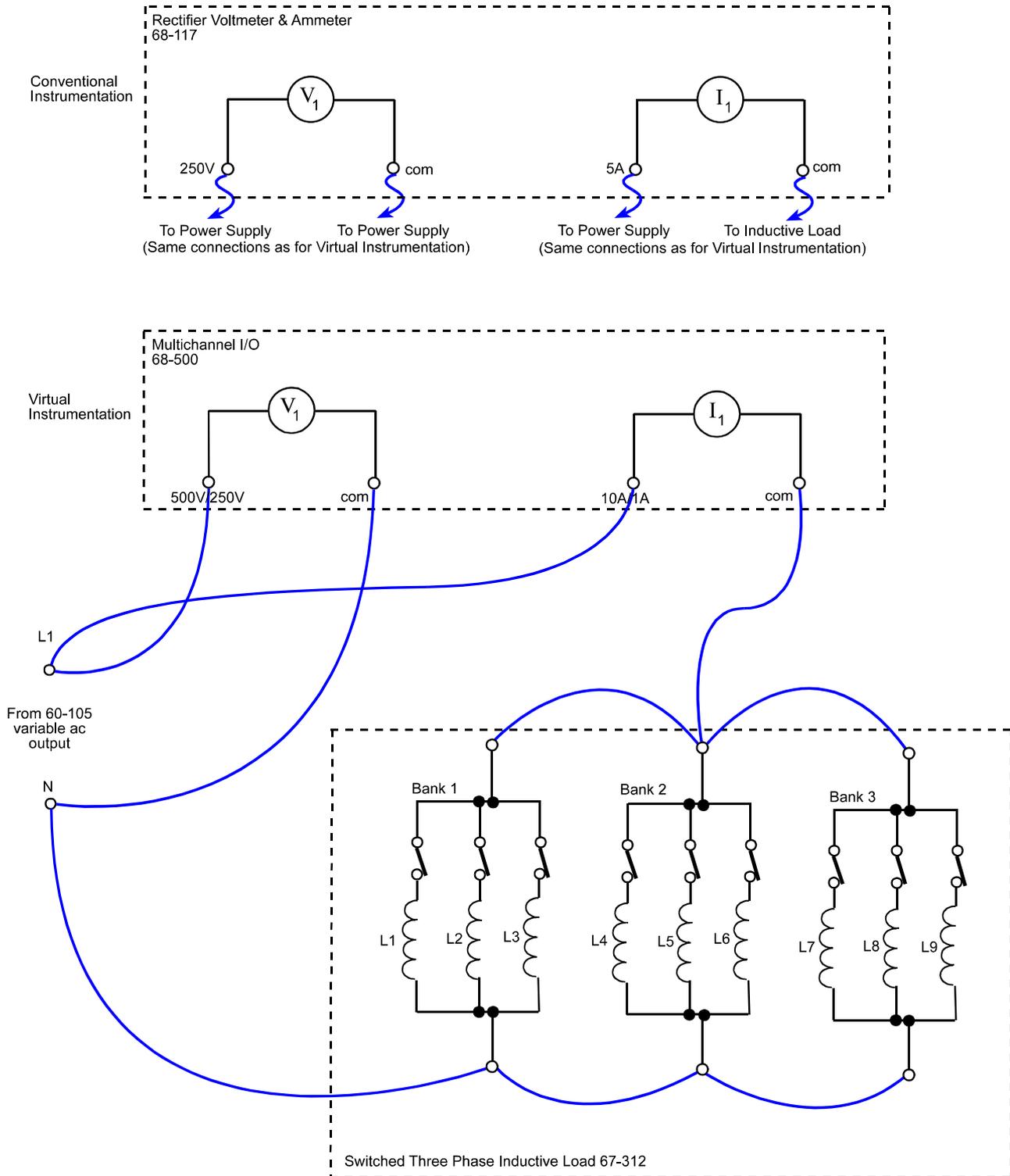
#### 10.7.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-10-7 which relates to the theoretical circuit in Figure 3-10-6.



**Figure 3-10-6**



**Figure 3-10-7: Practical 10.2 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase inductive load 67-312, set all the banks of switches to the on position so that the inductance in circuit is.....

On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Rotate the 'variable output voltage' control until the voltmeter indicates..... as shown on the virtual or conventional instrumentation.

Measure and record on a copy of the appropriate Practical 10.2, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for a supply voltage of .....

Repeat this procedure for voltages of ..... recording all results on your copy of Practical 9.2, Results Table.

Product Version	
230 V	120 V
560 mH	
50 V ac	
50 V ac	
100 V, 150 V and 200 V	

For each voltage, calculate the impedance and record on your copy of Practical 9.2, Results Table

$$Z = \frac{V_{\text{rms}}}{I_{\text{rms}}}$$

**Question 10.7**      *What is the average value of impedance of the coil?*



### **10.7.2 Frequency Effect**

The impedance (inductive reactance) of an inductor is directly proportional to frequency as shown below.

We know that (from Practical 10.1) for an inductor, if:

$$i = I_{\max} \sin \omega t$$

then the applied voltage,  $v$ , will be given by:

$$v = LI_{\max} \omega \cos \omega t$$

and when  $\cos \omega t = 1$ ,  $v = V_{\max}$

thus  $V_{\max} = LI_{\max} \omega$

$$\frac{V_{\max}}{I_{\max}} = \omega L$$

$$Z = \omega L$$

$$X = 2\pi fL$$



### 10.8 Practical 10.3 - Calibration of Inductors

The inductance of each inductor may differ from its nominal value. It must be therefore be calibrated for future reference.

#### 10.8.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-10-9, which equates to the theoretical circuit shown in Figure 3-10-8.

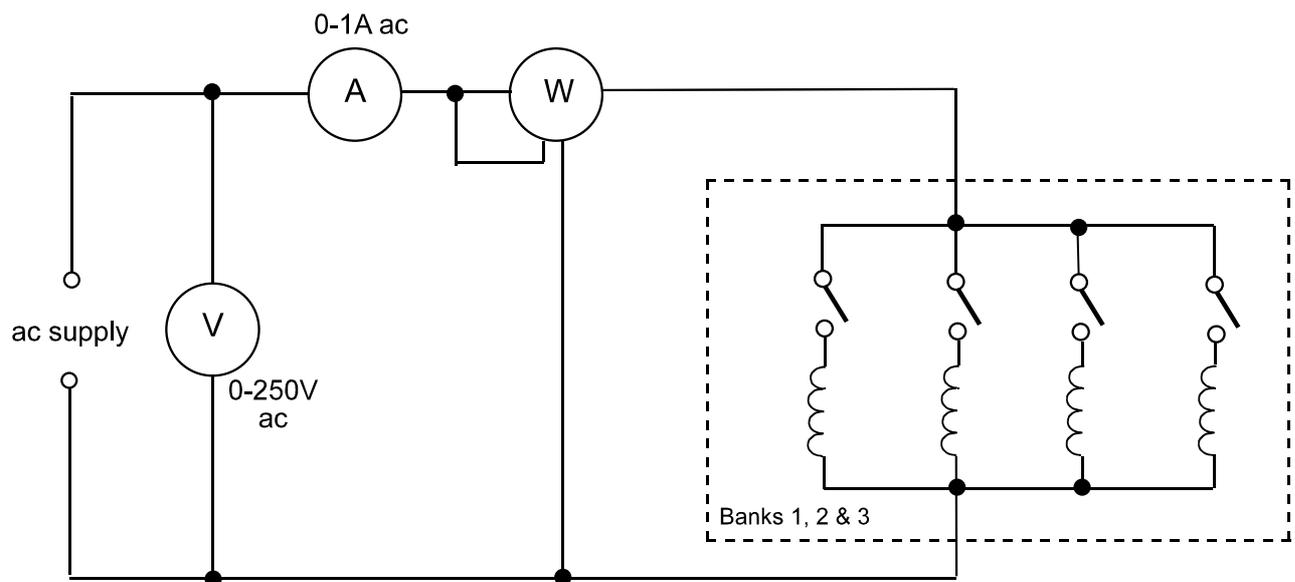
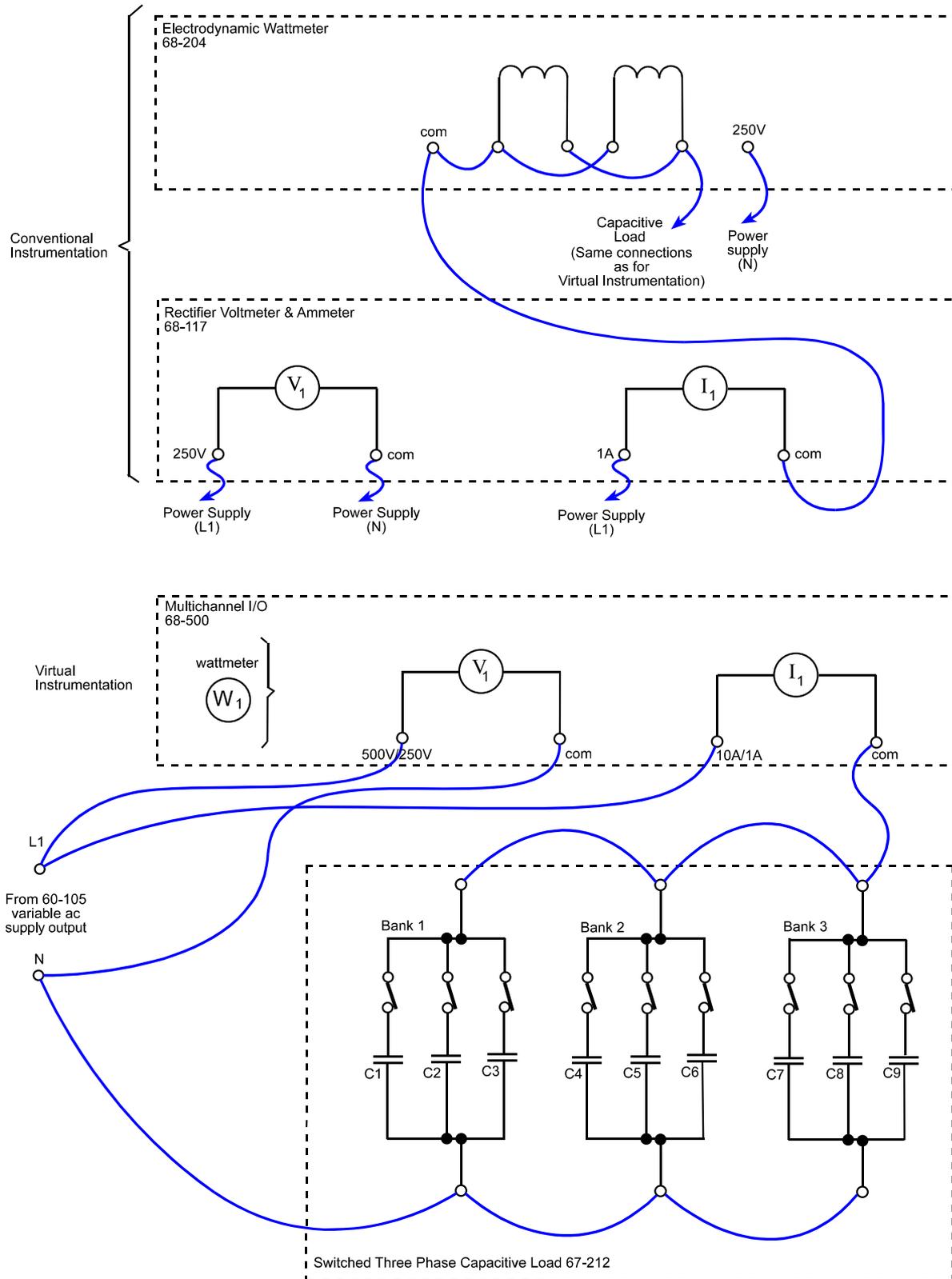


Figure 3-10-8



**Figure 3-10-9: Practical 10.3 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase inductive load 67-312, set all the switch on all the banks to on to give an inductance of .....

On the Universal Power Supply 60-105, ensure the 'variable output voltage control' is set to 0% then set the '3 phase circuit breaker' to the on position.

Rotate the 'variable output voltage' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 10.3, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for an inductance of .....

Repeat this procedure for inductance values of .....  
 For each value of inductance, observe the wattmeter and record the result in your copy of Practical 10.3, Results Table.

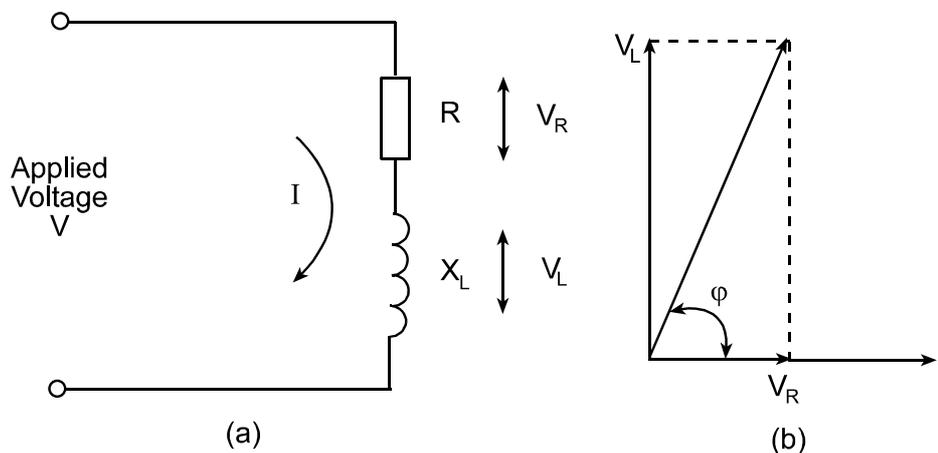
On the Universal Power Supply 60-105, set the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.

Product Version	
230 V	120 V
0.56 H	
200 V ac	
0.56 H	
1, 1.5 and 2 H	

**10.8.2 Analysis of Results**

The inductors are wire-wound devices. An ideal inductor would have the property of pure inductance and would absorb no power; however, no conventional wire-wound device can produce a pure inductance, since the winding has resistance. The practical device not only absorbs power in the winding resistance, but also, if it is wound on a magnetic core, this too will cause power losses. The power losses can be significant, and we need to evaluate them for at least one core position to assess how significant they are.

The inductor can be viewed as possessing a resistance R in series with an inductive reactance  $X_L$ , the whole acting as an impedance Z, as shown in Figure 3-10-10(a). The phasor diagram relating voltage and current in the inductor is shown in Figure 3-10-10 (b).



**Figure 3-10-10**

Assuming that we have a 1 H inductor and the following circuit values, we have in this case:

$$V_a = 200 \text{ V} \qquad I = 636.9 \text{ mA} \qquad W = 42 \text{ W}$$

$$\text{then: } R = \frac{W}{I^2} = \frac{42}{(0.6369)^2} = 17 \text{ } \Omega$$

$$\text{also: } Z = \frac{V}{I} = \frac{200}{0.6369} = 314 \text{ } \Omega$$

$$\text{and: } X_L = \sqrt{Z^2 - R^2} = \sqrt{98596 + 289} = 314.46 \text{ } \Omega$$

This shows that although R is approximately 5% of Z, the value of  $X_L$  is within 0.15% of Z in this case.

Calculate  $X_L$  for each inductor then, since  $X_L = \omega_L = 2\pi fL$ , calculate:

$$L = \frac{X_L}{2\pi f} \text{ henry, where } f \text{ is the supply frequency.}$$

### 10.8.3 Exercise 10.2

Record the calculated  $X_L$  and inductance (L) in your copy of Practical 10.3, Results Table.

On a copy of the graph axis given in the Results Tables section for Practical 10.3, plot a graph of measured values of inductance against nominal values using the tabulated results in your copy of Practical 10.3, Results Table.

From the example above using the value of R, we can calculate the angle  $\phi$  by which the current in the inductive element lags the applied voltage.

When 1 H is selected, we know that our typical case  $I = 636.9 \text{ mA}$  and  $R = 17 \text{ ohms}$ . Also from the phasor diagram, the cosine of the angle  $\phi$  is seen to be the ratio of  $V_R$  to V.



Since  $V_R = I \times R$

$$\cos \phi = \frac{IR}{V} = \frac{0.6369 \times 17}{200} = 0.054 \quad \therefore \phi = 87^\circ$$

Alternatively, since  $W = V \times I \cos \phi$

$$\cos \phi = \frac{W}{VI}$$

can be used.

The term  $\cos \phi$  is often referred to a '**power factor**' and is widely used in electrical power calculations.

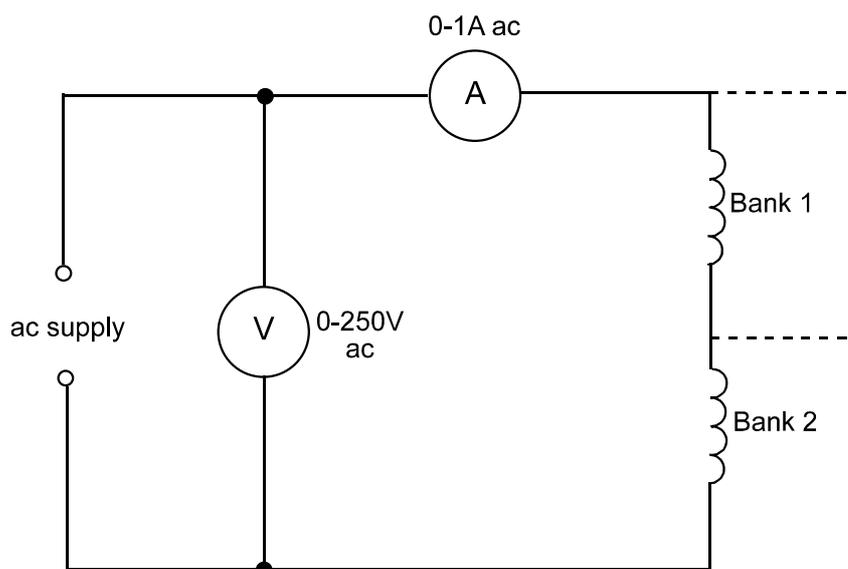
### 10.9 Practical 10.4 – Inductors in Series

Using the calibration of inductors procedure given in Practical 10.3, it is possible to show the effect of connecting inductors in series.

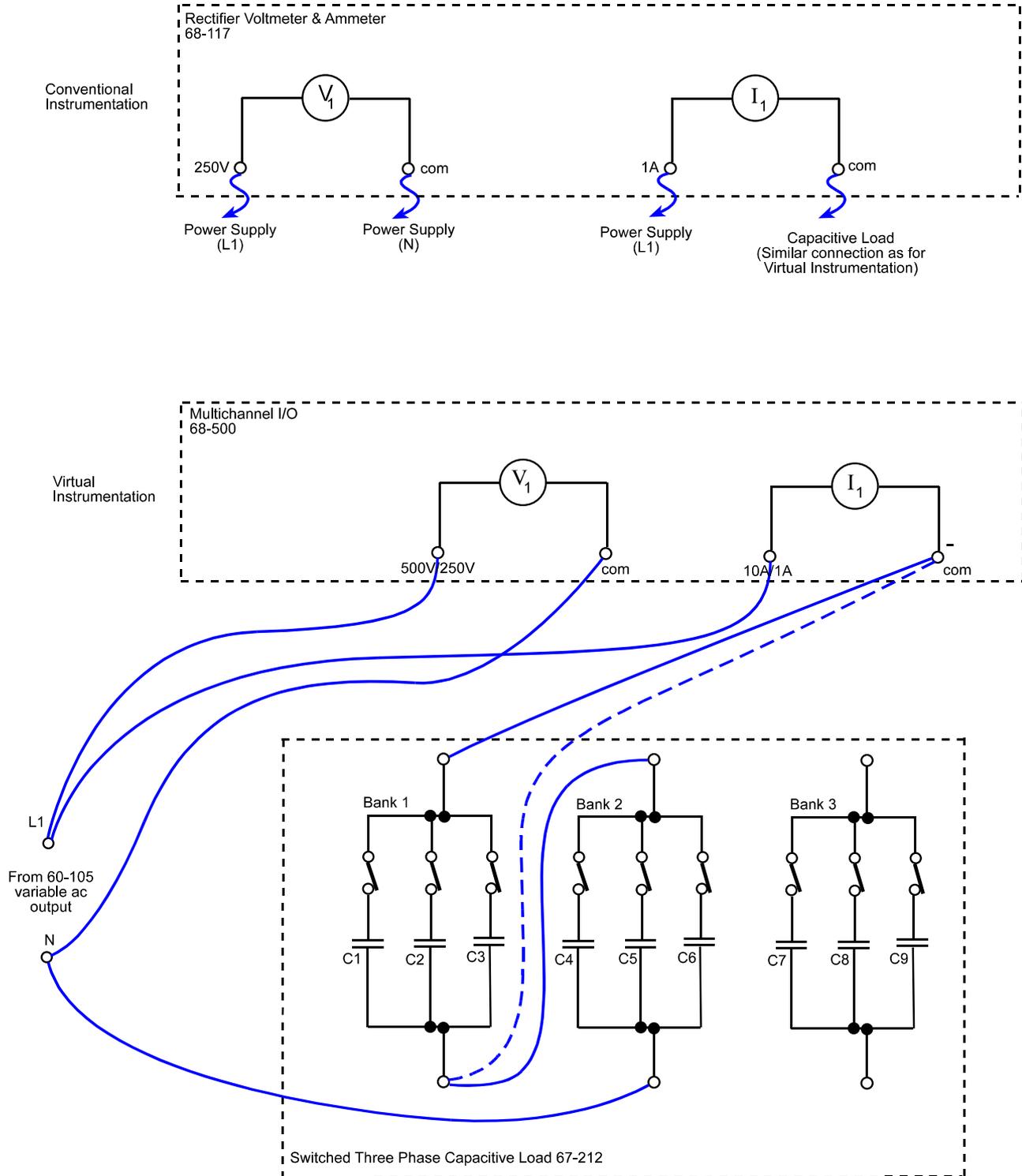
#### 10.9.1 Procedure

On the Universal Power Supply 60-105, ensure the '*3 phase circuit breaker*' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-10-12, which equates to the theoretical circuit shown in Figure 3-10-11.



**Figure 3-10-11**



**Figure 3-10-12: Practical 10.4 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase inductive load 67-312, set banks 1 and 2 switches to on to give an inductance of..... across each bank, and bank 3 switches to off.

Connect a shorting link (connecting lead) across bank 1 as shown by the dotted line in Figure 3-10-12.

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 10.4, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for an inductance of.....

Disconnect the supply.

Remove the shorting link so that bank 1 is in series with bank 2.

Repeat the procedure for inductors in series and record the result in your copy of Practical 10.4, Results Table.

On the Universal Power Supply 60-105, set the '*variable output voltage*' control to 0% then set the '*3 phase circuit breaker*' to the off position.

**10.9.2 Exercise 10.3**

For a single inductor bank (1.7 H), use the measured voltage and current to calculate the inductive reactance ( $X_L$ ) and enter the results in your copy of Practical 10.4, Results Table.

$$X_L = \frac{V}{I}$$

$$= 2\pi fL$$

Product Version	
230 V	120 V
1.7 H	
200 V ac	
1.7 H	



where  $f$  is the supply frequency.

