Feedback

Powerframes

Transformers Student's Manual

60-070-TFM-S

Interactive Discovery Software

Electricity & Electronics

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Technology Training for tomorrow's world

Powerframes

Transformers

Student's Manual

60-070-TFM-S

Feedback Instruments Limited

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Feedback Part No. 1160–60070TFMS

Notes

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.

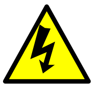
If, in specific cases, circumstances exist in which a potential hazard may be brought about by careless or improper use, these will be pointed out and the necessary precautions emphasised.

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.

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.

ACKNOWLEDGEMENTS

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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. Results obtained are entered into tables and, if necessary, plotted on graph paper. 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 - Description. Provides a description of the trainer.
- Chapter 2 - Preliminary Checks. Provides inspection and operation information and references Utility Sheets.
- Chapter 3 - Single Phase Transformer Assignments. Consists of practical assignments that can be performed by the student.
- Chapter 4 - Three Phase Transformer 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.

Notes

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Contents

1 Trainer Description

1.1 Introduction

The 60-070-TFM option of the *Powerframes* range of trainers consists of a Single Phase Transformer Panel and a Three Phase Transformer Panel which allow the properties of single and three phase power transformer theory, configuration and application 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 Equipment

The Single Phase Transformer Trainer with Virtual Instrumentation is shown in Figure 1-2 and with Conventional Instrumentation in Figure 1-3. The Three Phase Transformer Trainer with Virtual Instrumentation is shown in Figure 1-4 and with Conventional Instrumentation in Figure 1-5. Equipment required to use with the Transformers TFM Option is as follows:

- Universal Power Supply 60-105
- Single Phase Transformer 61-106
- Three Phase Transformer 61-107
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	Multichannel I/O Unit	68-500
	Software Pack	68-912-USB
	or	
Conventional Instrumentation 60-070-CI1	Electronic Single & Three Phase Measurements	68-100
Conventional Instrumentation 60-070-CI2	Rectifier Voltmeter & Ammeter (2 off)	68-117
	Electrodynamic Wattmeter (2 off)	68-204

Auxiliary Equipment

- Differential Voltage/Current Probe (2 off) 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.

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.