For two inductors in series, use Ohm's Law to calculate the circuit's total inductive reactance and enter the result in your copy of Practical 10.4, Results Table.

$$X_{L\text{Total}} = X_{L1} + X_{L2}$$

For each combination of inductors, calculate its value using the following formula and enter the results in your copy of Practical 10.4, Results Table.

$$L = \frac{X_L}{2\pi f}$$

**Question 10.8**      *Is the inductance of two inductors connected in series lesser or greater than that of a single inductor?*

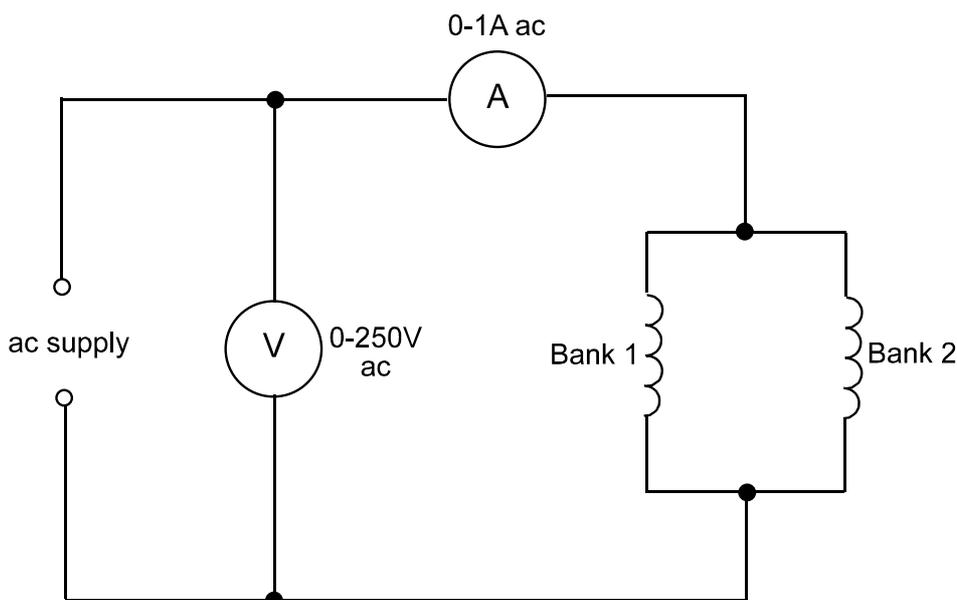
**Question 10.9**      *Can you state a formula for calculating directly the theoretical value of inductors in series?*

### 10.10 Practical 10.5 – Inductors in Parallel

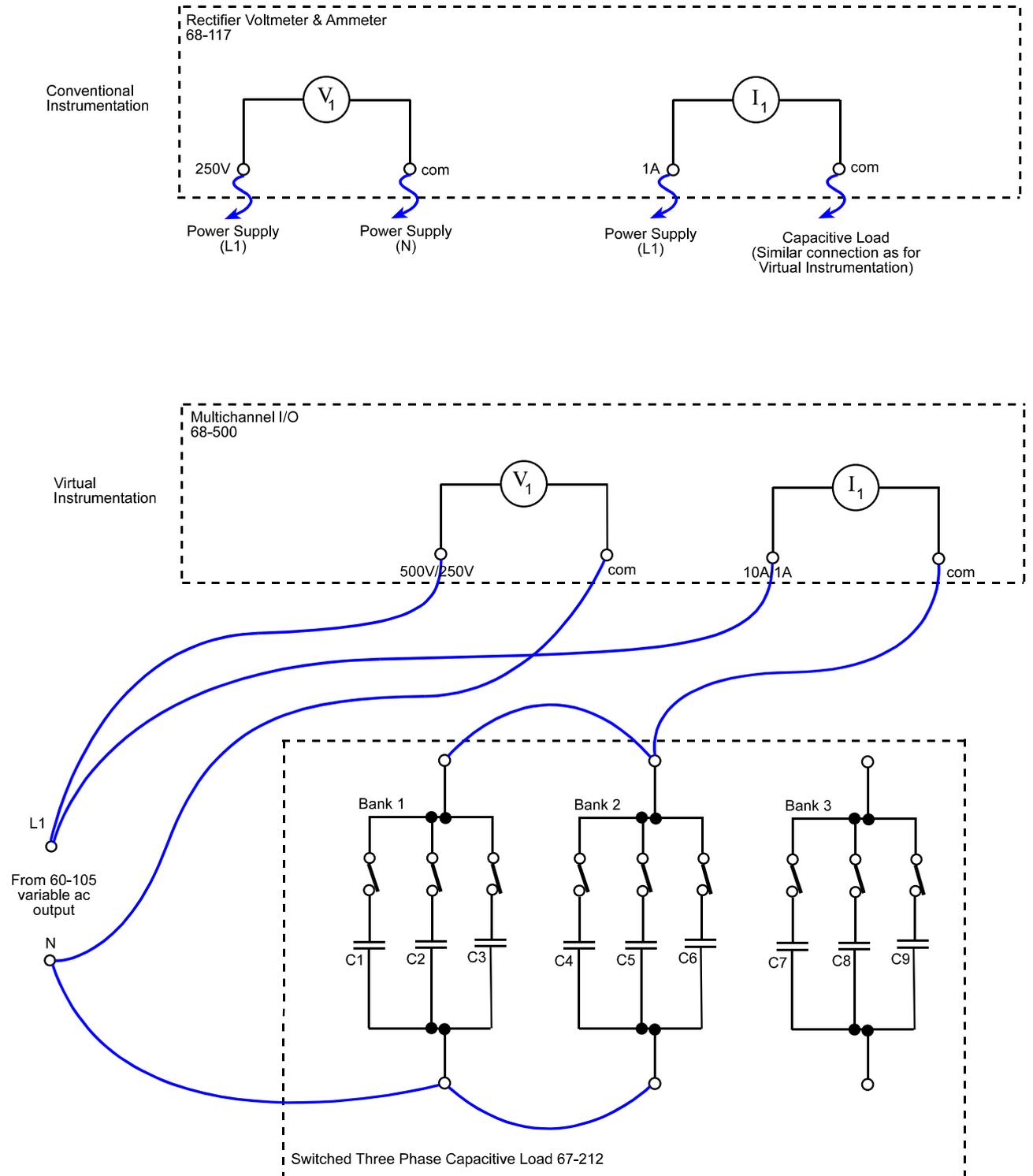
Using the calibration of inductors procedure given in Practical 10.3, it is possible to show the effect of connecting capacitors in parallel.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-10-14, which equates to the theoretical circuit shown in Figure 3-10-13.



**Figure 3-10-13**



**Figure 3-10-14: Practical 10.5 Circuit Diagram**



If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase inductive load 67-312, set bank 1 switches to give an inductance of..... and banks 2 and 3 switches to off.

On the Universal Power Supply 60-105, ensure the 'variable output voltage control is set to 0% then set the '3 phase circuit breaker' to the on position.

Rotate the 'variable output voltage' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 10.5, Results Table (230 V or 120 V product version), the current flowing in the circuit as read by the virtual or conventional ammeter for an inductance of.....

On the switched three phase inductive load 67-312, set bank 2 switches to on to give an inductance of .....; bank 1 switches should remain in the on position and bank 3 switches in the off position.

Repeat the procedure for inductors in parallel and record the result in your copy of Practical 10.5, Results Table.

Disconnect the supply.

**10.10.1 Exercise 10.4**

For single inductor bank (1.7 H), use the measured voltage and current to calculate the inductive reactances ( $X_L$ ) and enter the result in your copy of Practical 10.5, Results Table.

$$X_L = \frac{V}{I}$$

$$= 2\pi fL$$

Product Version	
230 V	120 V
1.7 H	
200 V ac	
1.7 H	
1.7 H	



where  $f$  is the supply frequency.

For two inductor banks in parallel, use Ohm's Law to calculate the circuit's total inductive reactance and enter the result in your copy of Practical 10.5, Results Table.

$$X_{L_{\text{total}}} = \frac{1}{X_{L1}} + \frac{1}{X_{L2}}$$

For each combination of capacitors, calculate its value using the following formula and enter the results in your copy of Practical 10.5, Results Table.

$$L = \frac{X_L}{2\pi f}$$

**Question 10.10**      *Is the inductance of two inductors connected in parallel lesser or greater than that of a single inductor?*

**Question 10.11**      *Can you state a formula for calculating directly the theoretical value of inductors in parallel?*

### **10.11 Practical Aspects**

#### **10.11.1 Practical 10.1**

By its nature of operation, an inductance will create a magnetic field around it. With an alternating current flowing through the inductor, the magnetic field around it will be alternating. If the inductor is in the presence of other components or conductors, this alternating magnetic field will link with these conductors and induce emfs in them. These emfs will generally be unwanted, and give rise to noise, hum, or interfering signals. For this reason, inductors are often magnetically screened in cans, or housings made from a non-magnetic material such as mumetal or aluminium.

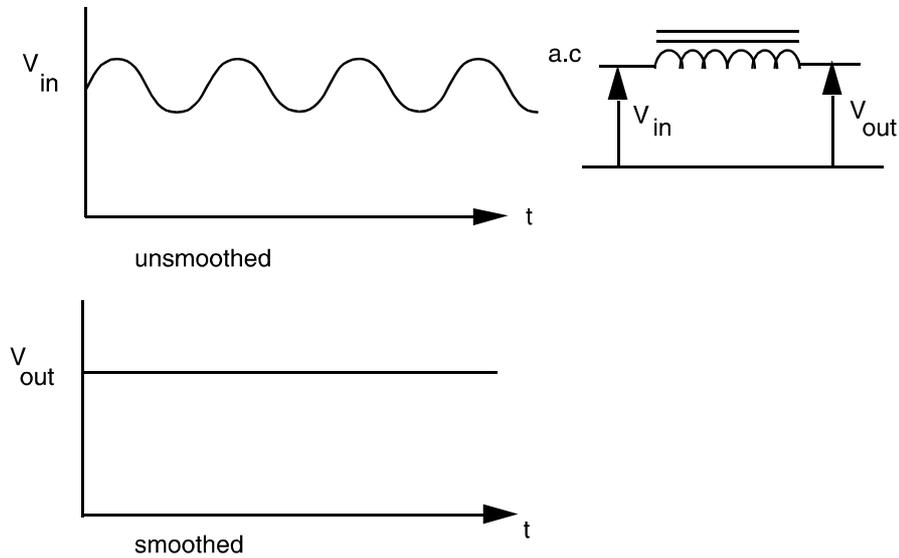
When designing inductors, care must be taken in the selection of type and gauge of wire used. Obviously the lowest possible resistance is desired and, at low frequencies, this means the thickest possible wire gauge consistent with a reasonable sized winding; however at high frequencies, multi-stranded litz wire (from the German word litzendraht, meaning woven) is often better to minimise the skin effect.

#### **10.11.2 Practical 10.2**

The inductor is the converse of the capacitor in that it shows an impedance which is practically zero to dc, but increases with frequency. Like a capacitor, an inductor can also be used in smoothing circuits, but it is used in series with the dc line instead of across it. See Figure 3-10-15. The dc is passed without effect while the ac is greatly impeded by the inductor.

In this application the inductor is often called a 'Choke'.

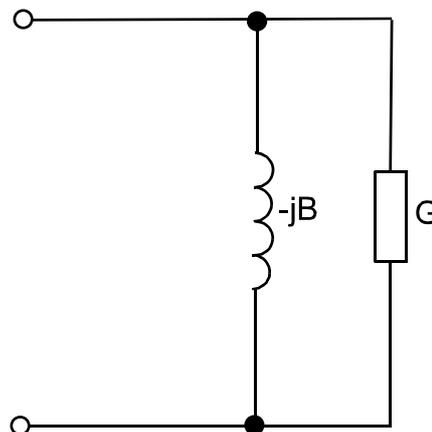
When an inductor contains magnetic material such as iron, it can only maintain its inductance over a limited range of current. Excessive current causes the 'iron' to saturate (ie, fail to permit more than a limited amount of flux). The inductance therefore decreases. This is why you were advised to omit any readings for which the current exceeded 60 mA.



**Figure 3-10-15**

### 10.11.3 Practical 10.3

An inductor can be regarded in ways different from the series  $X_L$ ,  $R$  combination. One which is useful to power engineers is as an inductive susceptance  $B$  in parallel with a conductance  $G$  as shown in Figure 3-10-16.



**Figure 3-10-16**

The advantage of this equivalent circuit is that the power (W) and the reactive volt-amperes (VAR) can be considered separately, since they are effectively consumed by  $G$  and  $B$  respectively (see Appendix B.6).



**10.11.4 Practical 10.4/5**

There are many practical applications for series and parallel inductors in electronic circuits including achieving a special value of inductance. For this purpose, the formula:

$$L_T = L_1 + L_2$$

should be used for series inductor circuits and:

$$\frac{1}{L_T} = \frac{1}{L_1} + \frac{1}{L_2}$$

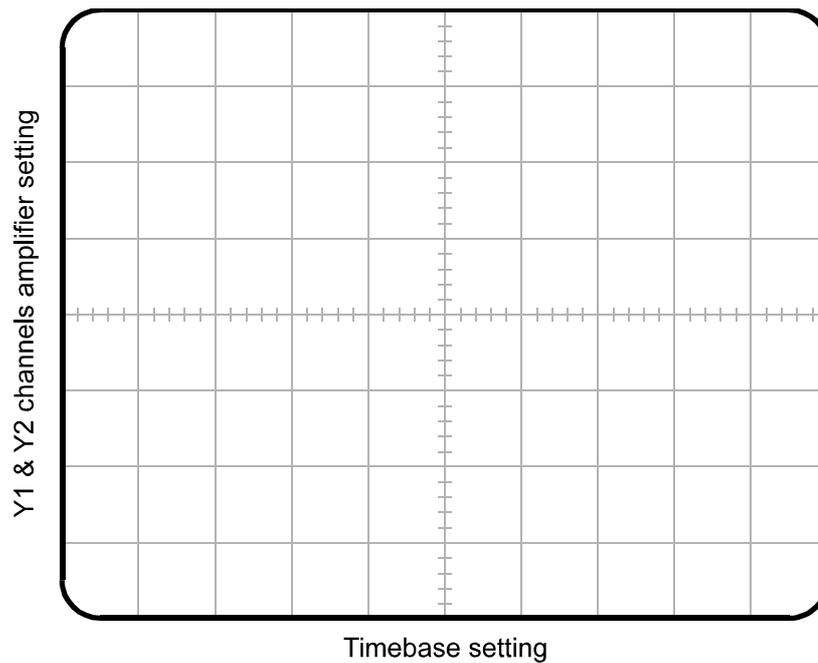
for parallel inductor circuits.



Notes



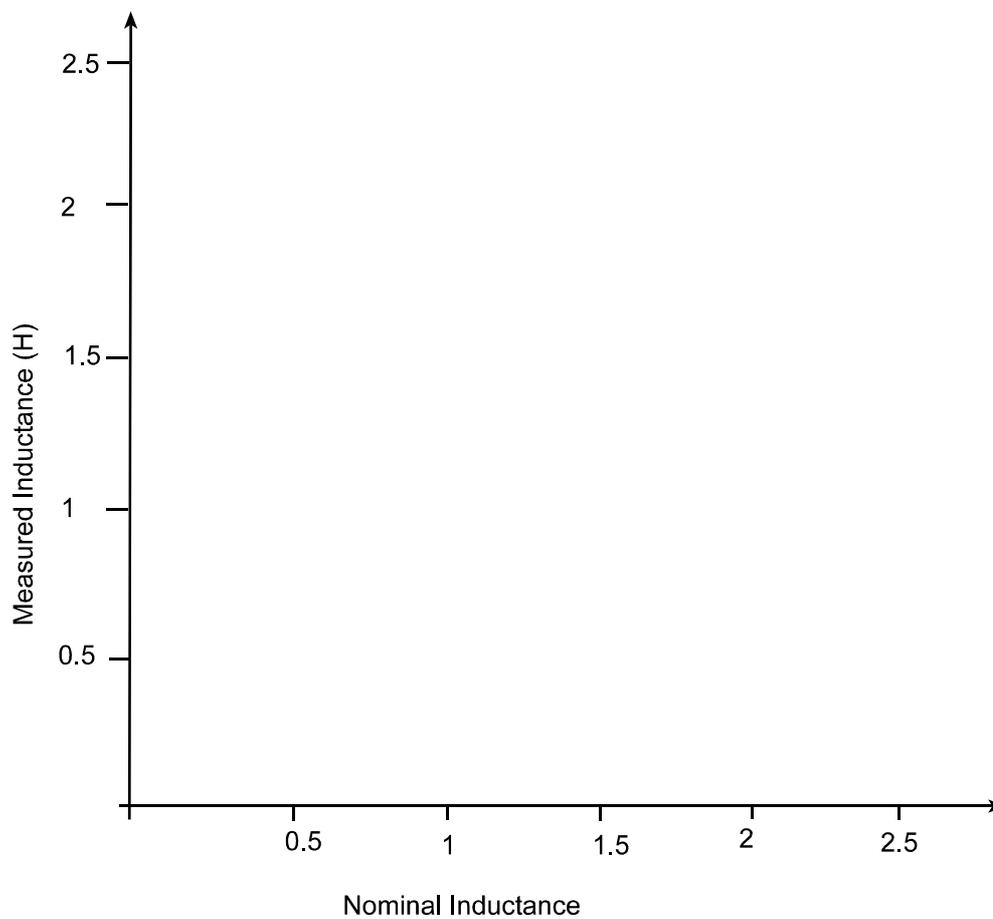
**10.12 Practical 10.1 - Oscilloscope Screen Graticule Representation**  
**(230 & 120 V Product Version)**





**10.13 Practical 10.2 - Results Tables and Graphs (230 V Product Version)**

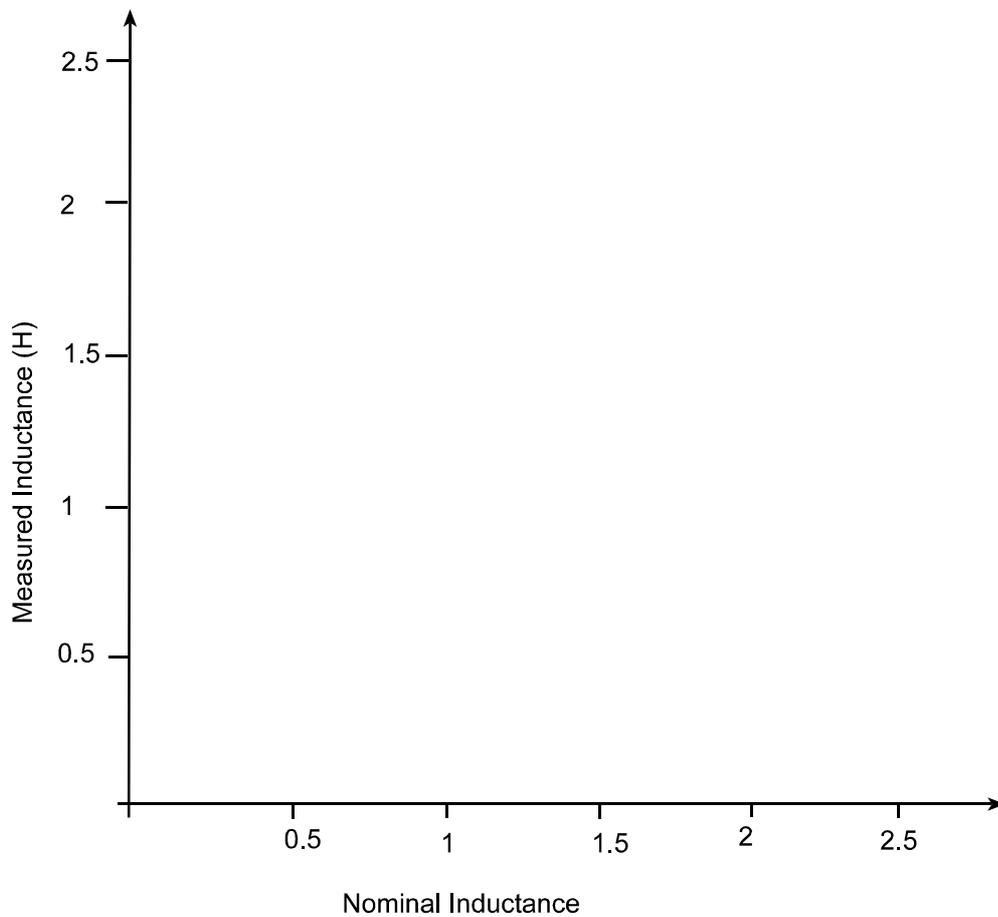
rms voltage (V)	rms current (A)	Impedance ( $\Omega$ )
50		
100		
150		
200		





**10.14 Practical 10.2 - Results Tables and Graphs (120 V Product Version)**

rms voltage (V)	rms current (A)	Impedance ( $\Omega$ )





**10.15 Practical 10.3 - Results Tables (230 V Product Version)**

Nominal		Measured			Calculated	
Voltage (V)	Inductance (H)	Voltage (V)	Current (A)	Power (W)	$X_L = V/I$ ( $\Omega$ )	Inductance (H)
200	0.56					
200	1.0					
200	1.5					
200	2.0					

**10.16 Practical 10.4 - Results Tables (230 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Inductance (H)	Voltage (V)	Current (A)	$X_L = V/I$ ( $\Omega$ )	Inductance (H)
200	1.7				
200	1.7 + 1.7				

**10.17 Practical 10.5 - Results Tables (230 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Inductance (H)	Voltage (V)	Current (A)	$X_L = V/I$ ( $\Omega$ )	Inductance (H)
200	1.7				
200	1.7 + 1.7				



**10.18 Practical 10.3 - Results Tables (120 V Product Version)**

Nominal		Measured			Calculated	
Voltage (V)	Inductance (H)	Voltage (V)	Current (A)	Power (W)	$X_L = V/I$ ( $\Omega$ )	Inductance (H)

**10.19 Practical 10.4 - Results Tables (120 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Inductance (H)	Voltage (V)	Current (A)	$X_L = V/I$ ( $\Omega$ )	Inductance (H)

**10.20 Practical 10.5 - Results Tables (120 V Product Version)**

Nominal		Measured		Calculated	
Voltage (V)	Inductance (H)	Voltage (V)	Current (A)	$X_L = V/I$ ( $\Omega$ )	Inductance (H)



Notes



## 11 Combinations of Load Elements

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### 11.1 Assignment Information

#### 11.1.1 Objectives

When you have completed this assignment you will:

- know the effects associated with combining a resistor and capacitor as a load in an ac circuit.
- know the effects associated with combining a resistor and inductor as a load in an ac circuit.

#### 11.1.2 Knowledge Level

Before you start this assignment:

- you should have completed or read Assignment 1 Familiarisation.
- you should have completed Assignments 7 to 10.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### 11.1.3 Practicals

1. Resistor and Capacitor in Series
2. Resistor and Inductor in Series

#### **NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **11.2 Theory**

### **11.2.1 Introduction**

By connecting a resistor and a reactor (ie, inductor or capacitor) to an ac supply, loads can be set up which are analogous to those found in practice. Many loads, such as motors, can be represented as combinations of inductance and resistance. The combination of resistance and capacitance is rarer, but can occur with lightly loaded transmission lines, or in installations which include power factor correction.



### 11.3 Content

The practicals in this assignment familiarise the student with the concepts of alternating current theory when various representative loads are connected.

### 11.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- Switched Three Phase Capacitive Load 67-212
- Switched Three Phase Inductive Load 67-312
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual  
Instrumentation  
(Option  
60-070-VIP)

Multichannel I/O Unit  
Software Pack

68-500  
68-912-USB

**or**

Conventional  
Instrumentation

Rectifier Voltmeter & Ammeter (Option CI2) 68-117

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 11.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



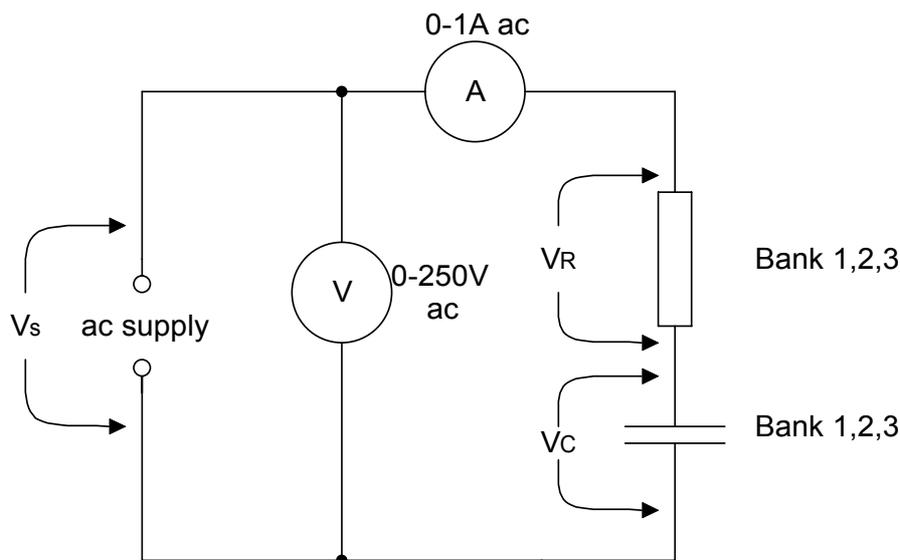
### 11.6 Practical 11.1 – Resistor and Capacitor in Series

A capacitor has no internal losses (unlike an inductor) and it is, therefore, easier to analyse its behaviour.

#### 11.6.1 Procedure

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-11-2, which relates to the theoretical circuit shown in Figure 3-11-1.



**Figure 3-11-1: Theoretical Circuit**

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

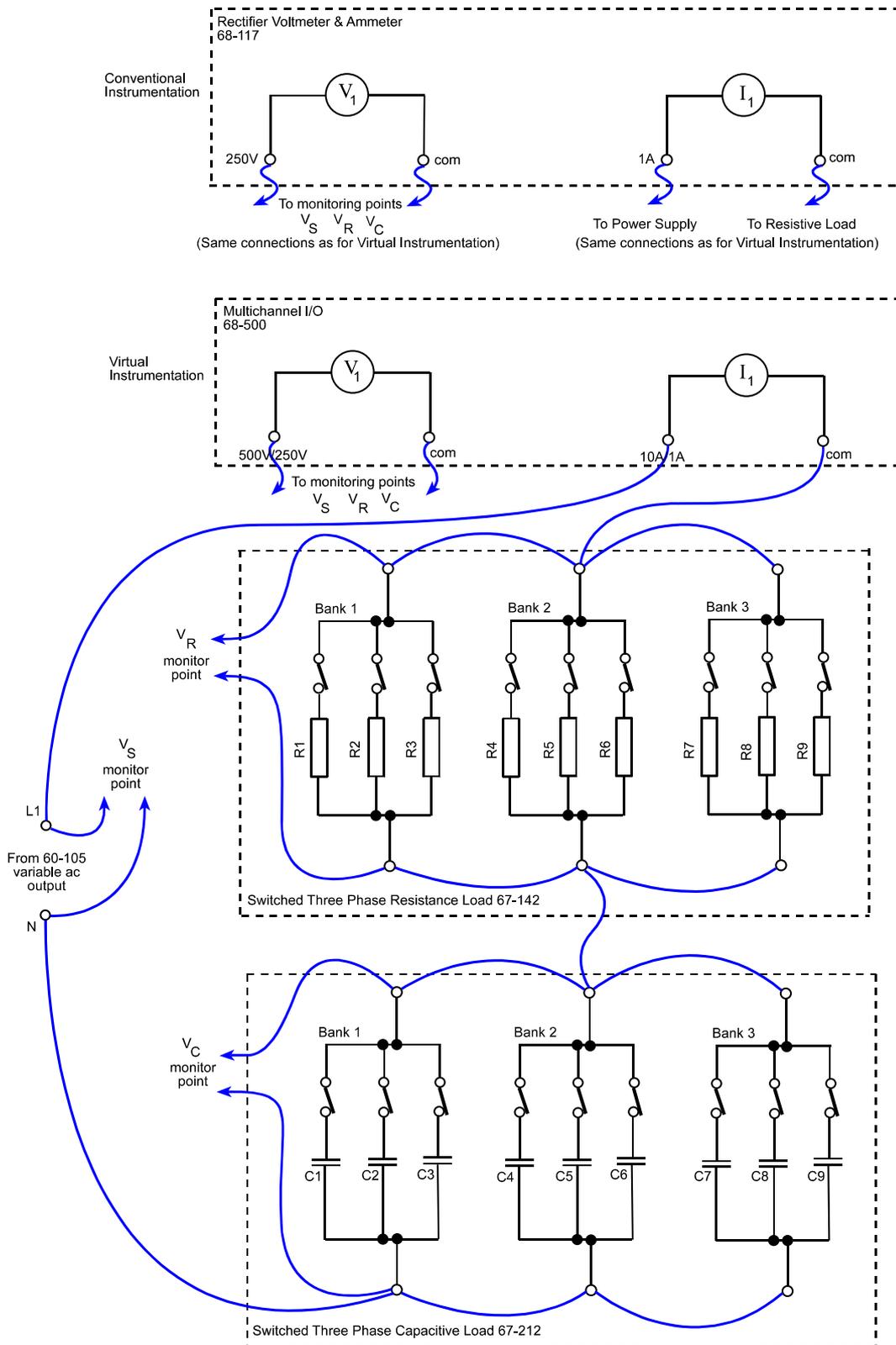


Figure 3-11-2: Practical 11.2 Circuit Diagram



Product Version	
230 V	120 V
21 $\mu F$	
182 $\Omega$	
200 V ac	
182 $\Omega$ resistor column	
213, 253, 317, 428, 650 and 1257 $\Omega$ in circuit	
213 ohms  253 ohms  317 ohms 428 ohms 650 ohms 1257 ohms	

On the switched three phase capacitive load 67-212, set banks 1 to 3 switches to on to give a capacitance of.....

On the switched three phase resistive load 67-142, set all the switches to on to give a resistance of.....

On the Universal Power Supply 60-105, ensure the 'variable output voltage control is set to 0% then set the '3 phase circuit breaker' to the on position.

Rotate the 'variable output voltage' control until the voltmeter indicates..... as shown on the virtual or conventional instrumentation.

Measure and record on copy of the appropriate Practical 11.1, Results Table (230 V or 120 V product version), voltages  $V_S$ ,  $V_R$  and  $V_C$  and current (I) in the .....

Repeat the above procedure and record results on your copy of Practical 11.1, Results Table with.....

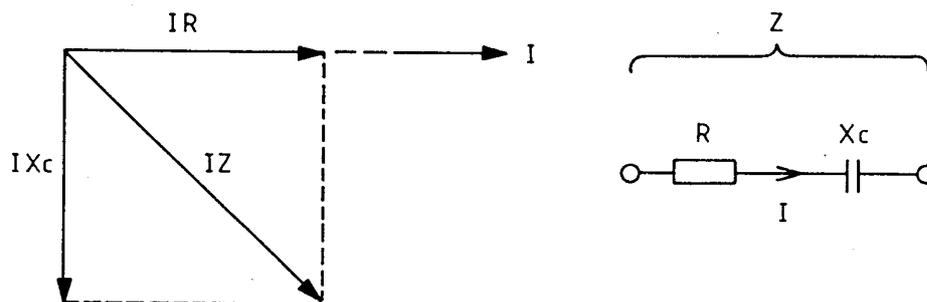
To obtain the resistance values listed, set the switches on the 67-142 as follows: R1,R2,R4,R5,R7 and R8 to on, all other switches off for.....  
 For the next value set R1,R3,R4,R6,R7 and R9 switches to on and all others off, for the value of.....  
 Set R1,R4 and R7 switches on and all others off for a value of.....  
 Set R2,R3,R5,R6,R8 and R9 switches on, all others to off for.....  
 Set R2,R5 and R8 switches on and all others off for.....  
 Set R3,R6 and R9 switches on and all others off for.....

On the Universal Power Supply 60-105, set the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.



**11.6.2 Analysis of Results (RC)**

The phasor diagram for a pure capacitance in series with a resistance is given in Figure 3-11-3.



**Figure 3-11-3**

Since the current  $I$  flows through both components, the voltages across them are proportional to their impedances  $R$  and  $V_C$  respectively. Because the voltage across the capacitance lags the current, its voltage phasor is at right angles to that for the resistance. If the impedance of the combination is called  $Z$ , then the whole voltage drop is  $IZ$ , with phasor  $IZ$  as shown.

The magnitudes of the phasors in Figure 3-11-3 can be calculated from your experimental results, from the following formulae:

$$IZ = V, IR = V_R, IX_C = V_C$$

If we did not know the values of  $R$  and  $C$ , we could calculate them from our measurements of voltage and current.

$$R = \frac{V_R}{I} \text{ ohms}, \quad X_C = \frac{V_C}{I} \text{ ohms}$$

then:

$$C = \frac{10^6}{2\pi f X_C} \mu\text{F}$$

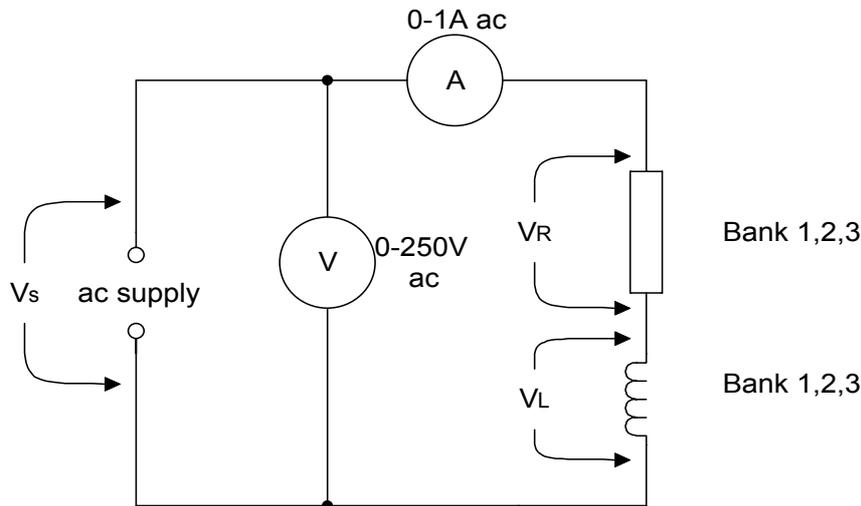
where  $f$  is the supply frequency.



**11.7 Practical 11.2 - Resistor and Inductor in Series**

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-11-5, which relates to the theoretical circuit shown in Figure 3-11-4.



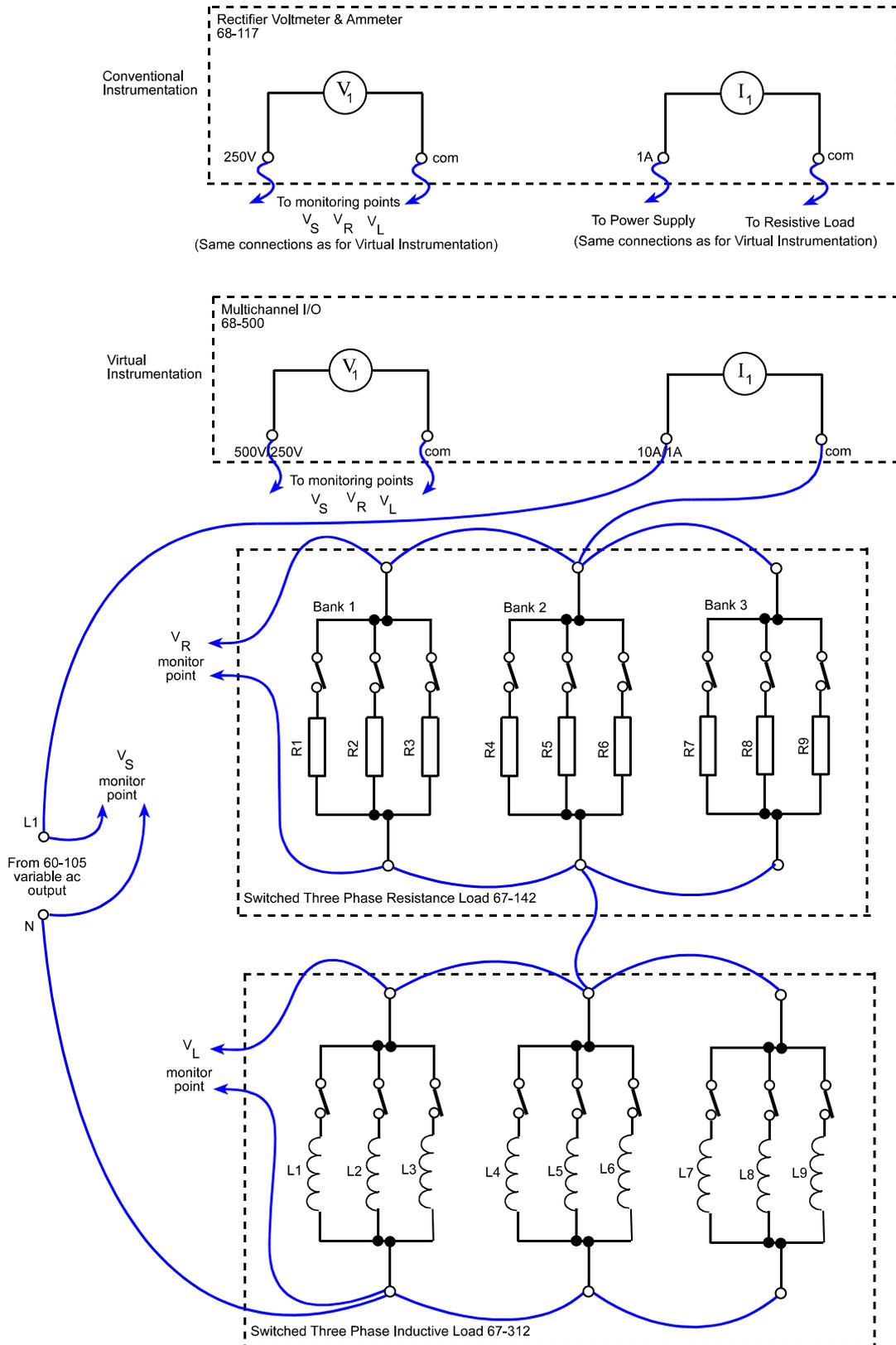
**Figure 3-11-4**

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

On the switched three phase inductive load 67-312, set all the switches to on to give an inductance of.....

On the switched three phase resistive load 67-142, set all the switches to on to give a resistance of.....

Product Version	
230 V	120 V
560 mH	
182 Ω	



**Figure 3-11-5: Practical 11.2 Circuit Diagram**



On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.

Rotate the 'variable output voltage' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 11.2, Results Table 1 (230 V or 120 V product version), voltages  $V_S$ ,  $V_R$  and  $V_L$  and current (I) in the.....

Repeat the above procedure and record results in your copy of Practical 11.2, Results Table 1 with .....

Product Version	
230 V	120 V
200 V ac	
182 $\Omega$ resistor column	
213, 253, 317, 428, 650 & 1257 $\Omega$ in circuit.	

On the Universal Power Supply 60-105, set the 'variable output voltage' control to 0% then set the '3 phase circuit breaker' to the off position.

### 11.7.1 Analysis of Results (RL)

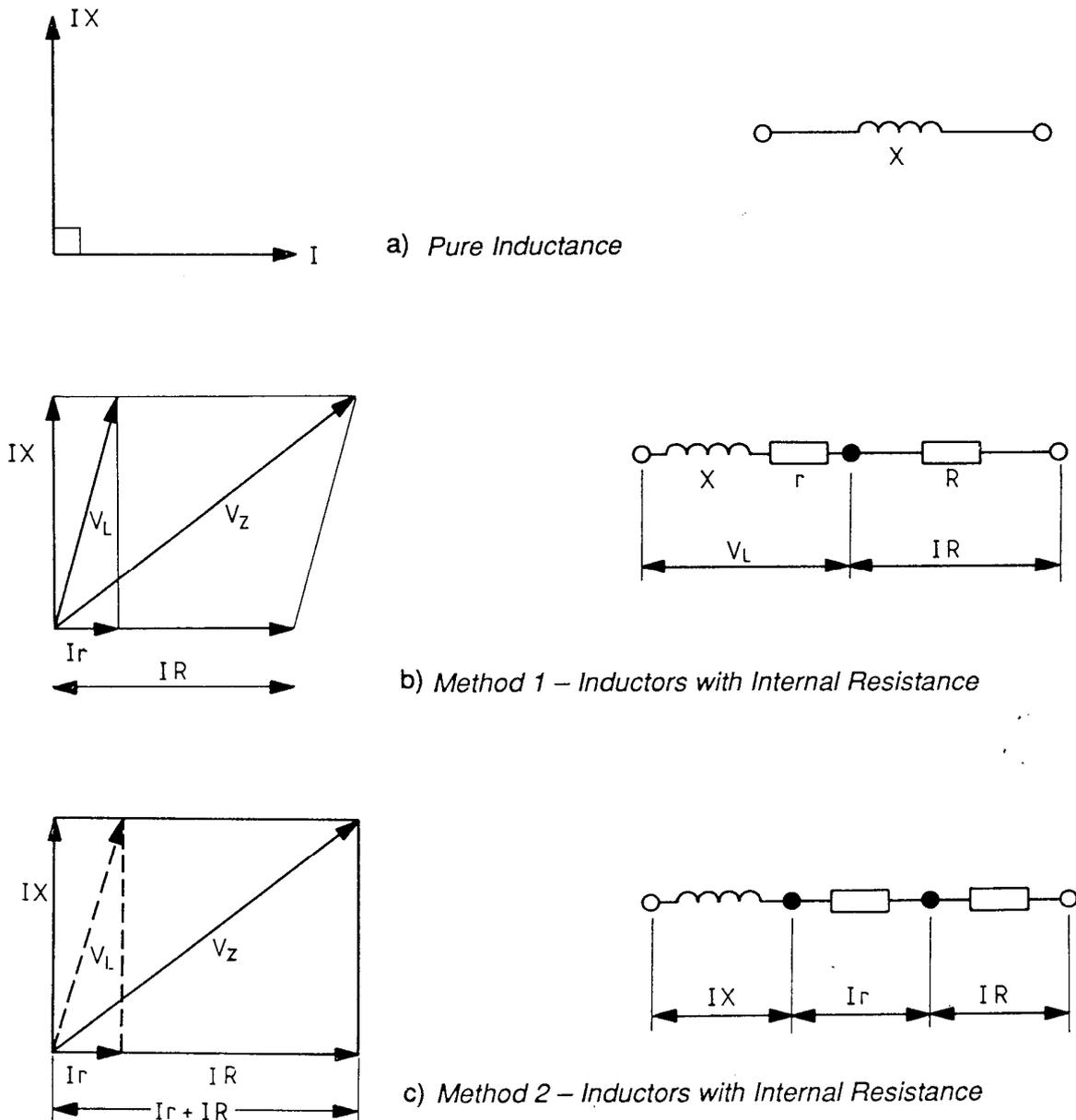
The phasor diagram for a pure inductance in series with a resistance is shown in Figure 3-11-6 (a). That for a practical inductor, having internal series resistance  $r$ , is shown in Figure 3-11-6 (b) and (c).

It can be seen that the internal resistance of the inductor makes very little alteration to the magnitude of voltage across the inductor.  $V_L$  is nearly equal to  $IX$  in magnitude. However, it makes a much bigger contribution to the voltage across the whole load. This can be looked at in two ways, represented by Figure 3-11-6 (b) and by (c) respectively:

- The voltage  $V_Z$  across the whole load can be considered as the phasor sum of the inductor voltage  $V_L$  and  $Ir$ . On this view, the important effect of  $r$  is the phase shift which rotates the  $V_L$  phasor, thus stretching  $V_Z$ .
- Alternatively,  $V_Z$  can be considered as the phasor sum of the reactive volt drop  $IX$  and the total resistive volt drop  $I(R + r)$ . (This is the approach used in analysis by complex algebra). Here it looks more as if the presence of  $r$  stretches the horizontal phasor ( $Ir + IR$ ), which in turn enlarges  $V_Z$ .



The equations needed for an exact analysis are quite complicated, and (given the presence of errors in measurement) may not even give the most accurate possible result. However,  $V_L$  and  $IX$  differ by so little that the instruments can hardly tell the difference. If we assume that they are equal, a much simpler analysis follows.



**Figure 3-11-6**



**11.7.2 Exercise 11.1**

Use your results for the nominal value of R to calculate the resistance  $r$  of the inductor, as follows enter the result in an appropriate copy of Practical 11.2 Results Table 2 (230 V or 120 V product version):

Product Version	
230 V	120 V
182 $\Omega$	

Nominal value of resistor R = .....

Measured value of  $R = \frac{V_R}{I}$

Impedance  $Z = \frac{V}{I}$

Reactance  $X_L = \frac{V_L}{I}$

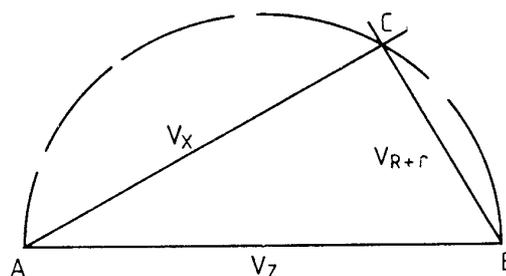
Total resistance  $R_T = \sqrt{Z^2 - X^2}$

Internal resistance  $r = R_T - R$

**11.7.3 Circuit Diagram**

If your results are correct, it should be possible to draw a 'circle diagram' similar to that shown in Figure 3-11-7, as follows.

Start by drawing the base line AB to a scale representing the total supply voltage  $V_Z$ . For each line in the table, draw point C, preferably by using a compass, so that the distance AC is proportional to  $V_L$ , and the distance BC is proportional to the total resistance  $(R + r)$ . The result should be a semicircle.



**Figure 3-11-7**



As shown in Figure 3-11-7, the phasor AC represents the voltage across the reactance, CB that across the resistance. (Note that the horizontal reference is now not the current phasor, as in some previous phasor diagrams). AC and BC must be at right angles to one another; geometry tells us that as AC, BC vary, if the angle ACB is a right angle, C traces out a circle. (Circle diagrams can be quite useful in the theory of some types of motor).

### **11.8 Practical Aspects**

Load elements were made up containing a reactance X and separate resistance R. When the reactance was capacitive it was confirmed that the volt drops across X and R were in quadrature (their phasors were at right angles).

When an inductor was used, its internal resistance  $r$  caused departures from the ideal behaviour of an inductance. It was found that if X was much greater than  $r$ , the voltage across the combination was close in magnitude to the voltage across X alone (not accessible for measurement). However,  $r$  caused a phase shift whose effects were significant in the total impedance Z.

The volt drops across a resistance and a reactance in series are combined not by a simple addition, but by adding two phasors at right angles. The circle diagram is a useful reminder of this.



Notes



**11.9 Practical 11.1 - Results Table (230 V Product Version)**

Resistance ( $\Omega$ )	182	213	253	317	428	650	1257
Applied Voltage (V)							
Volts across Resistor ( $V_R$ )							
Volts across Capacitor ( $V_C$ )							
Current (mA)							

**11.10 Practical 11.2 - Results Table 1 (230 V Product Version)**

Resistance ( $\Omega$ )	182	213	253	317	428	650	1257
Applied Voltage (V)							
Volts across Resistor ( $V_R$ )							
Volts across Inductor ( $V_L$ )							
Current (mA)							

**11.11 Practical 11.2 - Results Table 2 (230 V Product Version)**

Nominal value of resistor R	182
Measured value of R ( $\frac{V_R}{I}$ )	
Impedance Z ( $\frac{V}{I}$ )	
Reactance $X_L$ ( $\frac{V_L}{I}$ )	
Total resistance $R_T$ ( $\sqrt{Z^2 - X^2}$ )	
Internal resistance r ( $R_T - R$ )	



**11.12 Results Table (120 V Product Version)**

Resistance ( $\Omega$ )							
Applied Voltage (V)							
Volts across Resistor ( $V_R$ )							
Volts across Capacitor ( $V_C$ )							
Current (mA)							

**11.13 Practical 11.2 - Results Table 1 (120 V Product Version)**

Resistance ( $\Omega$ )							
Applied Voltage (V)							
Volts across Resistor ( $V_R$ )							
Volts across Inductor ( $V_L$ )							
Current (mA)							

**11.14 Practical 11.2 - Results Table 2 (120 V Product Version)**

Nominal value of resistor R	
Measured value of R ( $\frac{V_R}{I}$ )	
Impedance Z ( $\frac{V}{I}$ )	
Reactance $X_L$ ( $\frac{V_L}{I}$ )	
Total resistance $R_T$ ( $\sqrt{Z^2 - X^2}$ )	
Internal resistance $r$ ( $R_T - R$ )	



## **12 Power in ac Circuit**

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### **12.1 Assignment Information**

#### **12.1.1 Objectives**

When you have completed this assignment you will:

- have investigated the power dissipation of various components in an ac circuit.

#### **12.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignment 1 Familiarisation.
- you should have completed or read Assignments 6 to 11.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **12.1.3 Practicals**

1. Component Power Dissipation

**NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## **12.2 Theory**

### **12.2.1 Introduction**

We know that the power dissipated by a component at any instant is given by the product of the voltage across that component and the current through it, at that instant.

$$\text{ie, } P = VI$$

The concepts of electrical power and power transfer in a dc circuit were investigated in Assignment 6. This assignment investigates power dissipation of components in an ac circuit.

Phasors diagrams are used in this assignment. For further information on phasors, see Appendix B.1.



### 12.3 Content

The practical in this assignment familiarises the student with the concept of power dissipation of components in an ac circuit.

### 12.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- Switched Three Phase Inductive Load 67-312
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
<b>or</b>		
Conventional Instrumentation	Rectifier Voltmeter & Ammeter (Option CI2)	68-117
Ancillary Equipment	Differential Voltage/Current Probe (2 off)	68-150
	Two channel oscilloscope with at least 20 MHz time base	

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 12.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).

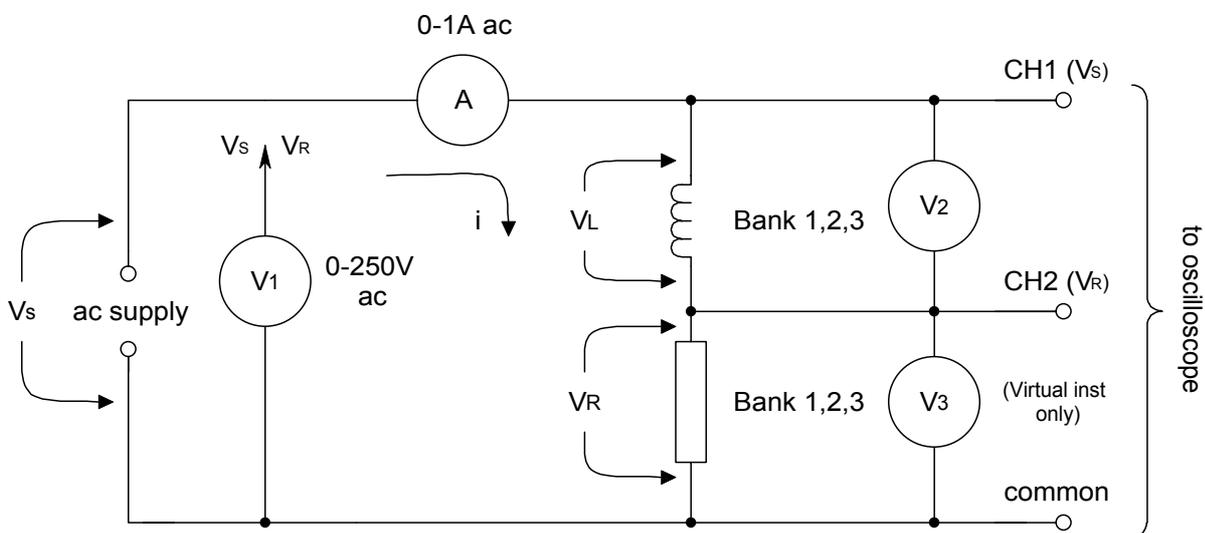


### 12.6 Practical 12.1 - Component Power Dissipation

In an ac circuit, both  $V$  and  $I$  are continually varying and  $P$ , therefore, also varies continually. It is the average power that is usually of interest.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off

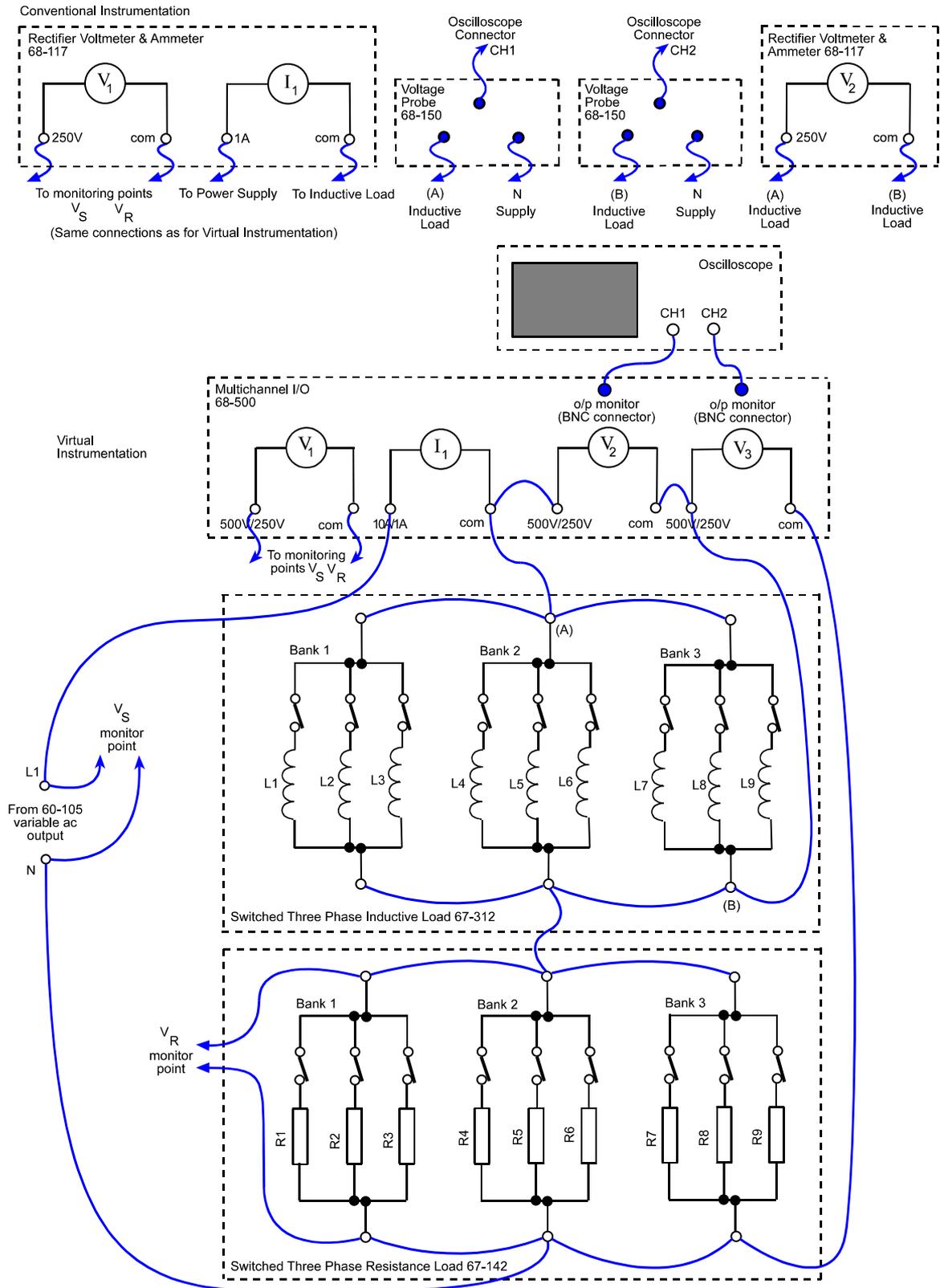
Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-12-2, which equates to the theoretical circuit shown in Figure 3-12-1



**Figure 3-12-1**

If virtual instrumentation is being used, set the 250 V/500 V range switches for the  $V_1$ ,  $V_2$  and  $V_3$  channels to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switch for the I1 channel to '1 A'. This allows currents of up to 1 A to be monitored when the 10 A/1 A socket is connected or 200 mA to be monitored when the 200 mA socket is connected.

If conventional instrumentation is being used, switch on the differential probes and ensure that the attenuation ratio is set to 1/20.



**Figure 3-12-2: Practical 12.1 Circuit Diagram**



Product Version	
230 V	120 V
560 mH	
182 Ω	
100 V ac	

On the switched three phase inductive load 67-312, set banks 1 to 3 switches to on to give an inductance of.....

On the switched three phase resistive load 67-142, set banks 1 to 3 switches to on to give a resistance of.....

On the Universal Power Supply 60-105 , ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter on the virtual or conventional instrumentation indicates.....

Display  $V_S$  and  $V_R$  on the two traces ( $Y_1$  and  $Y_2$ ) of the oscilloscope and measure and note the phase difference between them as accurately as you can.

Measure and note the voltage across the resistor,  $V_R$ , using the virtual or conventional voltmeter.

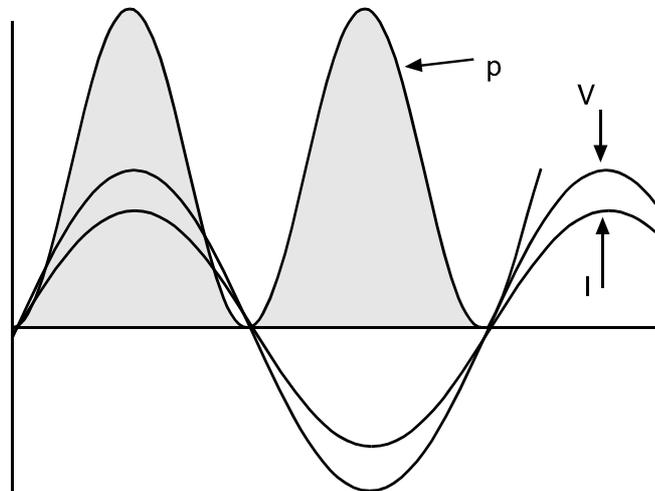
Turn the '*variable output voltage*' control to 0% on the Universal Power Supply 60-105 and then switch off the '*3 phase circuit breaker*'.

*Question 12.1*      *What is the phase relationship between the current through and the voltage across the resistor?*

**12.6.1 Exercise 12.1**

Using a copy of the graph axis given for Practical 12.1 in the Results Tables section at the end of this assignment, draw two sine waves on the same axis to show the phase relationship between the current round the circuit and the resistor voltage. They do not have to be to scale.

As  $P = V I$ , construct the power curve on the same axes (remember that  $-V \times -I = +P$ ).



**Figure 3-12-3: Purely Resistive Circuit**

Calculate  $I$ , from  $V_R$  and the value of the resistor.

Using  $P_R = V_R \cdot I$ , calculate the power dissipated by the resistor.

Now, let us examine the voltage and current in the inductor.

Calculate the internal resistance of the inductor using the formula given in Assignment 11, Practical 11.2, Exercise 11.1.

ie,  $R_L = R_T - R$

where  $R_L =$  internal resistance

$$R_T = \text{total resistance} = \sqrt{Z^2 - X^2}$$

$$R = \text{calculated value of resistor} = \frac{V_R}{I}$$

Using  $P_L = I^2 R_L$ , calculate the power dissipated by the inductor.

**Question 12.2**      *What is the phase relationship between the current through and the voltage across an inductor.*

Using a further copy of the graph axis given for Practical 12.1 in the Results Tables section, draw the voltage and current curves for an inductor showing the relative phases. Construct the power curve.

**Question 12.3**      *What is the average power dissipated by the inductor in each cycle of current?*

You should have a power curve which has two cycles for every cycle of current but which is symmetrical about the voltage axis. Thus for each cycle of current, the average power dissipated is zero.



### Further work

When a resistor and an inductor are connected together in a circuit, there will be a phase shift between the voltage and the current. This is shown in Figure 3-12-4.

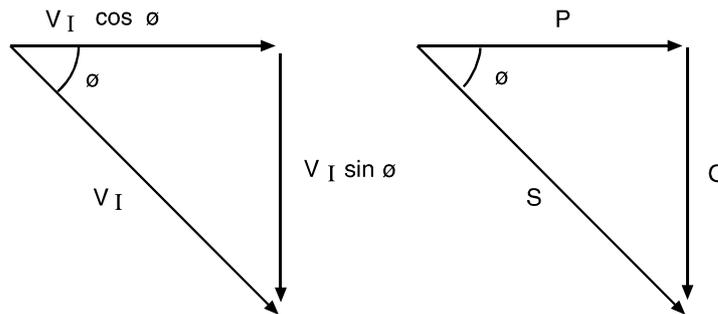


Figure 3-12-4

Construct the power wave for such a case.

You will see that the power wave cuts the voltage axis, but is not symmetrical about it. The amount by which the power wave cuts the axis is proportional to  $\phi$ .

In fact the relationship between the power  $V$ ,  $I$  and  $\phi$  is given by:

$$\text{Average Power} = V I \cos \phi$$

where  $V$  and  $I$  are rms values.

The factor,  $\cos \phi$  is called the **POWER FACTOR** of the circuit, and is unity for a pure resistance.

For a purely inductive circuit, the power factor is 0 and similarly for a purely capacitive circuit.

Calculate the total power dissipated in the circuit from:

$$P_T = P_L + P_R$$

From your earlier measured value of  $\phi$ , calculate the total average power given by  $V I \cos \phi$

Compare this with your result from  $P_L + P_R$ .

$\phi$  is also given by the formula  $\phi = \tan^{-1} X_L/R$  where  $X_L = 2\pi fL$ . Calculate  $\phi$  from this expression and, using that value, calculate  $V I \cos \phi$ .

Compare this with the experimental values.



### Practical Aspects

Power at ac is given by the expression:

$$P = V I \cos \phi$$

The unit of electrical power is the watt (W). 1000 W = 1 kilowatt (kW).

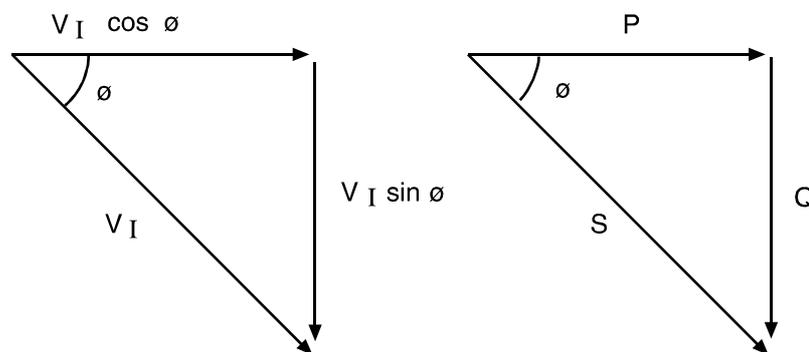
The product  $V I$  is called the apparent power, and may be designated by the symbol  $S$ .

The units of  $S$  are the volt-ampere (VA) and kilovolt-ampere (kVA).

The product  $V I \sin \phi$  is called the reactive power (or wattless power) and is indicated by the symbol  $Q$ .

The units of  $Q$  are also the volt-ampere (VA) and kilovolt-ampere (kVA). To avoid confusion, it is common practice to add the letter R to distinguish reactive power. Thus, while  $S$  is always expressed in VA and its multiples,  $Q$  may be expressed in VAR and its multiples.

A power phasor triangle may be constructed as in Figure 3-12-5.



**Figure 3-12-5**

Only the real power,  $P$ , is taken as energy from the supply.



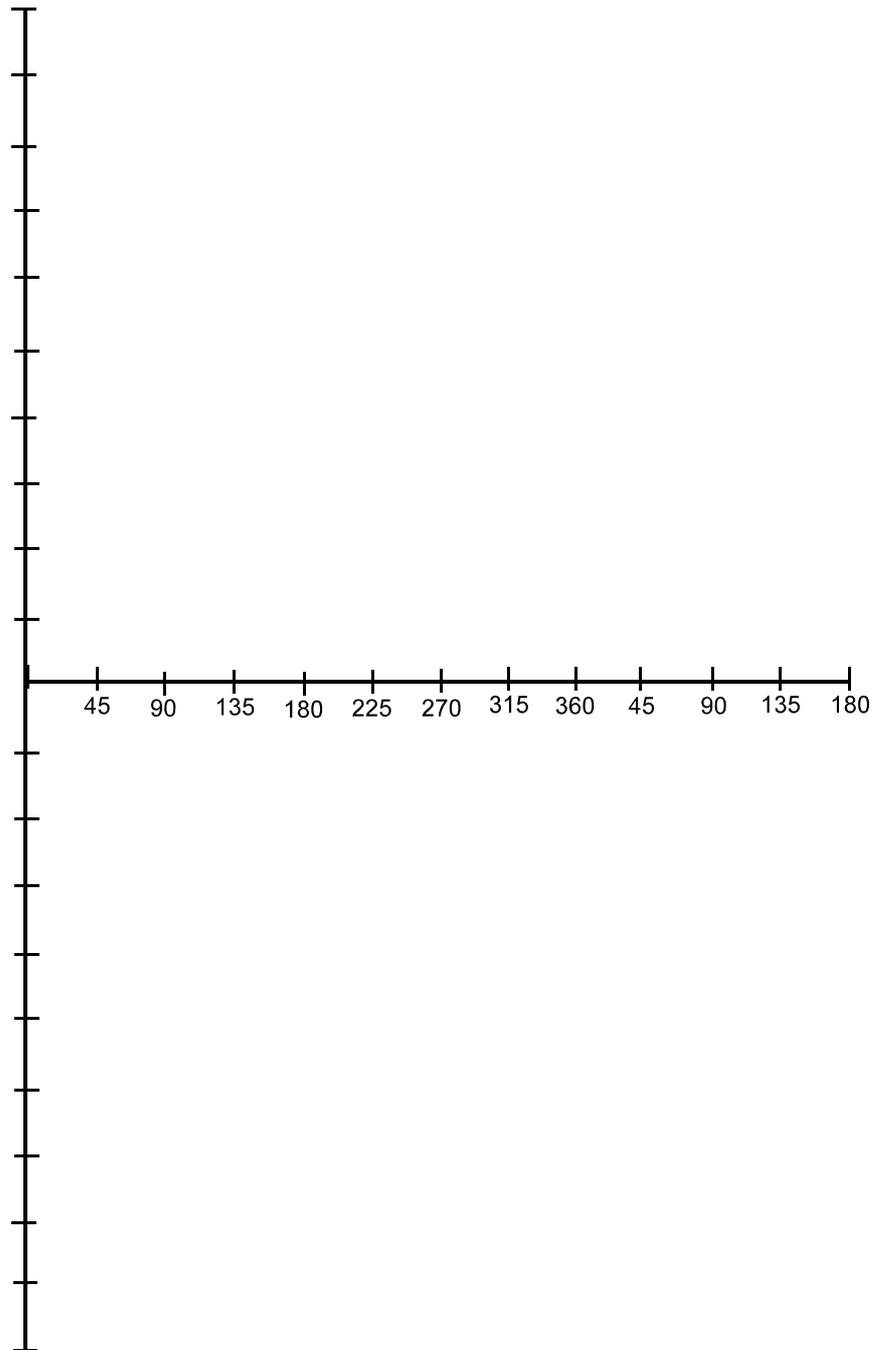
*Powerframes*  
**ELECTRICAL CIRCUITS**  
**STUDENT'S MANUAL**

**Chapter 3**  
**Assignment 12**  
**Power in ac Circuit**

Notes



**12.7 Practical 12.1 - Graph Axis (230 & 120 V Product Versions)**





Notes



## 13 Three Phase Voltage & Current Relationships

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### 13.1 Assignment Information

#### 13.1.1 Objectives

When you have completed this assignment you will:

- be able to derive the relationship between line and phase voltages in a balanced star connected three phase supply load.
- be able to derive the relationship between line and load currents in a balanced delta connected three phase supply load.

#### 13.1.2 Knowledge Level

Before you start this assignment:

- you should have completed or read Assignment 1 Familiarisation.
- you should have completed or read Assignment 5 and 7.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### 13.1.3 Practicals

1. Voltage Relationships in a Balanced Star Supply Star Load
2. Current Relationships in a Balanced Star Supply Delta Load

**NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## 13.2 Theory

### 13.2.1 Introduction

In a typical three phase power system, the generator has a star connected output and usually includes either star or delta connected loads. Voltage relationships are considered when a star load is connected, and current relationships when a delta load is connected.

Figure 3-13-1 shows a star connected generator supplying a balanced star connected load via a three phase line. Assuming a positive phase sequence (phase order ABC), the supplied voltages are:

$$E_{An} = |E_p| \angle 0^\circ$$

$$E_{Bn} = |E_p| \angle -120^\circ$$

$$E_{Cn} = |E_p| \angle -240^\circ$$

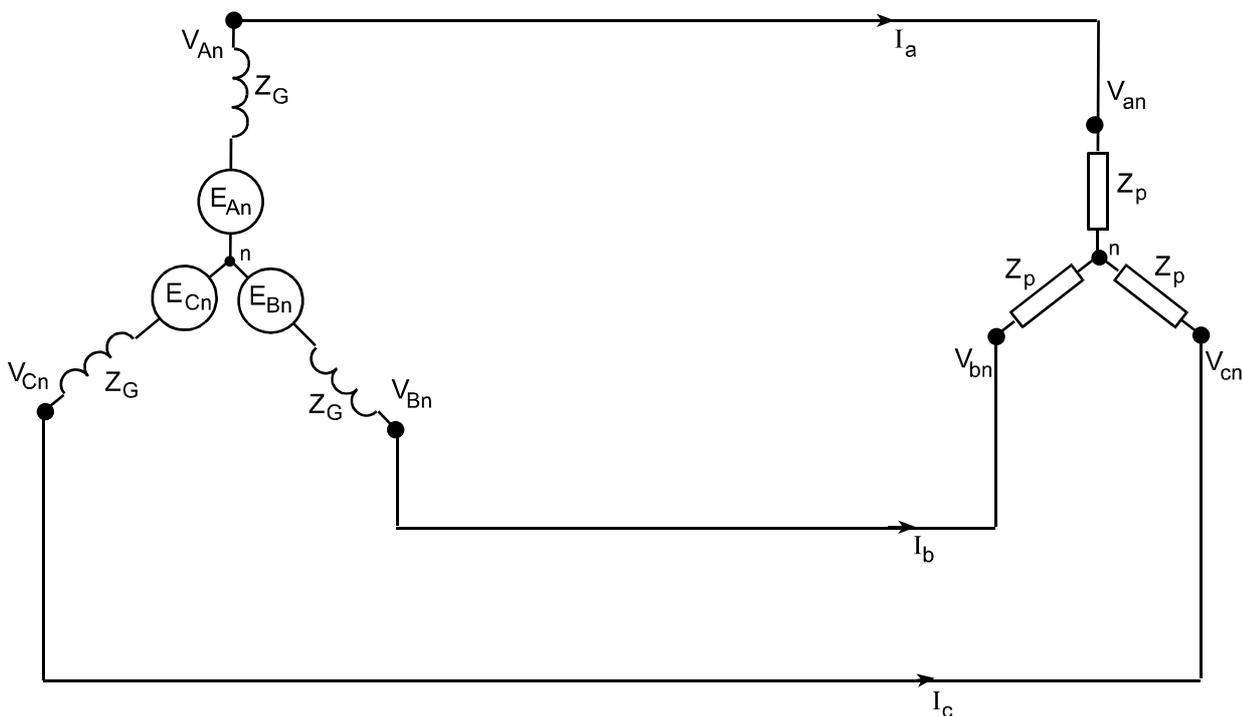


Figure 3-13-1: Star Connected Generator supplying a Star Connected Load

In power systems, great care is taken to ensure that the loads of transmission lines are balanced. For balanced loads, the terminal voltages of the generator  $V_{An}$ ,  $V_{Bn}$  and  $V_{Cn}$  and the phase voltages  $V_{an}$ ,  $V_{bn}$  and  $V_{cn}$  at the load terminals are balanced.



### 13.2.2 Voltage Relationships (Star Load)

To find the relationship between the line voltages (line-to-line voltages) and the phase voltages (line-to-neutral voltages) of a balanced three phase supply connected to a star connected load, the line-to-neutral voltage of 'phase A' is arbitrarily chosen as the reference, thus:

$$V_{an} = |V_p| \angle 0^\circ$$

$$V_{bn} = |V_p| \angle -120^\circ$$

$$V_{cn} = |V_p| \angle -240^\circ$$

where  $|V_p|$  represents the magnitude of the phase voltage (line-to-neutral voltage).

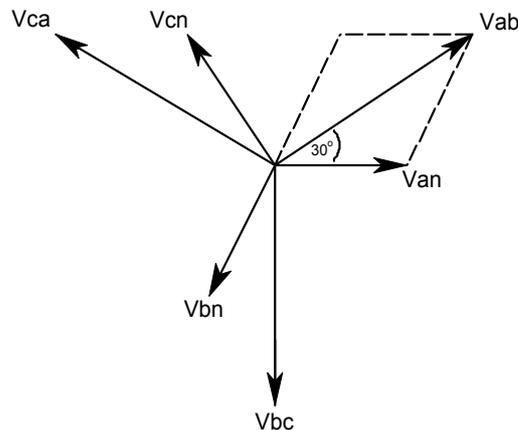
The line voltages at the load terminals in terms of the phase voltages are found by the application of Kirchhoff's voltage law:

$$V_{ab} = V_{an} - V_{bn} = |V_p| (1 \angle 0^\circ - 1 \angle -120^\circ) = \sqrt{3} |V_p| \angle 30^\circ$$

$$V_{bc} = V_{bn} - V_{cn} = |V_p| (1 \angle -120^\circ - 1 \angle -240^\circ) = \sqrt{3} |V_p| \angle -90^\circ$$

$$V_{ca} = V_{cn} - V_{an} = |V_p| (1 \angle -240^\circ - 1 \angle 0^\circ) = \sqrt{3} |V_p| \angle -150^\circ$$

The voltage phasor diagram of the star connected loads shown in Figure 3-13-1 is shown in Figure 3-13-2. The relationship between the line voltage and phase voltage is demonstrated graphically.



**Figure 3-13-2: Phase and Line Voltages**

If the rms value of any of the line voltages is denoted by  $V_L$ , then one of the important characteristics of the star connected three phase load may be expressed as:

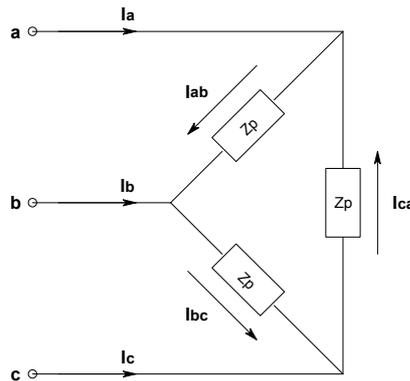
$$V_L = \sqrt{3} |V_p| \angle 30^\circ$$

Thus in the case of star connected loads, the magnitude of the line voltage is  $\sqrt{3}$  times the magnitude of the phase voltage, and for a positive phase sequence, the set of line voltages leads the set of phase voltages by  $30^\circ$ .



**13.2.3 Current Relationships (Delta Load)**

The relationship between the phase and line currents of a balanced three phase supply connected to a delta connected load is considered and reference should be made to Figure 3-13-3. It should be noted that each phase has equal impedances.

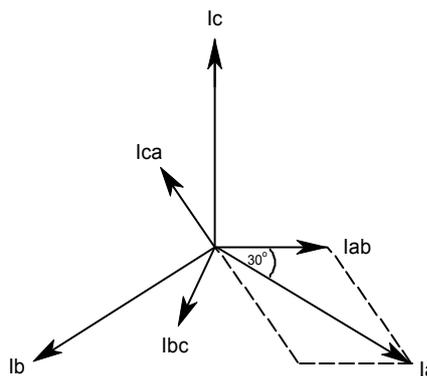


**Figure 3-13-3: Delta Connected Load**

As the line currents  $I_a$ ,  $I_b$  and  $I_c$  are similar and phase impedances  $Z_p$  are equal, line voltages ( $V_L$ ) must be the same as the phase voltages ( $V_p$ ):

$$V_L = V_p$$

Consider the phasor diagram shown in Figure 3-13-4, where the phase current  $I_{ab}$  is arbitrarily chosen as reference.



**Figure 3-13-4: Phase and Line Currents**

Thus:

$$I_{ab} = |I_p| \angle 0^\circ$$

$$I_{bc} = |I_p| \angle -120^\circ$$

$$I_{ca} = |I_p| \angle -240^\circ$$

where  $|I_p|$  represents the magnitude of the phase current.



The relationship between the phase and line currents can be obtained by applying Kirchhoff's current law at the corners of the delta load:

$$I_a = I_{ab} - I_{ca} = |I_p| (1\angle 0^\circ - 1\angle -240^\circ) = \sqrt{3}|I_p|\angle -30^\circ$$

$$I_b = I_{bc} - I_{ab} = |I_p| (1\angle -120^\circ - 1\angle 0^\circ) = \sqrt{3}|I_p|\angle -150^\circ$$

$$I_c = I_{ca} - I_{bc} = |I_p| (1\angle -240^\circ - 1\angle -120^\circ) = \sqrt{3}|I_p|\angle 90^\circ$$

The relationship between the line currents and phase currents is demonstrated graphically in Figure 3-13-4.

If the rms of any of the line currents is denoted by  $I_L$ , then one of the important characteristics of the delta connected three phase load may be expressed as:

$$I_L = \sqrt{3}|I_p|\angle -30^\circ$$

Thus for delta connected loads, the magnitude of the line current is  $\sqrt{3}$  times the magnitude of the phase current, and with positive phase sequence, the set of line currents lags the set of phase currents by  $30^\circ$ .



### 13.3 Content

The practicals in this assignment familiarise the student with voltage and current relationships of balanced star and delta loads in a three phase system.

### 13.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual  
Instrumentation  
(Option  
60-070-VIP)

Multichannel I/O Unit  
Software Pack

68-500  
68-912-USB

**Or**

Conventional  
Instrumentation

Rectifier Voltmeter & Ammeter (Option CI2) 68-117

#### NOTES:

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 13.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 13.6 Practical 13.1 - Voltage Relationships in a Balanced Star Supply Star Load

The star connected supply is applied to a star connected load. Measurements are taken of line current and voltage and phase voltage.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-13-6, which equates to the theoretical circuit shown in Figure 3-13-5.

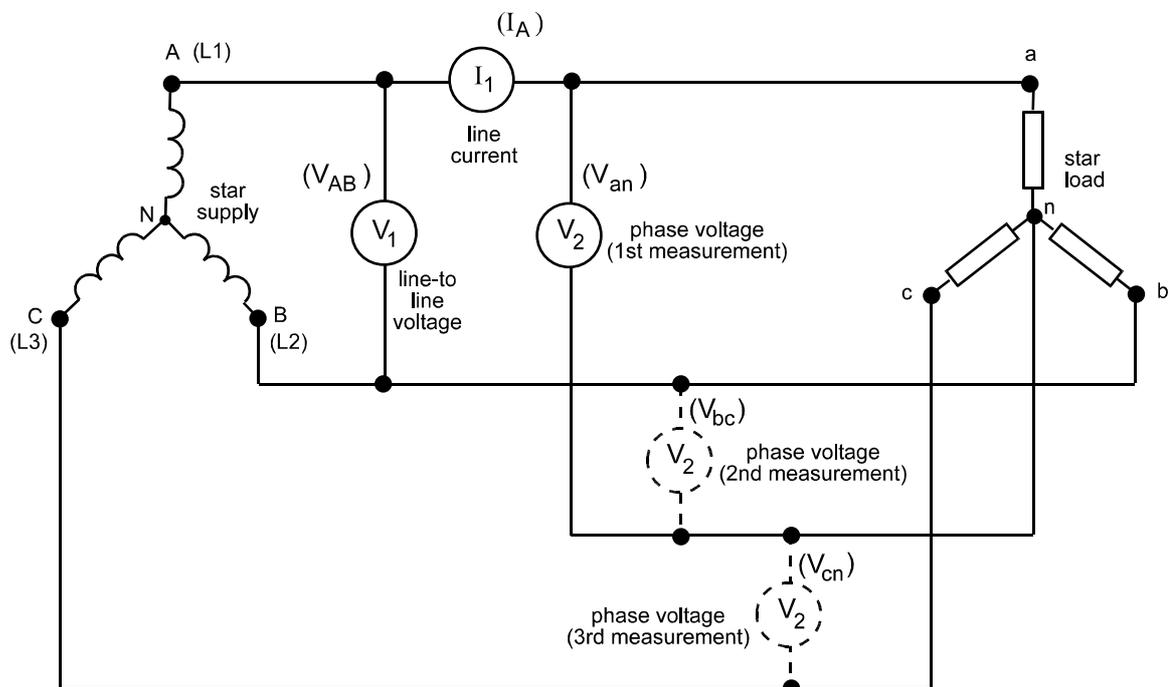
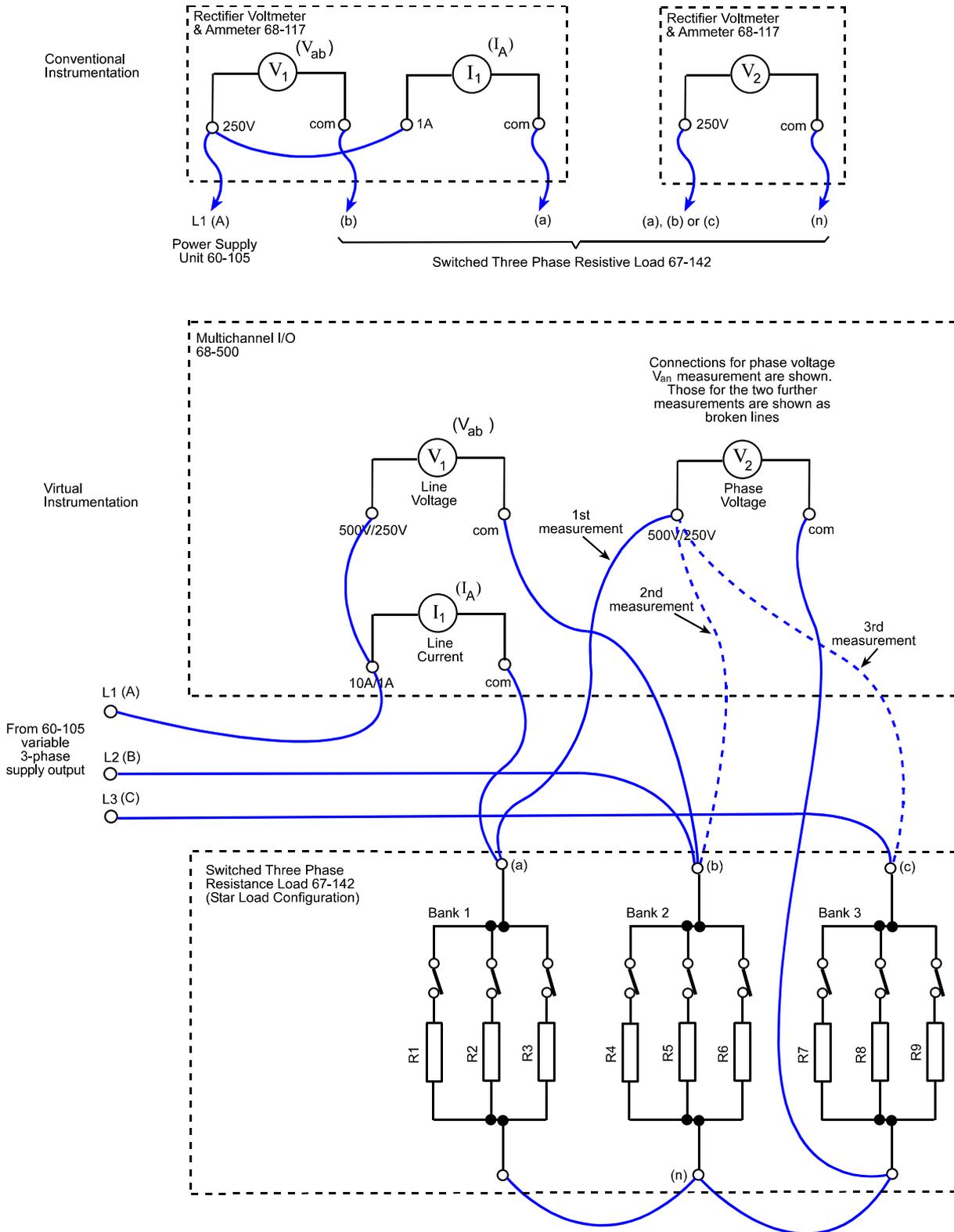


Figure 3-13-5: Theoretical Circuit

If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1 and V2 channels to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switch for I1 to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' socket is connected or 200 mA to be monitored when the '200 mA' socket is connected.



**Figure 3-13-6: Practical 13.1 Circuit Diagram**



		Product Version	
		230 V	120 V
On the switched three phase resistive load 67-142, set all switches to on so that each bank provides a resistive load of.....	546 Ω		
On the Universal Power Supply 60-105, ensure the 'variable output voltage' control is set to 0% then set the '3 phase circuit breaker' to the on position.			
Rotate the 'variable output voltage' control until the voltmeter V1 on the virtual or conventional instrumentation indicates.....	200 V ac line-to-line		

**13.6.1 Measurement Procedure**

Measure and record on a copy of the appropriate Practical 13.1, Results Table (230 V or 120 V product versions) parameters associated with the resistive load set above for each leg as follows:

- Line current
- Line voltage
- Phase voltage  $V_{an}$

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the off position.

Disconnect V2 from across leg 'an' of the load and reconnect it across leg 'bn' of the load.

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.

In your copy of Practical 13.1, Results Table, record phase voltage  $V_{bn}$

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the off position.

Disconnect V2 from across leg 'bn' of the load and reconnect it across leg 'cn' of the load.

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.

In your copy of Practical 13.1, Results Table, record phase voltage  $V_{cn}$ .



Product Version	
230 V	120 V
640 Ω	
759 Ω (S1 & S3 on, S2 off) & 950 Ω (S1 on, S2 & S3 off)	

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the off position.

On the switched three phase resistive load 67-142, set the switches on all three banks such that S1 and S2 (upper and middle) are on and S3 (lower) is off so that each bank provides a resistive load of.....

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.

Repeat the measurement procedure as previously described and on your copy of Practical 13.1, Results Table parameters associated with the resistive load set above for each leg as follows:

- Line current
- Line voltage
- Phase voltages  $V_{an}$ ,  $V_{bn}$  and  $V_{cn}$

Repeat the above procedure in conjunction with resistive loads of ..... set on each of the three individual load banks and record all results in your copy of Practical 13.1, Results Table.

### 13.6.2 Analysis of Results

Because the system shown in Figure 3-13-5 is balanced, you should have observed that the phase-to-neutral voltages are equal. Additionally, the line voltages will also be equal. Therefore:

$$\text{Line voltage } (V_L) = V_{AB} = V_{BC} = V_{CA}$$

$$\text{Phase voltages } (V_p) = V_{an} = V_{bn} = V_{cn}$$

Comparing the measured line voltage with any measured phase voltage, it is found that the line voltage is  $\sqrt{3}$  (1.732) times the magnitude of the phase voltage; that is:

$$\frac{V_L}{V_p} = \sqrt{3} = \frac{200}{115.47} = 1.732 \text{ or } \sqrt{3}$$

Check that this is true by calculating the phase voltage from the line voltage, using the values recorded in your copy of Practical 13.1, Results Table and the formula:  $V_p = V_L / \sqrt{3}$

Complete the last column in your table by taking the average value of the three phase voltages ( $V_p$ ) and then calculating the ratio  $V_L/V_p$ .



### 13.7 Practical 13.2 – Current Relationships in a Balanced Star Supply Delta Load

The star connected supply is applied to a delta connected load. Measurements are taken of line current and voltage and phase current.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make all the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-13-8, which equates to the theoretical circuit shown in Figure 3-13-7.

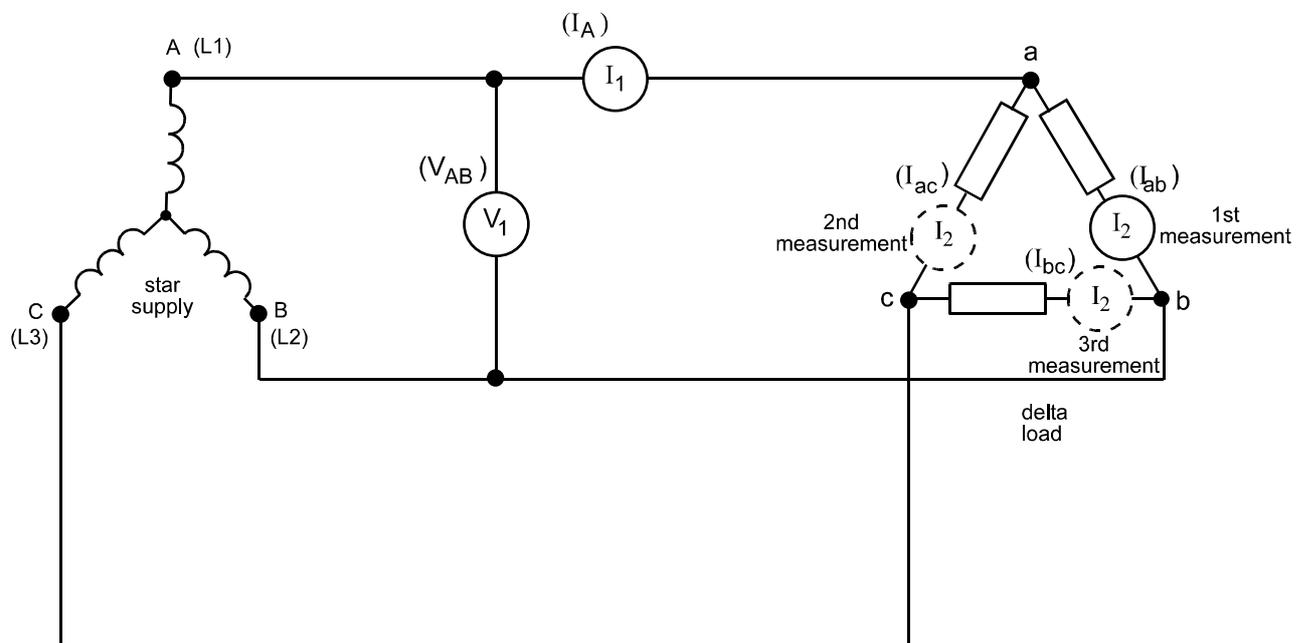
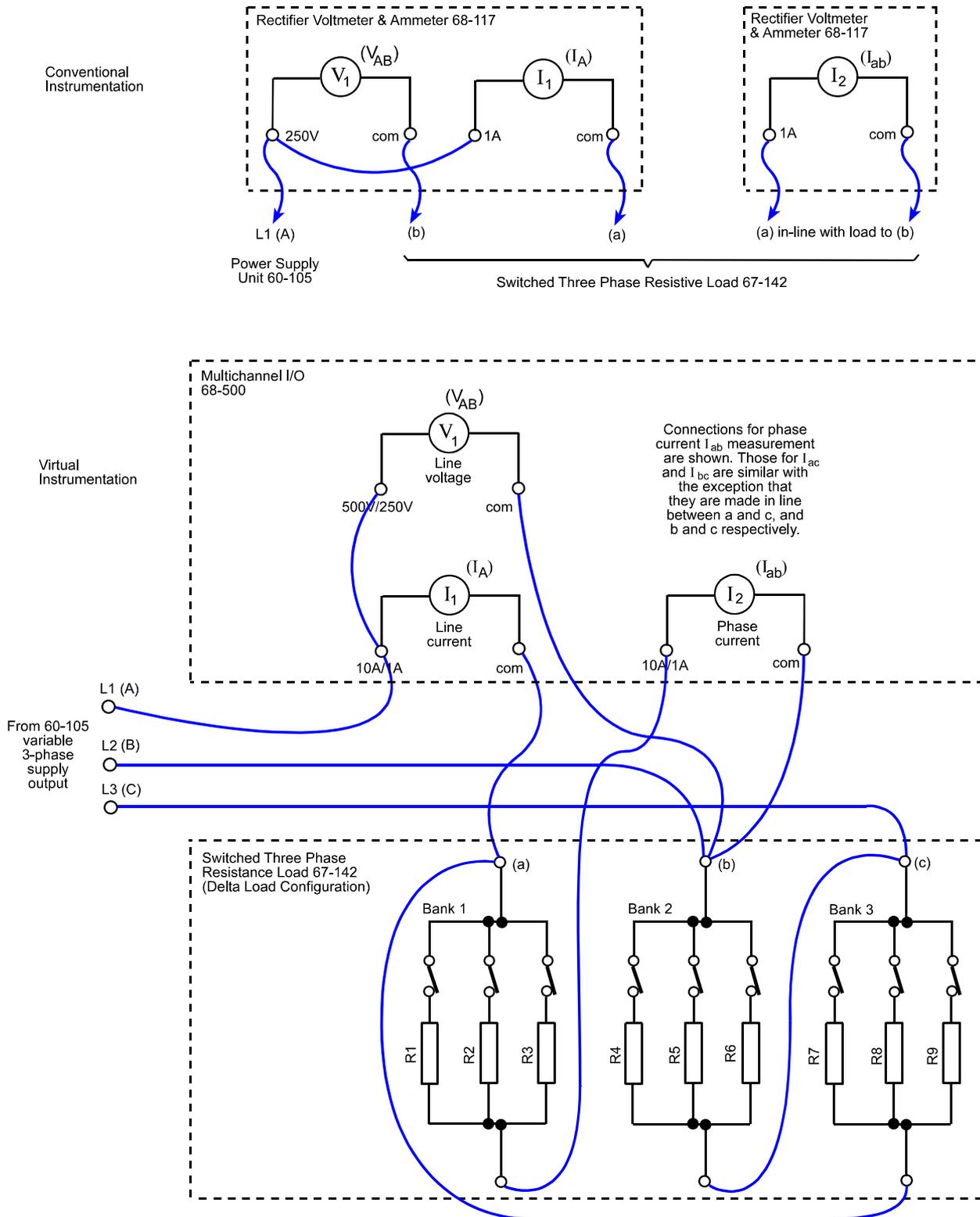


Figure 3-13-7: Theoretical Circuit

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 channel to '250 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' socket is connected. Additionally, set the 1 A/10 A range switches for I1 and I2 to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' sockets are connected or 200 mA to be monitored when the '200 mA' sockets are connected.



**Figure 3-13-8: Practical 13.2 Circuit Diagram**



On the switched three phase resistive load 67-142, set all switches to on so that each bank provides a resistive load of.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter V1 on the virtual or conventional instrumentation indicates.....

Product Version	
230 V	120 V
548 $\Omega$	
200 V ac line-to-line	

**13.7.1 Measurement Procedure**

Measure and record on a copy of the appropriate Practical 13.2, Results Table (230 V or 120 V product versions) parameters associated with the resistive load set above for each leg as follows:

- Line current
- Line voltage
- Phase current  $I_{ab}$

On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the off position.

Disconnect I2 from leg '*ab*' of the load and reconnect it in-line with leg '*ac*' of the load. Link '*ab*' in place of the ammeter.

On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the on position.

In your copy of Practical 13.2, Results Table, record phase current  $I_{ac}$

On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the off position.

Disconnect I2 from leg '*ac*' of the load and reconnect it in-line with leg '*bc*' of the load. Link '*ac*' in place of the ammeter.

On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the on position.

In your copy of Practical 13.2, Results Table, record phase current  $I_{bc}$ .



On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the off position.

On the switched three phase resistive load 67-142, set the switches on all three banks such that S1 and S2 (upper and middle) are on and S3 (lower) is off so that each bank provides a resistive load of.....

On the Universal Power Supply 60-105, set the '3 phase circuit breaker' to the on position.

Repeat the measurement procedure as previously described and record on your copy of Practical 13.2 Results Table parameters associated with the resistive load set above for each leg as follows:

- Line current
- Line voltage
- Phase currents  $I_{ab}$ ,  $I_{ac}$  and  $I_{bc}$ .

Repeat the above in conjunction with resistive loads of ..... set on each of the three individual load banks and record all results in your copy of Practical 13.2 Results Table.

Product Version	
230 V	120 V
640 $\Omega$	
759 $\Omega$ (S1 & S3 on, S2 off) & 950 $\Omega$ (S1 on, S2 & S3 off)	

**13.7.2 Analysis of Results**

Because the system shown in Figure 3-13-7 is balanced, you should have observed that the phase currents are equal. Additionally, the line currents will also be equal. Therefore:

Line current ( $I_L$ ) =  $I_{AB}$  =  $I_{BC}$  =  $I_{CA}$ .

Phase current ( $I_p$ ) =  $I_{ab}$  =  $I_{ac}$  =  $I_{bc}$

Comparing the measured line current with any measured phase current, it is found that the line current is  $\sqrt{3}$  (1.732) times the magnitude of the phase current; that is:

$$\frac{I_L}{I_p} = \sqrt{3}$$

$$\frac{364 \times 10^{-3}}{210 \times 10^{-3}} = 1.732 \text{ or } \sqrt{3}$$



Check that this is true by calculating the phase current from the line current, using the values recorded in your copy of Practical 13.2 Results Table using the formula:

$$I_p = \frac{I_L}{\sqrt{3}}$$

Complete the last column in your table by taking the average of the three phase currents (IP) and calculating the ratio  $I_L/I_P$ .

### **13.8 Practical Aspects**

In a balanced three phase system, a star connected device (transformer, Motor, etc) carries the whole line current, and  $1/\sqrt{3}$  times the line voltage. That is, the magnitude of the line voltage is  $\sqrt{3}$  times the magnitude of the phase voltage.

A star connected supply and load provides a neutral point.

In a balanced three phase system, a delta connected device carries  $1/\sqrt{3}$  times the line current and the whole line voltage. That is, the magnitude of the line current is  $\sqrt{3}$  times the magnitude of the phase current.

A delta connected supply and load has no neutral point.



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**13.9 Practical 13.1 - Results Table (230 V Product Version)**

<b>Phase Resistance (<math>\Omega</math>)</b>	<b>Line Current (mA)</b>	<b>Line Voltage (V)</b>	<b>Phase Voltage <math>V_{an}</math> (V)</b>	<b>Phase Voltage <math>V_{bn}</math> (V)</b>	<b>Phase Voltage <math>V_{cn}</math> (V)</b>
548					
640					
759					
950					

**13.10 Practical 13.2 - Results Table (230 V Product Version)**

<b>Phase Resistance (<math>\Omega</math>)</b>	<b>Line Current (mA)</b>	<b>Line Voltage (V)</b>	<b>Phase Current <math>I_{ab}</math> (mA)</b>	<b>Phase Current <math>I_{ac}</math> (mA)</b>	<b>Phase Current <math>I_{bc}</math> (mA)</b>
548					
640					
759					
950					



**13.11 Practical 13.1 - Results Table (120 V Product Version)**

<b>Phase Resistance (<math>\Omega</math>)</b>	<b>Line Current (mA)</b>	<b>Line Voltage (V)</b>	<b>Phase Voltage <math>V_{an}</math> (V)</b>	<b>Phase Voltage <math>V_{bn}</math> (V)</b>	<b>Phase Voltage <math>V_{cn}</math> (V)</b>

**13.12 Practical 13.2 - Results Table (120 V Product Version)**

<b>Phase Resistance (<math>\Omega</math>)</b>	<b>Line Current (mA)</b>	<b>Line Voltage (V)</b>	<b>Phase Current <math>I_{ab}</math> (mA)</b>	<b>Phase Current <math>I_{ac}</math> (mA)</b>	<b>Phase Current <math>I_{bc}</math> (mA)</b>



## **14 Balanced Three Phase Resistive Load in Star and Delta Connections**

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### **14.1 Assignment Information**

#### **14.1.1 Objectives**

When you have completed this assignment you will:

- have investigated the relationship between currents in different parts of a three phase system.

#### **14.1.2 Knowledge Level**

Before you start this assignment:

- you should have completed or read Assignment 1 Familiarisation.
- you should have completed Assignment 6, 12 and 13.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **14.1.3 Practicals**

1. Power and Power Factor for Star Connected Load
2. Power and Power Factor for Delta Connected Load

**NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



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**Assignment 14**

**Balanced Three Phase Resistive Load  
in Star and Delta Connections**

## **14.2 Theory**

### **14.2.1 Introduction**

Where a 3-phase supply and load are known to be correctly balanced, it is only necessary to measure line voltage, current and power in one phase, and assume that there will be corresponding values for the other phases. However, many practical systems have some imbalance. It is therefore advisable, where possible, to measure the voltage and current in all three phases, and to use either a two or three wattmeter method (as appropriate) to measure power.

The two wattmeter method is widely used in three-wire systems, since it can directly measure the power in both balanced and unbalanced systems, from which, with the voltage and current readings, the power factor can be calculated.

Power factor can also be measured directly by a dedicated power factor meter.



### 14.3 Content

The practicals in this assignment familiarise the student with the characteristics of balanced loads in a three phase system.

### 14.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	<b>or</b>	
Conventional Instrumentation	Electronic Single & Three Phase Measurements (Option CI1)	68-100
	Electrodynamic Wattmeter (Option CI2)	68-201 x 2

#### NOTES:

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 14.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 14.5.1 Practical 14.1 - Power and Power Factor for Star Connected Load

The star connected supply is applied to a star connected load. Measurements are taken of voltage, current power and power factor.

**NOTE:**

The supply neutral is not connected to the load neutral.  
This connection represents a three wire star system

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.  
Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-14-2, which relates to the theoretical circuit shown in Figure 3-14-1.

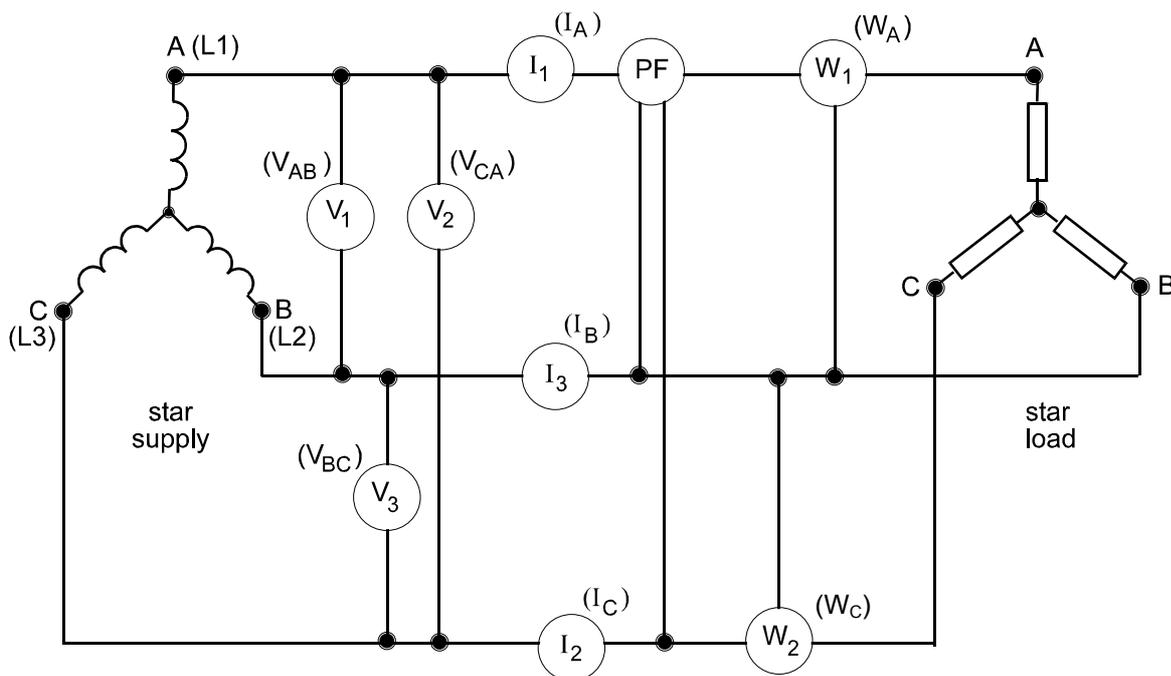
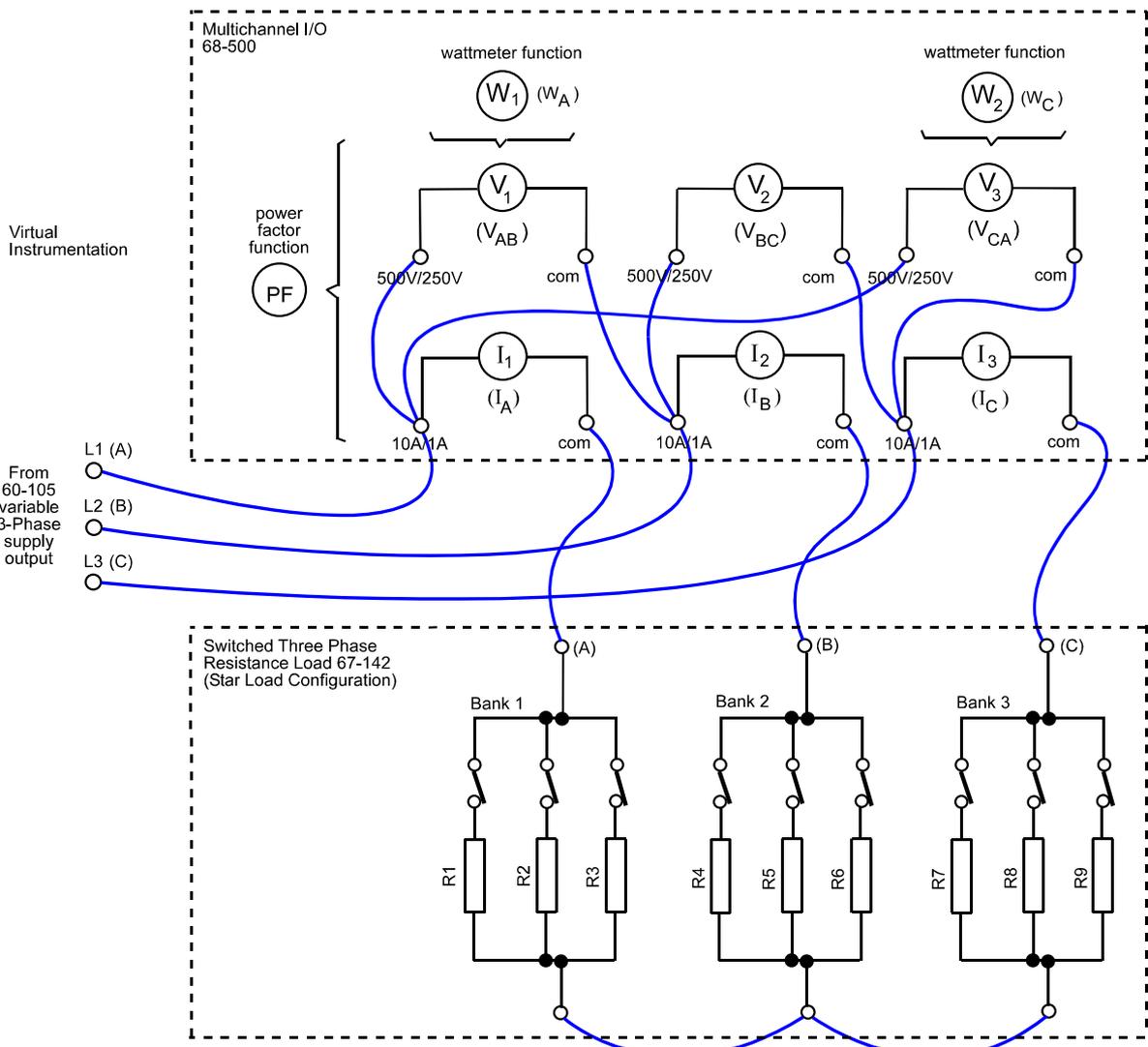
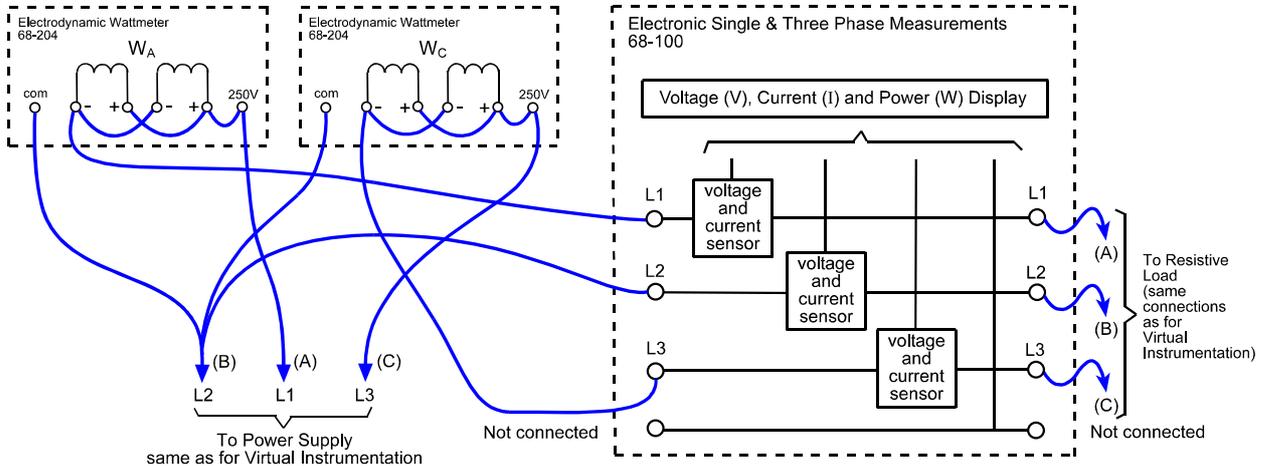


Figure 3-14-1: Theoretical Circuit

If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1, V2 and V3 channels to '500 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 500 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switches for I1, I2 and I3 channels to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' sockets are connected or 200 mA to be monitored when the 200 mA sockets are connected.



Conventional Instrumentation



**Figure 3-14-2: Practical 14.1 Circuit Diagram**



If conventional instrumentation is being used, the measurement of power for this practical and practical 14.2 is to be made using the two separate wattmeters and the readings entered into the result table. The 68-100 single and three phase measurements panel is used for taking measurements of voltage, current and power factor using the menu pages available.

Product Version	
230 V	120 V
546 $\Omega$	
400 V ac line-to- line	

On the switched three phase resistive load 67-142, set all switches to on, so that each bank provides a resistive load of.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter V1 on the virtual or conventional instrumentation indicates.....

Measure and record on a copy of the appropriate Practical 14.1, Results Table (230 V or 120 V product version), all parameter listed using values given on virtual or conventional instrumentation.

On the Universal Power Supply 60-105, set the '*variable output voltage*' control to 0% then set the '*3 phase circuit breaker*' to the off position.



**14.5.2 Analysis of Results**

Because the system shown in Figure 3-14-1 is balanced, the phase-to-neutral voltages are equal and likewise the line voltages. We may therefore write:

Line voltage  $= V_L = V_{AB} = V_{BC} = V_{CA}$

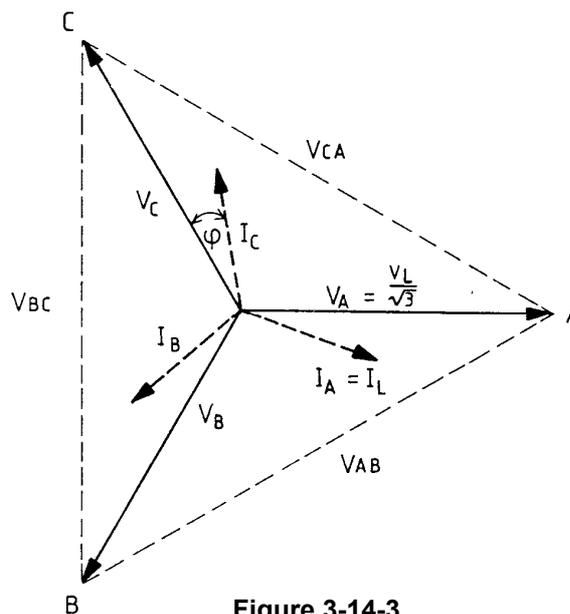
Phase-to-neutral voltage  $= V_P = V_A = V_B = V_C = V_L/\sqrt{3}$

Line current (in each line)  $= I_L$

The operating conditions for the star-connected system shown in Figure 3-14-1 are represented in the phasor diagram of Figure 3-14-3, in which show how  $\phi$  represents the phase difference between current and the voltage.

The conditions are summarised below:

For each phase	Phase voltage	Phase current	power
Star connected transformer	$V_L/\sqrt{3}$	$I_L$	$(V_L/\sqrt{3})I_L \cos \phi$
Star Load	$V_L/\sqrt{3}$	$I_L$	$(V_L/\sqrt{3})I_L \cos \phi$
Total power = $3(V_L/\sqrt{3})I_L \cos \phi$ $= \sqrt{3}V_L I_L \cos \phi$			



**Figure 3-14-3**



### **14.5.3 Exercise 14.1**

From your measured results, calculate average values of the line voltage and current. Take  $\cos \phi$  to be the reading from the power factor display (virtual or conventional instrumentation).

#### 14.5.3.1 Two Wattmeter Method

Add together the two wattmeter readings  $W_A$  and  $W_C$ . If either of the readings is negative, its magnitude should be subtracted.

Compare the resulting value of power with that previously calculated. They should agree quite closely.

**NOTE:**

The individual wattmeter readings are probably very different, although the system is balanced. This is because the wattmeter connections are not all symmetrical

A full explanation of the two wattmeter method of measuring power is given in Appendix B.2



### 14.6 Practical 14.2 – Power and Power Factor for Delta Connected Load

The star connected supply is applied to a delta connected load. Measurements are taken of voltage, current power and power factor.

**NOTE:**  
The supply neutral is not connected to the load neutral.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-14-5, which equates to the theoretical circuit shown in Figure 3-14-4.

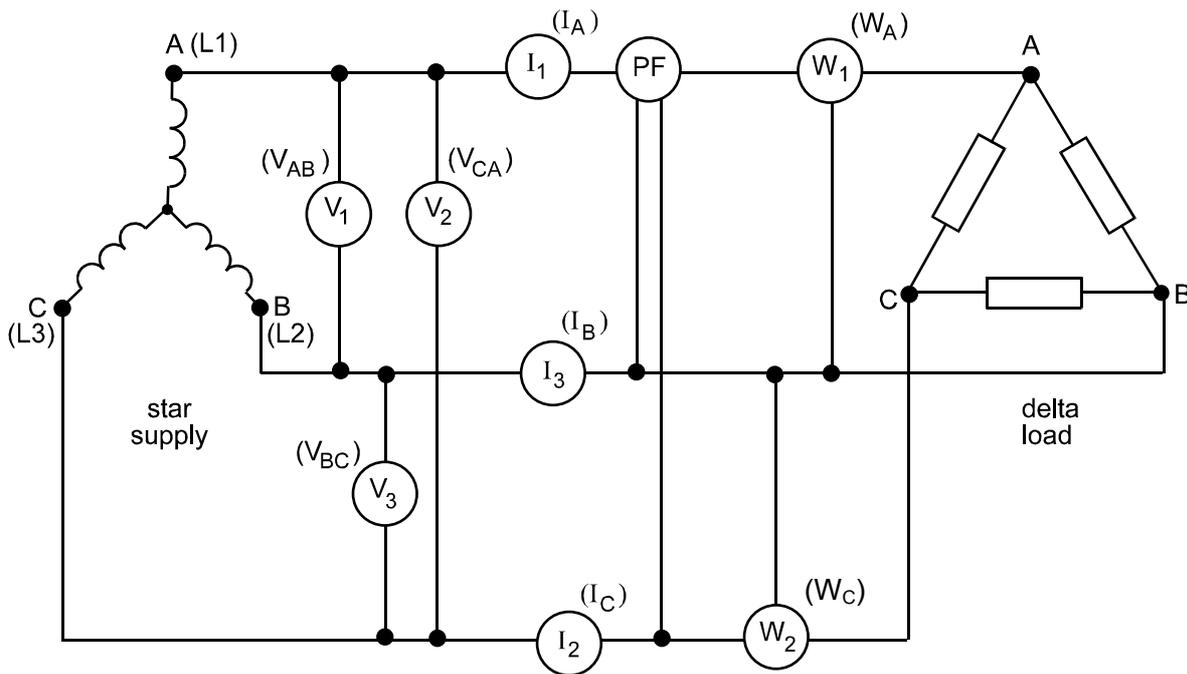
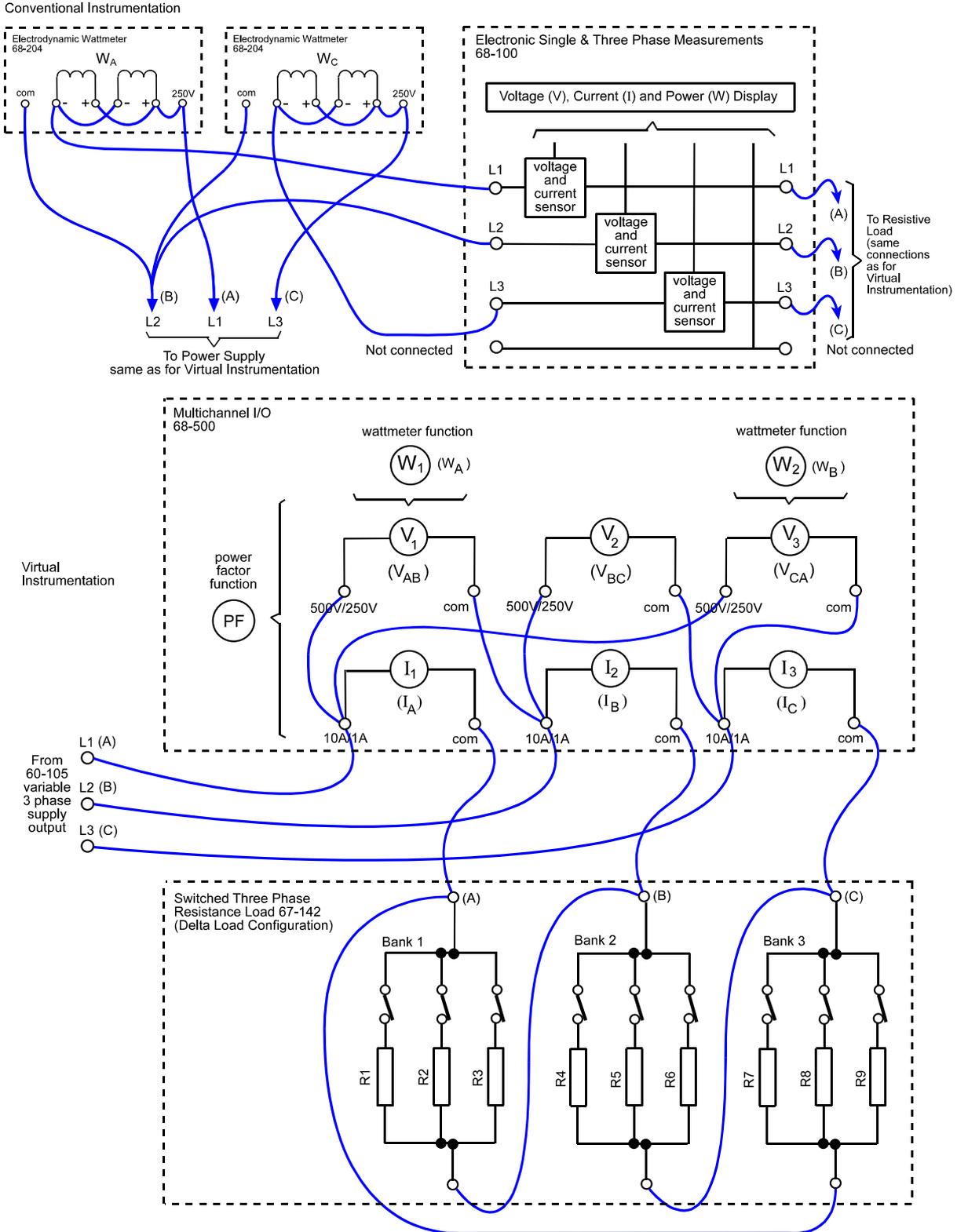


Figure 3-14-4: Theoretical Circuit

If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1, V2 and V3 channels to '500 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 500 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switches for I1, I2 and I3 channels to '1 A'. This allows currents of up to 1 A to be monitored when the '10 A/1 A' sockets are connected or 200 mA to be monitored when the 200 mA sockets are connected.



**Figure 3-14-5: Practical 14.2 Circuit Diagram**



On the switched three phase resistive load 67-142, set all switches to on so that each bank provides a resistive load of.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% then set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter V1 on the virtual or conventional instrumentation indicates.....

Product Version	
230 V	120 V
546 Ω	
230 V ac line-to-line	

Measure and record on a copy of the appropriate Practical 14.2, Results Table (230 V or 120 V product version), all parameters listed using values given on virtual or conventional instrumentation.

On the Universal Power Supply 60-105, set the '*variable output voltage*' control to 0% then set the '*3 phase circuit breaker*' to the off position.

**14.6.1 Analysis of Results**

Because the system shown in Figure 3-14-4 is balanced, the phase-to-neutral voltages are equal and likewise the line voltages. We may therefore write:

Line voltage                                    =  $V_L = V_{AB} = V_{BC} = V_{CA}$   
Phase-to-neutral voltage                =  $V_P = V_A = V_B = V_C = V_L/\sqrt{3}$   
Line current (in each line)               =  $I_L$

The voltages in the delta connection are represented by the triangle around the outside of Figure 3-14-6, so that the direction of the phasors for voltage is clearly shown. These phasors are also drawn in full lines meeting at the centre of Figure 3-14-6 (although a phasor has magnitude and direction like a vector, no meaning is attached to its position, unlike a vector).

The relationship between  $I_L$  and  $I_P$ , defined to be the current in each phase of a balanced delta load (eg,  $I_{CA}$ ), is shown in Figure 3-14-7. Notice that the line current is found by adding one  $I_P$  phasor to the negative of the other. This is because, if the phasors were drawn meeting at the terminal of, say, the A line, one would be pointing towards A and the other away from A.

The resultant line current is (in this balanced case)  $\sqrt{3}$  times the current in each phase.

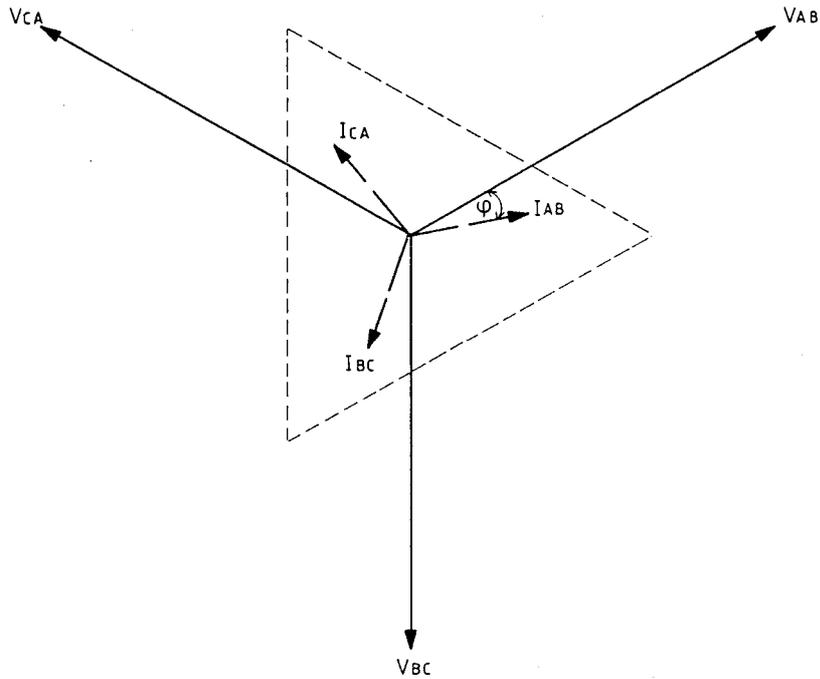


Figure 3-14-6

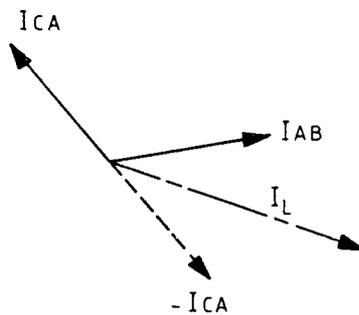


Figure 3-14-7



The conditions are summarised below:

For each phase	Phase voltage	Phase current	power
Delta load	$V_L$	$I_L/\sqrt{3}$	$V_L (I_L/\sqrt{3}) \cos \phi$
Total power = $3V_L (I_L/\sqrt{3}) \cos \phi$ $= \sqrt{3}V_L I_L \cos \phi$			

**14.6.2 Exercise 14.2**

Calculate the total power from the line voltage and current, as before. Calculate it also from the two-wattmeter readings and compare results.

A full explanation of the two-wattmeter method of measuring power is given in Appendix B.2.

Note the difference between the currents consumed by the same load elements when connected in delta and in star connection. This has a practical application in the star/delta starter for the three phase induction motors. The windings are connected in star at switch-on, to reduce the large initial starting current. When the motor is up to speed, the connection is changed to a delta, to enable the motor to develop its full power.

**14.7 Practical Aspects**

In a balanced three phase system, each phase of a star-connected (transformer or load) carries the whole line current, and  $1/\sqrt{3}$  times the line voltage.

In a balanced three phase system, each phase of a delta-connected device carries  $1/\sqrt{3}$  times the line current, and the whole line voltage.

In each case, the power is  $\sqrt{3}V_L I_L \cos \phi$ , where  $\cos \phi$  is the power factor.

In a three-wire system, the total power can be measured by adding the readings of two wattmeters (this applies to any three-wire system, not just a three phase one).



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**14.8 Practical 14.1 - Results Table (230 & 120 V Product Versions)**

<b>Supply</b>	<b>Load</b>	<b>V<sub>AB</sub></b> (L1)	<b>V<sub>BC</sub></b> (L2)	<b>V<sub>CA</sub></b> (L3)	<b>I<sub>A</sub></b> (L1)	<b>I<sub>B</sub></b> (L3)	<b>I<sub>C</sub></b> (L3)	<b>PF</b>	<b>W<sub>A</sub></b> (L1)	<b>W<sub>C</sub></b> (L3)

**14.9 Practical 14.2 - Results Table (230 & 120 V Product Versions)**

<b>Supply</b>	<b>Load</b>	<b>V<sub>AB</sub></b> (L1)	<b>V<sub>BC</sub></b> (L2)	<b>V<sub>CA</sub></b> (L3)	<b>I<sub>A</sub></b> (L1)	<b>I<sub>B</sub></b> (L2)	<b>I<sub>C</sub></b> (L3)	<b>PF</b>	<b>W<sub>A</sub></b> (L1)	<b>W<sub>C</sub></b> (L3)



Notes



## **15 Three Phase Sequence Determination**

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### **15.1 Assignment Information**

#### **15.1.1 Objectives**

When you have completed this assignment you will:

- know how to determine the sequence of phases in a three phase system

#### **15.1.2 Knowledge Level**

Before you start this assignment

- you should:have completed or read Assignment 1 Familiarisation.
- you should:have completed Assignments 7 and 13.
- if you have a Virtual Instrumentation System, you should be familiar with its use. (Refer to the 60-070-VIP manual for details on the equipment interconnection and software operation.)

#### **15.1.3 Practicals**

1. Three Phase Sequence Determination

**NOTE:**

Practicals cover both 230 V and 120 V versions of the trainer.

Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

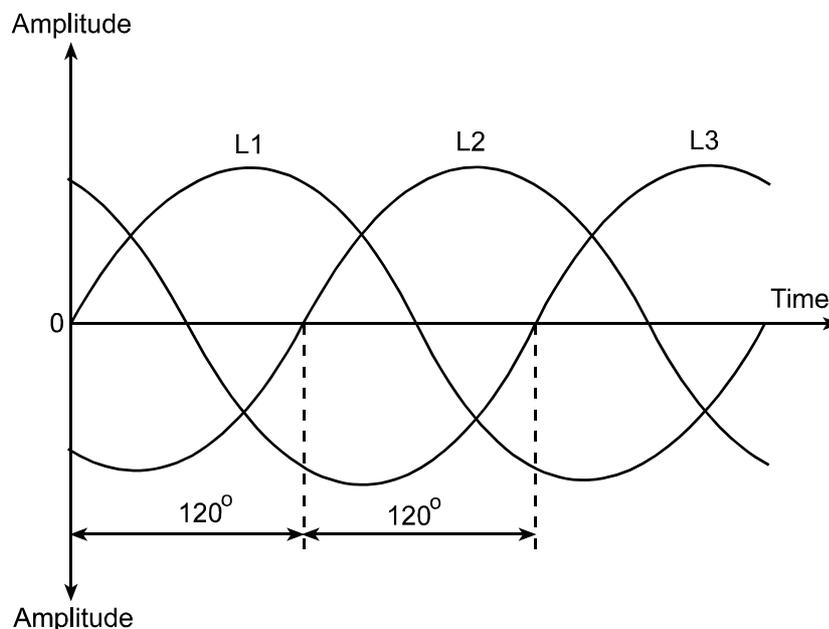
Results tables are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.



## 15.2 Theory

### 15.2.1 Introduction

Three phase alternating current supplies consist of three separate voltage waveforms of the same amplitude and frequency, but separated in phase by  $120^\circ$  ( $2/3 \pi$ ). Each of these voltages is referred to as the phase of the supply and is numbered L (line) 1, L2 and L3. In some systems, colours are used to denote phases. In this instance they become red, yellow and blue. Figure 3-15-1 shows the relationship between phases.



**Figure 3-15-1**

When connecting a three phase supply to certain devices such as motors, it is important to connect the lines in the correct order. Incorrect connection can cause a motor to drive in reverse. If the lines cannot be readily identified, a method to determine the three phase sequence is used to establish appropriate connections.



### 15.3 Content

The practical in this assignment familiarises the student with the procedure for three phase sequence determination.

### 15.4 Equipment Required

- Universal Power Supply 60-105.
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (Option 60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB

**or**

Conventional Instrumentation	Rectifier Voltmeter & Ammeter (Option CI2)	68-117
------------------------------	--	--------

Ancillary Equipment	Differential Voltage/Current Probe (2 off) (Required for conventional instruments only)	68-150
	General purpose oscilloscope two channel with at least 20 MHz bandwidth	

#### **NOTES:**

Refer to the Virtual Instrumentation System manual 60-070-VIP for the setting up of the virtual instrumentation voltmeters, ammeters etc, and the use of Set-Up files.

Do refer to the Help information in the 68-500-USB software.

### 15.5 Preliminary Set-up

Switch off all power by setting the '3 phase circuit breaker with no volt release' on the Universal Power Supply 60-105 to the 'off' position.

For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel<sup>®</sup> Spreadsheet you can use the facility in the 68-912-USB software to save and store sets of results, import them directly into Excel, automatically calculate results and draw graphs. (See the manual - *Virtual Instrumentation Pack 60-070-VIP, Appendix A*).



### 15.6 Practical 15.1 - Three Phase Sequence Determination

The star connected supply is applied to a star connected load. The phases of L1 and L2 are monitored together and then L1 and L3 to establish correct phase relationships and identity of power lines.

**NOTE:**

The supply neutral is not connected to the load neutral.

On the Universal Power Supply 60-105, ensure the '3 phase circuit breaker' is switched off.

Make the appropriate connections either for virtual or conventional instrumentation shown in Figure 3-15-3, which relates to the theoretical circuit shown in Figure 3-15-2.

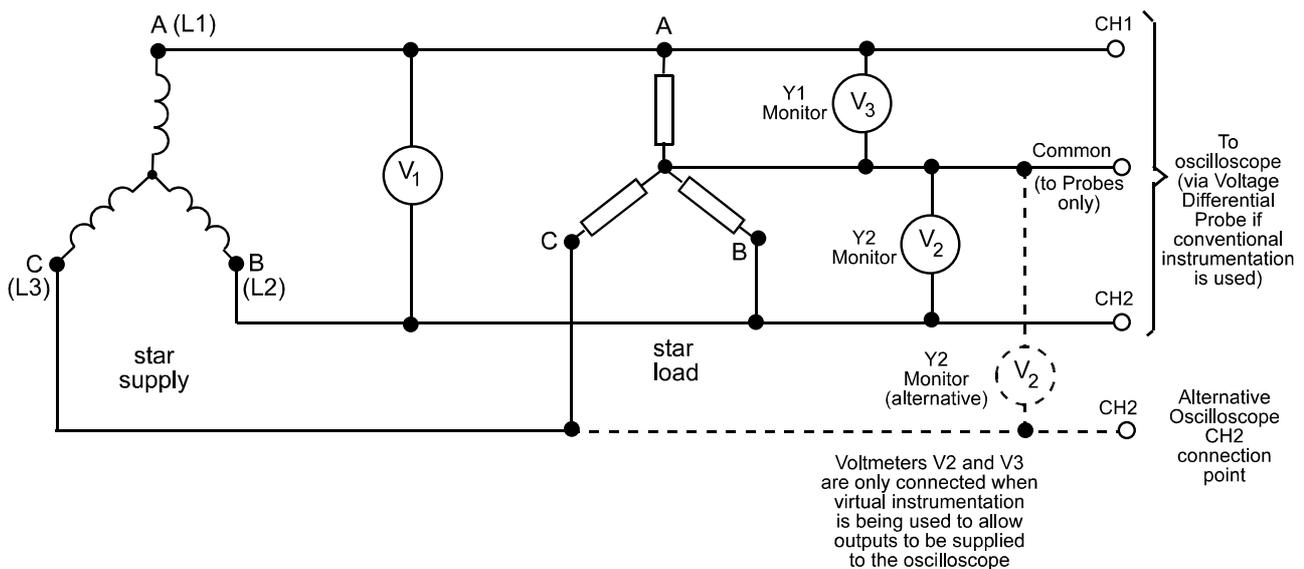
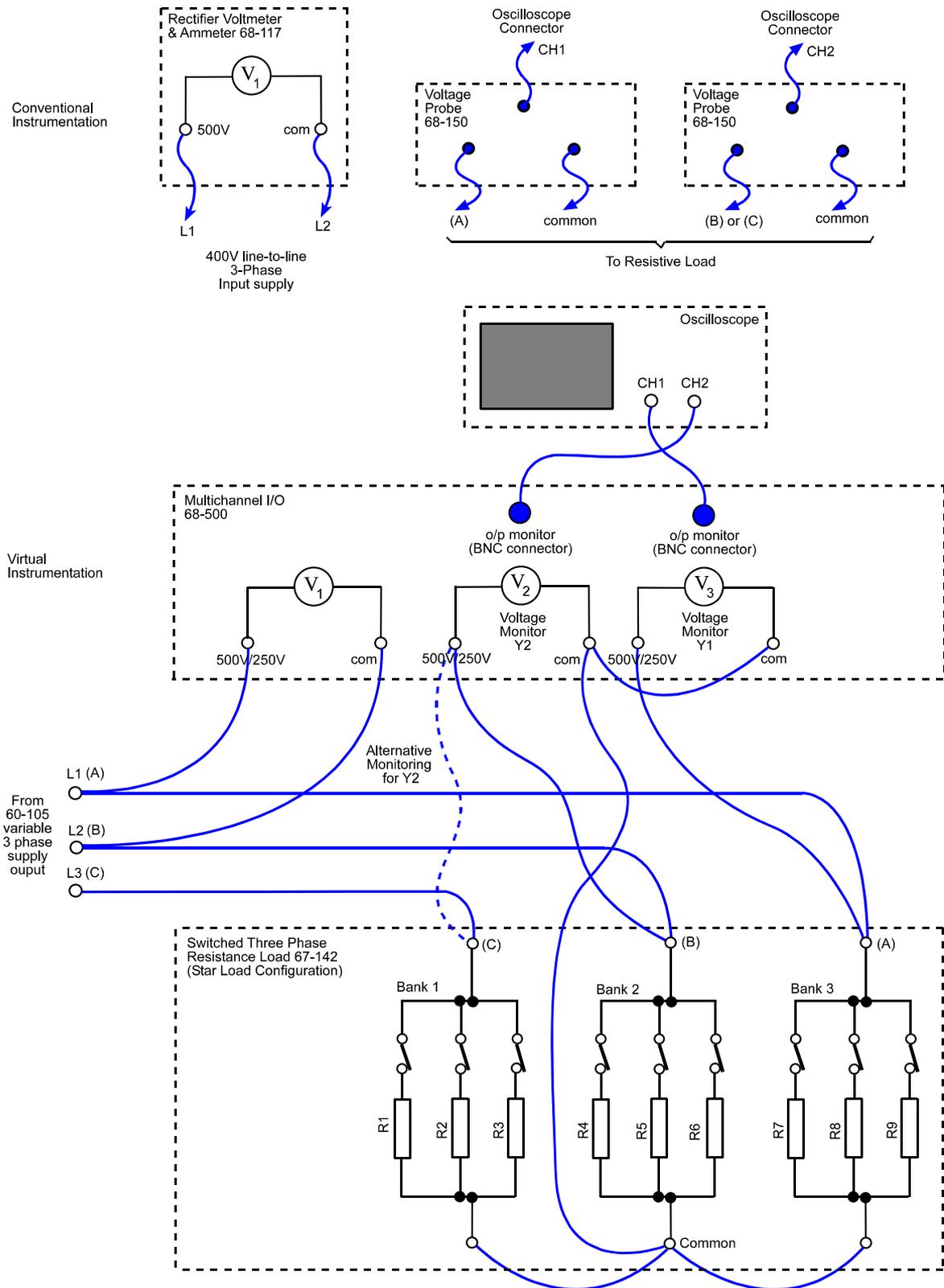


Figure 3-15-2: Theoretical Circuit

If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1, V2 and V3 channels to '500 V' on the Multichannel I/O Unit 68-500. This allows voltages of up to 500 V to be monitored when the '500 V/250 V' sockets are connected.



**Figure 3-15-3: Practical 15.1 Circuit Diagram**



Product Version	
230 V	120 V
546 Ω	
400 V ac line-to-line	

On the switched three phase resistive load 67-142, set all switches to on, so that each bank provides a resistive load of.....

On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0%.

If virtual instrumentation is being used, ensure power line L1 is connected to V3 channel and L2 is connected to V2 channel on the Multichannel I/O Unit 68-500. This allows outputs to be taken from the channel BNC connectors to oscilloscope terminals CH1 and CH2 respectively.

If conventional instrumentation is being used, ensure power line L1 is connected to oscilloscope terminal CH1 (Y1) via the differential voltage probe 68-150 and that the probe attenuation ratio is set to 1/20. Similarly, ensure power line L2 is connected to oscilloscope terminal CH2 (Y2) via the differential voltage probe 68-150 and that the probe attenuation ratio is set to 1/20. Connect the centre of the star load network (common) to the common input terminals of the differential voltage probes. See Figure 3-15-2.

Set the oscilloscope as follows:

- CH1 (Y1) channel – 5V/cm
- CH2 (Y2) channel – 5V/cm
- Timebase – 40 ms/cm

On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the on position.

Rotate the '*variable output voltage*' control until the voltmeter V1 on the virtual or conventional instrumentation indicates.....

On the oscilloscope, zero both traces and then observe the two waveforms.

Draw the waveforms you see on a copy of the oscilloscope screen graticule representation given in Practical 15.1 Results Tables at the end of this assignment. L1 should lead L2 by 120° as shown in Figure 3-15-1.

On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the off position.

Disconnect L2 from oscilloscope terminal CH2 and connect L3 to CH2.



On the Universal Power Supply 60-105, set the '*3 phase circuit breaker*' to the on position.

On the oscilloscope, zero both traces. That is with no input to either channel set the traces central on the X axis of the graticule and then observe the two waveforms.

Draw the L3 waveform on the copy of the oscilloscope screen graticule representation given in Practical 15.1 Results Table. L1 should lead L3 by  $240^\circ$  as shown in Figure 3-15-1.

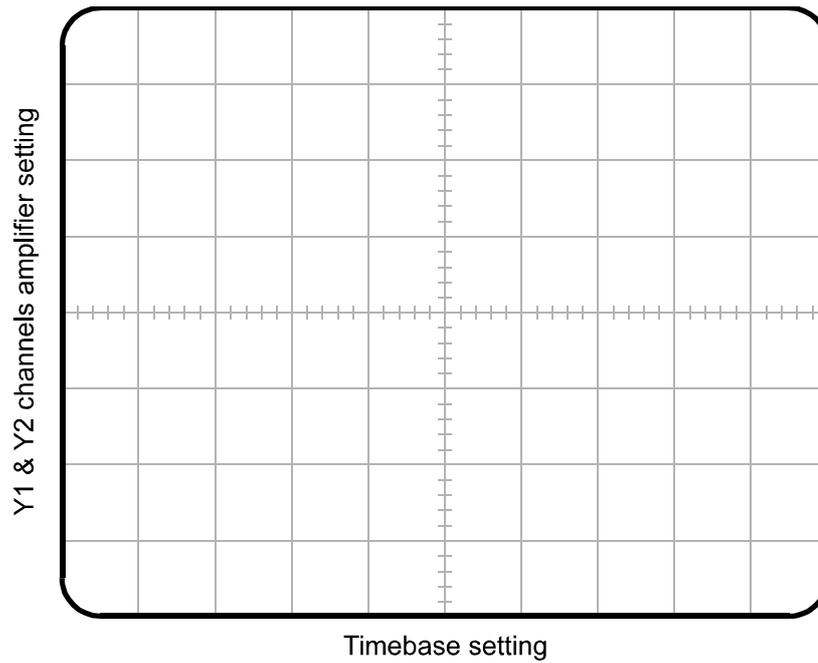
On the Universal Power Supply 60-105, ensure the '*variable output voltage*' control is set to 0% and then set the '*3 phase circuit breaker*' to the off position.



Notes



**15.7 Practical 15.1 - Oscilloscope Screen Graticule Representation  
(230 & 120 V Product Version)**





Notes



## **A Units**

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### **A.1 SI Units**

The units used throughout this Handbook are those of the Systeme International d'Unites (SI).

There are seven basic units in the International System (SI), these are:

**Table A-1-1. Basic SI Units**

<b>Quantity</b>	<b>Name of unit</b>	<b>Symbol</b>
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

From these seven basic units all other units may be derived; for example:

The derived unit for force is the newton (N), which is that force which, when applied to a body of one kilogram, gives it an acceleration of one metre per second squared.

Force (newton, N) = mass (kilogrammes, kg) x accn (metres per second squared,  $m/s^2$ ).

Tables of some of these derived SI units are to be found in this appendix and the definitions of those SI units with special names are to be found in section A.2.

Section A.3 gives the relationships between some UK units and SI units.

Some of the units are inconveniently large or small in practical circumstances. Hence standard multiples or sub-multiples of the basic unit are commonly used. These are shown in Table 2 reproduced overleaf.



The names of the multiples and sub-multiples of the units are formed by means of the following prefixes:

**Table A-1-2 Multiples and Submultiples**

<b>Factor by which the unit is multiplied</b>	<b>Prefix</b>	<b>Symbol</b>
1,000,000,000,000 = $10^{12}$	tera	T
1,000,000,000 = $10^9$	giga	G
1,000,000 = $10^6$	mega	M
1000 = $10^3$	kilo	k
100 = $10^2$	hecto	h
10 = $10^1$	deca	da
0.1 = $10^{-1}$	deci	d
0.01 = $10^{-2}$	centi	c
0.001 = $10^{-3}$	milli	m
0.000 0001 = $10^{-6}$	micro	$\mu$
0.000 000 000 = $10^{-9}$	nano	n
0.000 000 000 000 = $10^{-12}$	pico	p
0.000 000.000 000 001 = $10^{-15}$	femto	f
0.000 000 000 000 000 001 = $10^{-18}$	atto	a

In electronics, the ampere is frequently too large a unit for normal usage. Current is thus measured often in milliamperes. There are one thousand milliamperes in one ampere.

ie; 1000 mA = 1 A     1 mA = 0.001 A =  $10^{-3}$  A

The unit of the ohm is often too small a unit of resistance for resistors used in electronic circuits. Resistance may then be in kilohms or megohms.

ie; 1000  $\Omega$  = 1 k $\Omega$      1,000,000  $\Omega$  = 1 M $\Omega$  =  $10^6$   $\Omega$



**Table A-1-3 Some derived SI Units having special names**

<b>Physical quantity</b>	<b>SI unit</b>	<b>Unit symbol</b>
force	newton	$N = \text{kg m/S}^2$
work, energy, quantity of heat	joule	$J = N \text{ m}$
power	watt	$W = \text{J/s}$
electric charge	coulomb	$C = \text{As}$
electrical potential	volt	$V = \text{W/A}$
electric capacitance	farad	$F = \text{As/V}$
electric resistance	ohm	$\Omega = \text{V/A}$
frequency	hertz	$\text{Hz} = \text{s}^{-1}$
magnetic flux	weber	$\text{Wb} = \text{Vs}$
magnetic flux density	tesla	$T = \text{Wb/m}^2$
inductance	henry	$H = \text{V s/A}$

**Table A-1-4 Some derived SI units with complex names**

<b>Physical quantity</b>	<b>SI unit</b>	<b>Unit symbol</b>
area	square metre	$\text{M}^2$
volume	cubic metre	$\text{M}^3$
density (mass density)	kilogram per cubic metre	$\text{kg/m}^3$
velocity	metre per second	$\text{m/s}$
angular velocity	radian per second	$\text{rad/s}$
acceleration	metre per second squared	$\text{m/s}^2$
angular acceleration	radian per second squared	$\text{rad/s}^2$
pressure	newton per square metre	$\text{N/m}^2$
surface tension	newton per metre	$\text{N/m}$
thermal conductivity	watt per metre kelvin	$\text{W/(mK)}$
electric field strength	volt per metre	$\text{V/m}$
magnetic field strength	ampere per metre	$\text{A/m}$



## **A.2 Definition of Derived SI Units having Special Names**

<b>FORCE</b>	The unit of force called the newton is that force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one metre per second squared.
<b>ENERGY</b>	The unit of energy called the joule is the work done when the point of application of a force of one newton is displaced through a distance of one metre in the direction of the force.
<b>POWER</b>	The unit of power called the watt is equal to one joule per second.
<b>ELECTRIC CHARGE</b>	The unit of electric charge called the coulomb is the quantity of electricity transported in one second by a current of one ampere.
<b>ELECTRIC POTENTIAL</b>	The unit of electric potential called the volt is the difference of potential between two points of a conducting wire carrying a constant current of one ampere, when the power dissipated between these points is equal to one watt.
<b>ELECTRIC CAPACITANCE</b>	The unit of electric capacitance called the farad is the capacitance of a capacitor between the plates of which there appears a difference of potential of one volt when it is charged by a quantity of electricity equal to one coulomb.
<b>ELECTRIC RESISTANCE</b>	The unit of electric resistance called the ohm is such that a constant difference of potential of one volt, applied across a conductor of one ohm resistance, produces in this conductor a current of one ampere, this conductor not being the source of any electro-motive force.
<b>FREQUENCY</b>	The unit of frequency called the hertz is the frequency of a periodic phenomenon of which the periodic time is one second.
<b>MAGNETIC FLUX</b>	The unit of magnetic flux called the weber is the flux which, linking a circuit of one turn produces in it an electromotive force of one volt as it is reduced to zero at a uniform rate in one second.
<b>MAGNETIC FLUX DENSITY</b>	The unit of magnetic flux density called the tesla is the density of one weber of magnetic flux per square metre.



**ELECTRIC  
INDUCTANCE**

The unit of electric inductance called the henry is the inductance of a closed circuit in which an electromotive force of one volt is produced when the electric current in the circuit varies uniformly at the rate of one ampere per second.

**TEMPERATURE**

The units of Kelvin and Celsius temperature *interval* are identical, thus a Kelvin is the same as a degree on the Celsius scale. A temperature expressed in 'degrees Celsius' is equal to the temperature expressed in 'Kelvin' plus 273.15 degrees. Thus the zero point of the Kelvin scale is equivalent to  $-273.15\text{ }^{\circ}\text{C}$  on the Celsius scale (known as absolute zero).

This is true for the thermodynamic scale and for the international practical scale of 1948. There are, however, slight differences between thermodynamic scale and practical scale.



**A.3 Values of some UK Units in Terms of SI Units**

<b>Length</b>	1 yd	0.9144 m
	1ft	0.3048 m
	1 in	0.0254 m
	1 mile	1609.344 m
<b>Area</b>	1 in <sup>2</sup>	6.4516 x 10 <sup>-4</sup> m <sup>2</sup>
	1 ft <sup>2</sup>	0.092 903 0 m <sup>2</sup>
	1 yd <sup>2</sup>	0.836 127 m <sup>2</sup>
	1 mile <sup>2</sup>	22.589 99 x 10 <sup>6</sup> m <sup>2</sup>
<b>Volume</b>	1 in <sup>3</sup>	1.638 71 x 10 <sup>-5</sup> m <sup>3</sup>
	1 ft <sup>3</sup>	0.028 316 8 m <sup>3</sup>
	1 UK gal	0.4 546 092 m <sup>3</sup>
<b>Velocity</b>	1 ft/s	0.3048 m/s
	1 mile/h	0.447 04 m/s
<b>Mass</b>	1 lb	0.453 592 37 kg
<b>Density</b>	1 lb/in <sup>3</sup>	2.767 99 x 10 <sup>4</sup> kg/m <sup>3</sup>
	1 lb/ft <sup>3</sup>	16.0185 kg/m <sup>3</sup>
	1 lb/UK gal	99.7764 kg/m <sup>3</sup>
<b>Force</b>	1 lbf	4.448 22 N
<b>Pressure</b>	1 lbf/in <sup>2</sup>	6894.76 N/m <sup>2</sup>
<b>Energy</b>	1 ft lbf	1.355 82 J
	1 cal	4.1868 J
	1Btu	1055.06 J
<b>Power</b>	1 hp	745.700 W
<b>Temperature</b>	1 Rankine unit	$\frac{5}{9}$ of Kelvin unit
	(= 1 Fahrenheit unit)	(= $\frac{5}{9}$ of Celsius unit)



## B General Information

### B.1 Phasors

The alternating currents and voltages used in electrical power systems are sinusoidal quantities whose amplitude varies regularly with time as shown in Figure B-1-1.

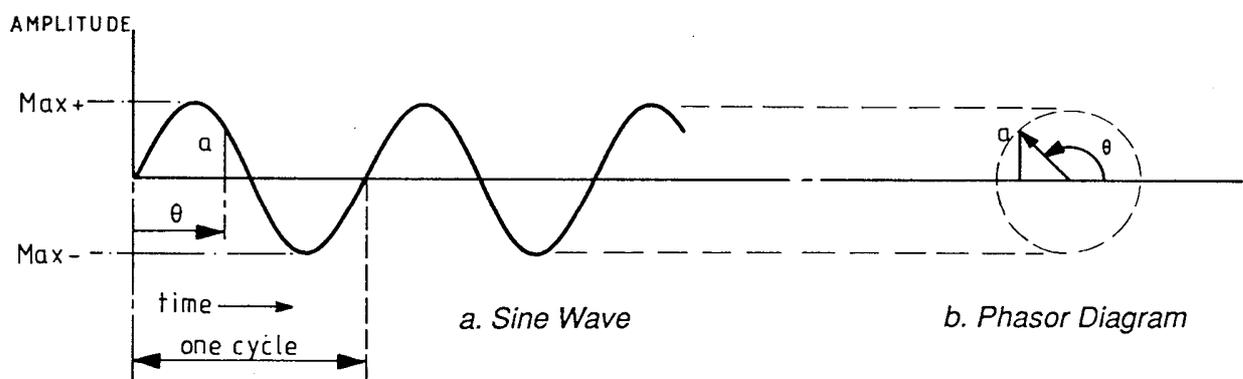


Figure B-1-1

Any sinusoidal quantity can also be represented graphically by a line or radius rotating at uniform velocity, moving through one revolution in the time taken for the sine wave to complete one cycle. This rotating line is known as a phasor since it shows both the amplitude and angular position or phase of the sinusoidal quantity at a given instant as in Figure B-1-2

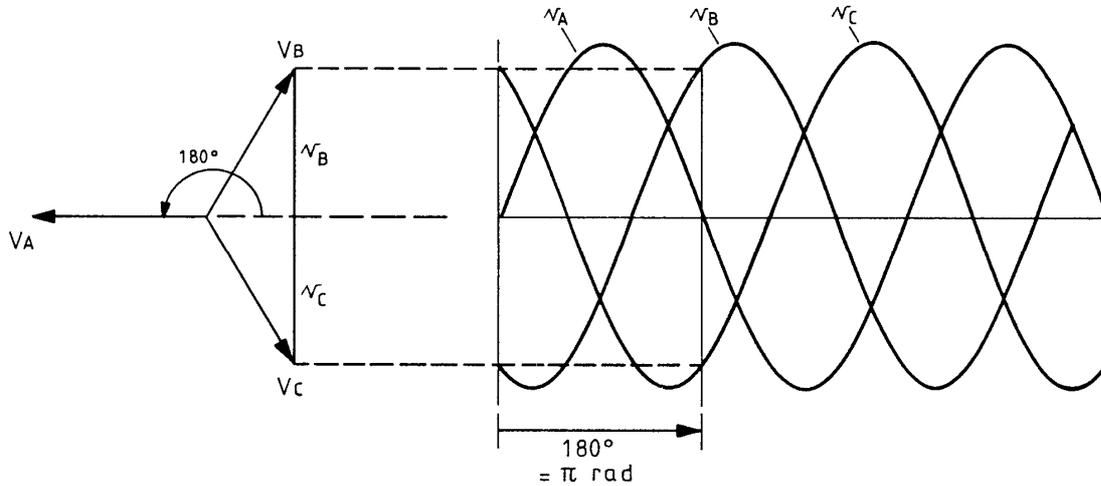
One cycle of the sine wave is equal to a phasor rotation of  $360^\circ$  or  $2\pi$  radian. If the sine wave has a frequency of  $f$  Hz, the phasor will rotate at an angular velocity of  $2\pi f$  radians per second. The term  $2\pi f$  is denoted  $\omega$  and the total swept angle after time  $t$  is  $\omega t$  radian.

The amplitude of the sine wave at any time  $t$  can be found from the equation:

$$a = A \sin \theta \quad \text{where} \quad \begin{aligned} a &= \text{amplitude} \\ A &= \text{maximum value} \\ \theta &= \omega t \end{aligned}$$

The phasor is conventionally taken to rotate counter-clockwise with increasing time.

More than one phasor can be represented on the same diagram and this provides a useful way of showing their relationship to one another. The phasor diagram and sinewave graph of Figure B-1-2 shows the amplitudes of the voltages in a three phase system of constant frequency at one instant.



**Figure B-1-2**

In any three phase system the three supply voltage phasors rotate at uniform angular velocity and maintain the same angular relationship to one another.  $V_B$  lags  $V_A$  by  $120^\circ$  and  $V_C$  lags  $V_A$  by  $240^\circ$ . Consequently, the amplitude in each case is:

$$V_A = V_A \sin \theta$$

$$V_B = V_B \sin (\theta - 120^\circ)$$

$$V_C = V_C \sin (\theta - 240^\circ)$$

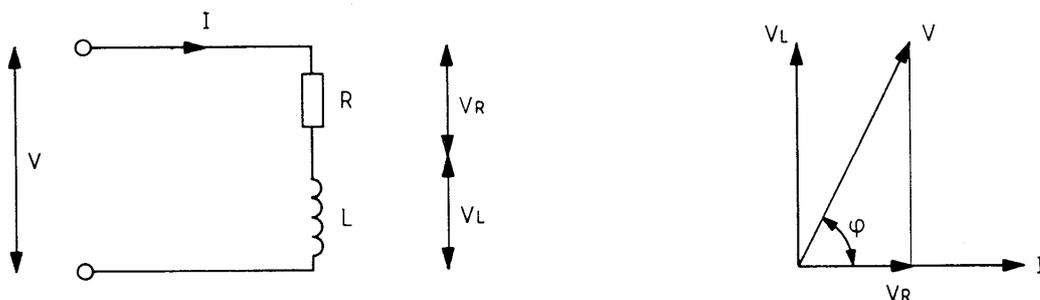
At the instant shown in Figure B-1-2, let us assume that the maximum values  $V_A$ ,  $V_B$  and  $V_C$  are 200 volts. Where  $V_A$  has swept through one half cycle or  $180^\circ$  from zero:

$$V_A = 200 \sin (180^\circ) = 0 \text{ volts}$$

$$V_B = 200 \sin (180^\circ - 120^\circ) = 173 \text{ volts}$$

$$V_C = 200 \sin (180^\circ - 240^\circ) = -173 \text{ volts}$$

Voltages and currents can also be shown on the same phasor diagram. The circuit in Figure B-1-3 shows a single phase supply connected to a load containing resistance and a pure inductance in series. In this case, the same current flows through both components but while the voltage across the resistor will be in phase with the current the voltage across the inductor will lead the current by  $90^\circ$ .



**Figure B-1-3**



From the phasor diagram we can find the angle  $\phi$  by which the current  $I$  lags the applied voltage  $V$ , since:

$$\frac{V_L}{V_R} = \tan \phi \quad \therefore \phi = \tan^{-1} \frac{V_L}{V_R}$$

### **B.1.1 Root Mean Square Values**

In the preceding part of this appendix, the instantaneous value of an alternating voltage or current was expressed in terms of its maximum or peak value.

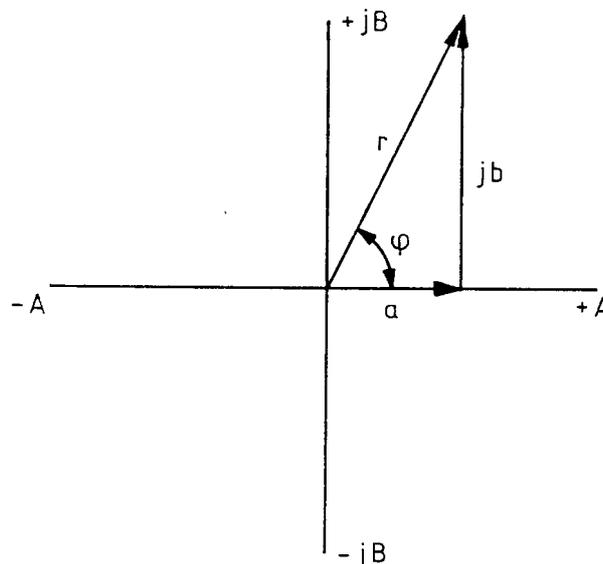
In power engineering, the root mean square (RMS) values of voltage or current are used almost exclusively for measurement and calculation. As we are concerned with sinusoidal quantities, the following relationship applies:

$$\text{RMS value} = \frac{\text{max value}}{\sqrt{2}} = 0.707 \text{ max value}$$

The application of phasor diagrams is therefore unaffected by the use of RMS values.

### **B.1.2 Symbolic Representation of Phasors**

The operator  $j$  provides a method for expressing phasor quantities algebraically.



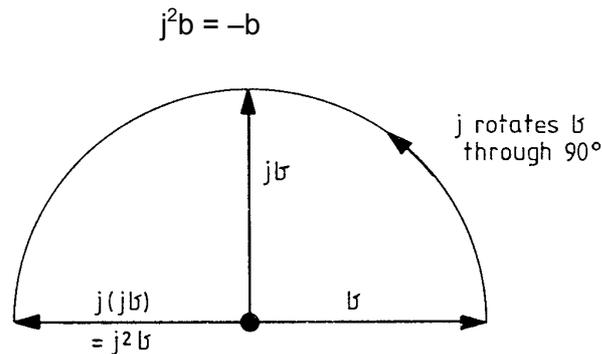
**Figure B-1-4**

The phasor can be resolved into component phasors, one in the reference direction, labelled  $a$ , and another at right angles to it, labelled  $jb$ . In other words, two component phasors  $a$  and  $jb$  can be found which, when added geometrically as shown, are equivalent to the original phasor. The  $j$  in  $jb$  denotes that this component phasor is *in quadrature*; ie, lies at right angles to the reference direction.



$j$  is a symbol used as an operator. It operates on any phasor, such as  $b$  in Figure B-1-5, by turning it  $90^\circ$  counter-clockwise. If the operator  $j$  is now applied to the phasor  $jb$ , the result could be written  $j(jb)$ , or  $j^2b$ . But it is convenient to use the same notation as with algebraic symbols, calling it  $j^2b$ .

Looking at  $j^2b$  in Figure B-1-5, it can be seen that rotating  $b$  twice through  $90^\circ$  has made it equal to  $-b$ . We can therefore write the equation:



**Figure B-1-5**

Equations involving phasors can therefore be manipulated using the equation:

$$j^2 = -1$$

The statement is often made that  $j = \sqrt{-1}$ , and this is a convenient way of thinking during algebraic work where powers of  $j$  occur. There is of course no real *number* which when multiplied by itself produces a negative number (but then  $j$  is an operator, not a *number*, and when squared it negates not a number but a phasor).

A quantity  $r$  when expressed as  $r = a + jb$  is termed a complex quantity which can be treated algebraically provided it is remembered that the operator  $j$  is not a multiplier but a means of rotating a quantity by  $90^\circ$ .

Two more complex quantities can be added:

$$(a + jb) + (c + jd) = (a + c) + j(b + d)$$

They can be multiplied:

$$(a + jb) \times (c + jd) = (ac - bd) + j(bc + ad)$$

They can be divided:

$$\frac{a + jb}{c + jd} = \frac{a + jb}{c + jd} \times \frac{c - jd}{c - jd} = \frac{ac + bd}{c^2 + d^2} + j \frac{bc - ad}{c^2 + d^2}$$

All these operations express the solution as an ordinary complex quantity that can be written in general terms as:

$$R = P + jQ \quad \text{where } R \text{ is the phasor quantity}$$

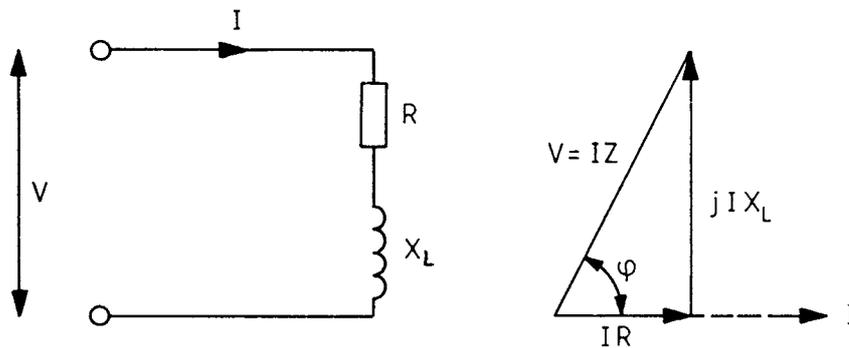
$P$  is the in-phase component

$Q$  is the quadrature component



The size of magnitude or  $R = \sqrt{P^2 + Q^2}$ , and the angle of R to the reference axis is where  $\tan \phi = \frac{Q}{P}$ .

In the circuit of Figure B-1-3, previously considered, a resistor and inductor in series are connected to a single phase ac supply. We can express the impedance of this circuit as a complex quantity as shown in Figure B-1-6.



**Figure B-1-6**

Then using the j notation we can write:

$$V = I (R + jX_L)$$

The impedance  $Z = \frac{V}{I} = R + jX_L$ , the magnitude of  $Z = \sqrt{R^2 + (X_L)^2}$

and the angle  $\phi$  is  $\arctan \frac{X_L}{R}$ .

This method can be used to deal with several impedances in series or in parallel, though in the latter case it is often more convenient to use conductance, G and susceptance B to obtain admittance Y.

In Appendix B.3, the operator h is introduced, and this has the effect of rotating a phasor quantity by 120° counter-clockwise.

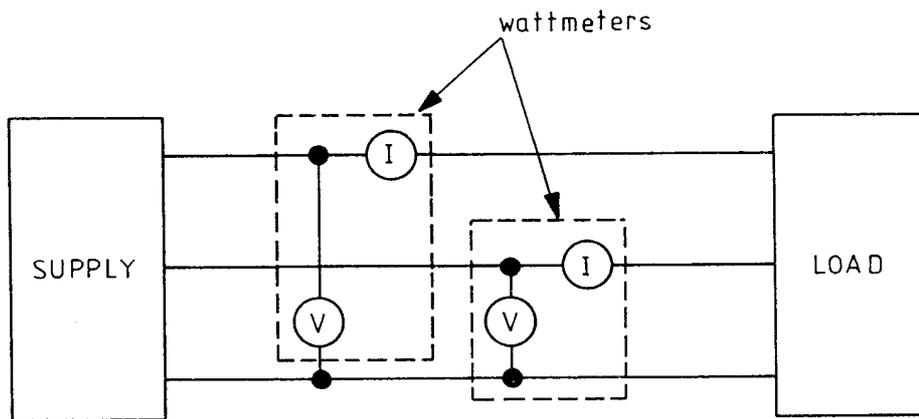
In this case:

$$h = -0.5 + j \frac{\sqrt{3}}{2}$$

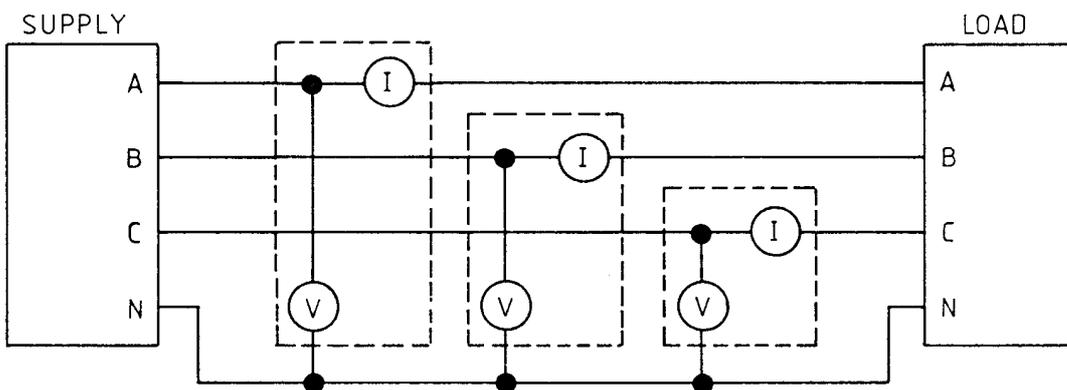
and

$$h^2 = -0.5 - j \frac{\sqrt{3}}{2}$$

This has many applications in the solution of unbalanced three phase conditions.



**Figure B-2-1**



**Figure B-2-2**



## **B.2 Two and Three Wattmeter Power Measurement**

It can be shown from first principles that if a network has  $n$  terminals, the total power entering it can be measured using  $(n - 1)$  wattmeters. Consequently:

- if only three wires are used to connect a three phase load (see Figure B-2-1), the power can be measured using only two wattmeters.
- if four wires are used to connect the load (see Figure B-2-1), three wattmeters are required.

### **NOTE:**

It is always possible to use one more wattmeter than the required minimum number, as explained at the end of this appendix under, 'Use of a Redundant Wattmeter'.

### **B.2.1 Proof (General Case)**

Take any one of the terminals as the reference point with respect to which voltages are measured. Let us call it terminal 0. There are then  $(n - 1)$  other terminals, which we may number from 1 to  $(n - 1)$ . Let the instantaneous voltage of terminal  $m$  (with respect to terminal 0) be  $v_m$ , and let instantaneous current entering terminal  $m$  be  $i_m$ . The definition of the voltage  $v_m$  is that it is the amount of work necessary to move unit charge between the relevant terminals. Thus, if an element of charge  $\delta q_m$  is transferred into terminal  $m$ , work is done, equal to  $v_m \delta q_m$ .

Next we look at the definition of power, which is rate of doing work. So if work  $v_m \delta q_m$  is done in time  $\delta t$ , the average power associated with the movement of charge is  $v_m \delta q_m / \delta t$ . The instantaneous power is therefore  $v \delta q_m / \delta t$  (the value found by reducing the time interval and the charge to very small values).

But the definition of current is that it is the rate at which charge is transferred; ie:

$$i_m = \delta q_m / \delta t$$

So, substituting  $i_m$  for  $\delta q_m / \delta t$  in the previous result, we find that the power entering terminal  $m$  is  $v_m i_m$ .

the power entering terminal 1 is  $v_1 i_1$

the power entering terminal 2 is  $v_2 i_2$

the power entering terminal 3 is  $v_3 i_3$

the power entering terminal 4 is  $v_4 i_4$

the power entering terminal  $n - 1$  is  $v (n - 1) i (n - 1)$

If each power is measured, the total power entering the network is found. This involves  $(n - 1)$  measurements of power.

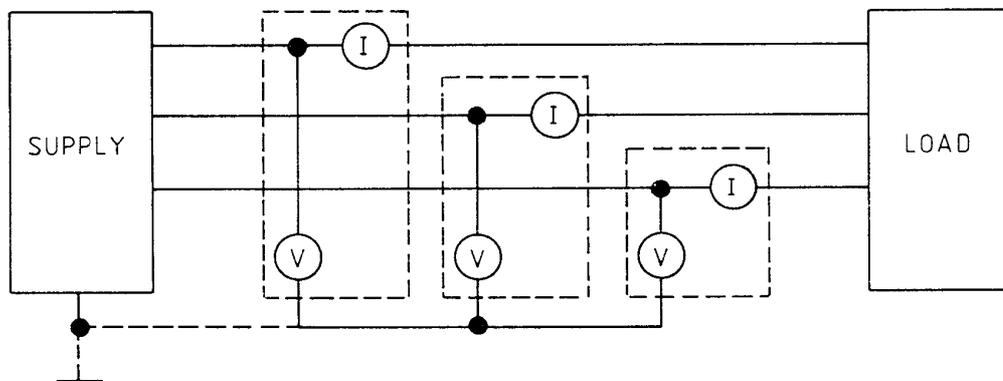
The proof has been given for instantaneous values of power. If it is proved for every instant, then it must also be true for values averaged over a period of time. In practice it is usually the power averaged over a period of time which is of interest, and this is what is measured by an ordinary wattmeter.



**B.2.2 Use of Redundant Wattmeter**

The proof above started by assuming that the voltage reference point was one of the above connecting terminals. Any other potential can be chosen as the voltage reference potential however, then the power transmitted by the currents in all  $n$  connections must be taken into account.

The case typically arises, as shown in Figure B-2-3, when three wattmeters are connected symmetrically in a three-wire three phase system, using earth or neutral as a potential reference point, but with no corresponding transmission wire.



**Figure B-2-3: Three Wattmeter Method – Three Terminal Load**



*Powerframes*  
**ELECTRICAL CIRCUITS  
STUDENT'S MANUAL**

**Appendix B**  
**General Information**



### **B.3 Why use Three Phase Systems**

In the generation, transmission and utilisation of electric power, three phase systems are predominant for both economic and operational reasons. In this appendix, it is shown that:

- a three phase system requires much less copper (or other conductor material) than a single phase system for the same load power.
- the power available from a three phase supply is constant, so avoiding torque pulsation in polyphase motors.

#### **B.3.1 Efficiency of Three Phase Transmission**

To compare the economy of three phase transmission with single phase, we may calculate the copper loss in the lines for the same mass of copper in each, transmitting the same total power. Alternatively we may calculate the relative mass of copper required in the two systems to transmit the same power with the same copper loss. In either case, the three phase system is seen to be much more economical.

For equivalent operating conditions in the two cases, let us assume:

- the same total power transmitted to the load.
- the same line length (ie, length of each conductor).
- the same voltage between line and earth.
- unity power factor.
- balanced conditions in the three phase system.
- V, I and P denote voltage, current and power, with suffixes 1 and 3 to denote the single and three phase cases respectively.

In the single phase case, the power is  $P_1 = V_1 I_1$  and in the three phase case the power is  $\sqrt{3}(V_3 I_3)$ .

$$\text{If } P_1 = P_3 \text{ then } V_1 I_1 = \sqrt{3}(V_3 I_3).$$

$$\text{But } V_3 = \sqrt{3} V_1$$

$$\therefore \frac{I_1}{I_3} = 3$$

The resistance R of a conductor of length  $\ell$  is inversely proportional to its mass M, since if it has resistivity ' $\rho$ ', density ' $\sigma$ ' and cross-sectional area 'a'.

$$R = \rho \ell / a$$

$$\text{and } M = \sigma \ell . a$$

$$\therefore RM = \sigma \rho \ell^2, \text{ which is a constant for the material and a given conductor length.}$$



**B.3.1.1 Method 1 – For the same weight of Copper in each System**

If  $R_1$ ,  $M_1$  and  $R_3$ ,  $M_3$  are the resistances and masses of each line conductor in the two systems, then for the same total mass of copper in each system,  $2M_1 = 3M_3$  and hence:

$$\frac{R_1}{R_3} = \frac{2}{3}$$

Denoting the copper loss as  $p_1$  for the single phase system and  $p_3$  for three phase, then;

$$p_1 = 2(I_1^2 R_1)$$

and 
$$p_3 = 3(I_3^2 R_3)$$

$$\therefore \frac{p_1}{p_3} = \frac{2(I_1^2 R_1)}{3(I_3^2 R_3)} = \frac{2 \times 9 \times 2}{3 \times 3} = 4$$

The copper loss in the single phase system is four times that for the three phase, whilst transmitting the same power.

**B.3.1.2 Method 2 – For the same Copper Loss in each System**

In this case,  $2(I_1^2 R_1) = 3(I_3^2 R_3)$  so that:

$$\frac{(I_1^2 R_1)}{(I_3^2 R_3)} = \frac{3}{2}$$

and  $I_1/I_3$  as before.

$$\therefore \frac{9(R_1)}{(R_3)} = \frac{3}{2}$$

$$\therefore \frac{(R_1)}{(R_3)} = \frac{1}{6}$$

Therefore, since the mass of the individual conductors is inversely proportional to their resistance,  $M_1/M_3 = 6$ .

The total mass of copper in the single phase system is  $2m_1$ ;

The total mass of copper in the three phase system is  $3m_3$ .

The ratio of the total mass of copper in the two systems is therefore:

$$\frac{2}{3} (6) = 4.$$

The mass of copper in the single phase system is four times that in the three phase one, for the same copper losses and load power.



### B.3.1.3 Effect of a Neutral Wire

So far it has been assumed that the three phase system is balanced, so that no neutral wire is required. In practice a neutral wire is usually provided, at least in the final stages of a distribution system, to carry any out of balance current. Its current capability need not exceed that of one line conductor; if it is made equal then the mass of copper is increased in the ratio  $4/3$ .

The ratio of copper required in a single phase system to that required in a four-wire three phase system is therefore 3. In more detail:

$$\frac{\text{single phase mass}}{\text{three phase mass}} = \frac{2(\text{wires}) \times 6 M_3 (\text{mass/wire})}{4(\text{wires}) \times M_3 (\text{mass/wire})}$$

### **B.3.2 Invariance of Three Phase Power**

At any instant, the power transmitted by a conductor carrying current  $i$  at potential  $v$  is  $vi$ . It is convenient to refer the potentials to the neutral point of the system. In a balanced three phase system, the voltages can then be written as:

$$v_A = V \sin \theta$$

$$v_B = V \sin (\theta - \pi/3)$$

$$v_C = V \sin (\theta - 2\pi/3)$$

where  $V$  is the peak voltage and  $\theta = 2\pi ft$  where  $f$  is the frequency,  $t$  is time.

If the power factor is  $\cos \phi$ , the line currents will be:

$$i_A = I \sin \theta - \phi$$

$$i_B = I \sin (\theta - \phi - \pi/3)$$

$$i_C = I \sin (\theta - \phi - 2\pi/3)$$

where  $I$  is the peak current.

The total power is therefore:

$$\begin{aligned} W &= VI[\sin(\theta)\sin(\theta - \phi) + \sin(\theta - \pi/3)\sin(\theta - \phi - \pi/3) + \sin(\theta - 2\pi/3)\sin(\theta - \phi - 2\pi/3)] \\ &= \frac{1}{2}VI[\cos(-\phi) - \cos(2\theta - \phi) + \cos(-\phi) - \cos(2\theta - \phi - 2\pi/3) + \cos(-\phi) - \cos(2\theta - \phi - 4\pi/3)]. \end{aligned}$$

But for any angle  $\alpha$ ,

$$\begin{aligned} \cos \alpha + \cos (\alpha - 2\pi/3) + \cos (\alpha - 4\pi/3) &= \cos \alpha + 2 \cos [(2\alpha - 2\pi)/2] \cos 2\pi/3 \\ &= \cos \alpha - 2 \cos (2\alpha/2) \\ &= \cos \alpha - \cos \alpha \\ &= 0 \end{aligned}$$



Putting  $\alpha = 2\theta - \varphi$ , we find that the power becomes:

$$\begin{aligned}W &= 1/2VI [3 \cos(-\varphi)] \\ &= (3/2)VI \cos \varphi.\end{aligned}$$

Since this expression does not contain  $\theta$  (or any other reference to time), the power is shown to have a constant value.

If now  $V_{\text{rms}}$  and  $I_{\text{rms}}$  are the rms values of voltage and current, (since  $V_{\text{rms}} = V/\sqrt{2}$  and  $I_{\text{rms}} = I/\sqrt{2}$ ), the power can be expressed as:

$$W = 3VI \cos \varphi$$

This result expresses the great advantage of a three phase system when supplying motors, that the power supplied does not fluctuate during the supply cycle. Consequently, the resulting shaft torque is constant during the supply cycle, which is not true for single phase systems.



#### B.4 Measuring Instruments

The power engineer depends on a number of different indicating instruments for the routine measurement of system performance and the analysis of faults or other special conditions.

All indicating instruments, or meters, contain a transducer and a display. In most analogue instruments, as listed in Table B-5-1, the transducer is an electromagnetic device that generates a torque proportional to some electrical quantity. Generally this turns a shaft against a restraining spring, so that the angle turned through is proportional to the generated torque. In these cases, the display is normally by a needle, mounted on the shaft, which moves across a scale.

Meter	Fixed Element	Moving Element	Deflecting Torque (Td)	Typical Applications
Moving Coil	Permanent magnet	Coil over Aluminium Frame	$k I$ linear scale	Mean dc (or ac rectified). Used with series or shunt resistors for voltage and current measurements. Can be scaled for rms.
Dynamometer	Air cored coil	Air cored coil	$k (I_1 \times I_2)$ linear power scale	ac or dc wattmeter. Fixed coil in series with load, moving coil with series resistor across supply voltage.
Moving Iron	Solenoid	Soft iron plate or strip	$k I^2$ scale cramped at lower end	dc or rms ac. Attraction type with moving plate generally used as voltmeter. Repulsion type with fixed and moving soft iron strips generally used as ammeter.
Induction Watt-hour	High inductance voltage solenoid Low inductance current solenoid	Aluminium disc free to rotate	$k VI \cos \phi$	The speed of rotation of the disc is proportioned to the torque due to the eddy currents. The number of revolutions in a given time is proportional to the electrical energy, $\int W dt$ . For measurement, power is integrated (see text). The torque generating elements, used with a restraining spring, form a wattmeter.

**Table B-5-1: Commonly Used Analogue Meters**

Integrating meters, such as watt-hour meters, require an indication which will continually increase at a *rate* proportional to a measured quantity (in this case the watts). Thus, if the power (watts) has a constant value  $W$ , the energy transmitted (joules) increases in proportion to time. When  $W$  can vary, the energy is given by:

$$\text{energy} = \int W dt.$$



In an analogue watt-hour meter, again a torque is generated, but this time the shaft carries an aluminium disc. As the shaft rotates, the disc passes between the poles of a fixed magnet, which induces voltages in the disc, proportional to the speed of rotation. Eddy currents result, also proportional to the speed, and these interact with the magnet to produce a restraining torque proportional to the speed. Thus the generated torque is balanced by the restraining torque when the speed of rotation is proportional to the generated torque. The display typically has a mechanism driven by reduction gearing from the shaft, driving numbered wheels.

### **B.4.1 Electronic Instruments**

Although analogue voltmeters and ammeters continue to be very widely used in ac measurements, several types of electronic instruments are now available that can provide good accuracy with economy, especially for the measurement of power, power factor and frequency.

In these, an electronic module or transducer converts the quantity to be measured into a low-level dc signal that can be applied either to a digital display or to a simple moving coil meter. In some instruments, the transducer converts the input voltage or current waveforms into trains of pulses, whose width, height and repetition rate are accurately defined and processed to produce the required measurement as a mean value. Table B-5-2 provides some examples.

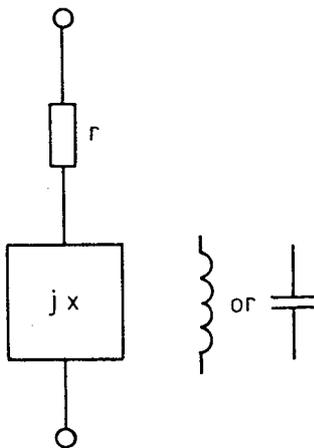
<b>Measurement</b>	<b>Inputs(s)</b>	<b>Process</b>	<b>Typical Output</b>
Power	ac voltage and current	pulse width modulation	0 to 1 mA $\propto$ cos $\phi$
Power factor	ac voltage and current	pulse summation	-0.5/0/+0.5 mA $\propto$ cos $\phi$
Frequency	alternating current	pulse timing	0 to 1 mA $\propto$ frequency

**Table B-5-2**

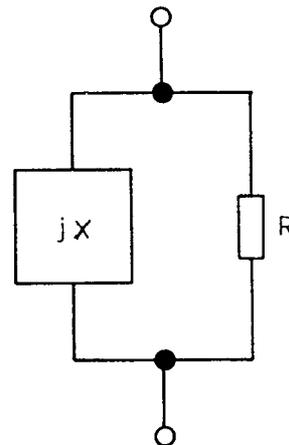


**B.5 Equivalence of Series and Parallel Components**

It is often convenient, when analysing a circuit or system, to replace some part of it by something different which behaves in the same way as what it replaces. If two circuits are different, yet behave in the same way, they are said to be equivalent. Often the equivalence only applies in some special set of circumstances; for instance, the circuits about to be discussed are only equivalent at one specific frequency. A series combination of resistance and reactance can, at any chosen single frequency, be replaced by a parallel combination of resistance and reactance, and vice versa. The transformation is often useful, especially when there are series elements in a circuit for which it is found convenient to calculate in terms of susceptance (reciprocal of impedance) rather than impedance. In such a case, using the equivalent parallel circuit simplifies calculations, and further simplification is made if the parallel elements are thought of as conductance and admittance. Figure B-6-1 shows the series circuit, having resistance  $r$  in series with reactance  $jx$ . Figure B-6-2 shows the parallel circuit, having resistance  $R$  in parallel with reactance  $jX$ . For the two circuits to be equivalent, their impedances must be equal. This occurs if the real parts of the two impedances are equal and also the imaginary parts are equal.



**Figure B-6-1**



**Figure B-6-1**

The impedances are, for series combination:

$$Z_s = r + jx$$

and for the parallel combination:

$$Z_p = \frac{RjX}{R + jX} = \frac{RjX(R - jX)}{(R + jX)(R - jX)} = \frac{RX^2 + jR^2X}{R^2 + X^2}$$

Equating the real parts of the two impedances:

$$r = \frac{RX^2}{R^2 + X^2}$$



Equating the imaginary parts:

$$x = \frac{R^2 X}{R^2 + X^2}$$

The inverse relationships (expressing, R and X in terms of r and x) can be found in the same way, using admittance instead of impedance.

Thus:

$$Y_p = \frac{1}{R} + \frac{1}{X} = \frac{1}{R} - j\frac{1}{X}$$

and

$$Y_s = \frac{r}{r + jx} = \frac{r - jx}{r^2 + x^2}$$

Therefore, equating real parts and inverting:

$$R = r(1 + x^2/r^2)$$

Equating imaginary parts and inverting:

$$X = x(1 + r^2/x^2)$$



Notes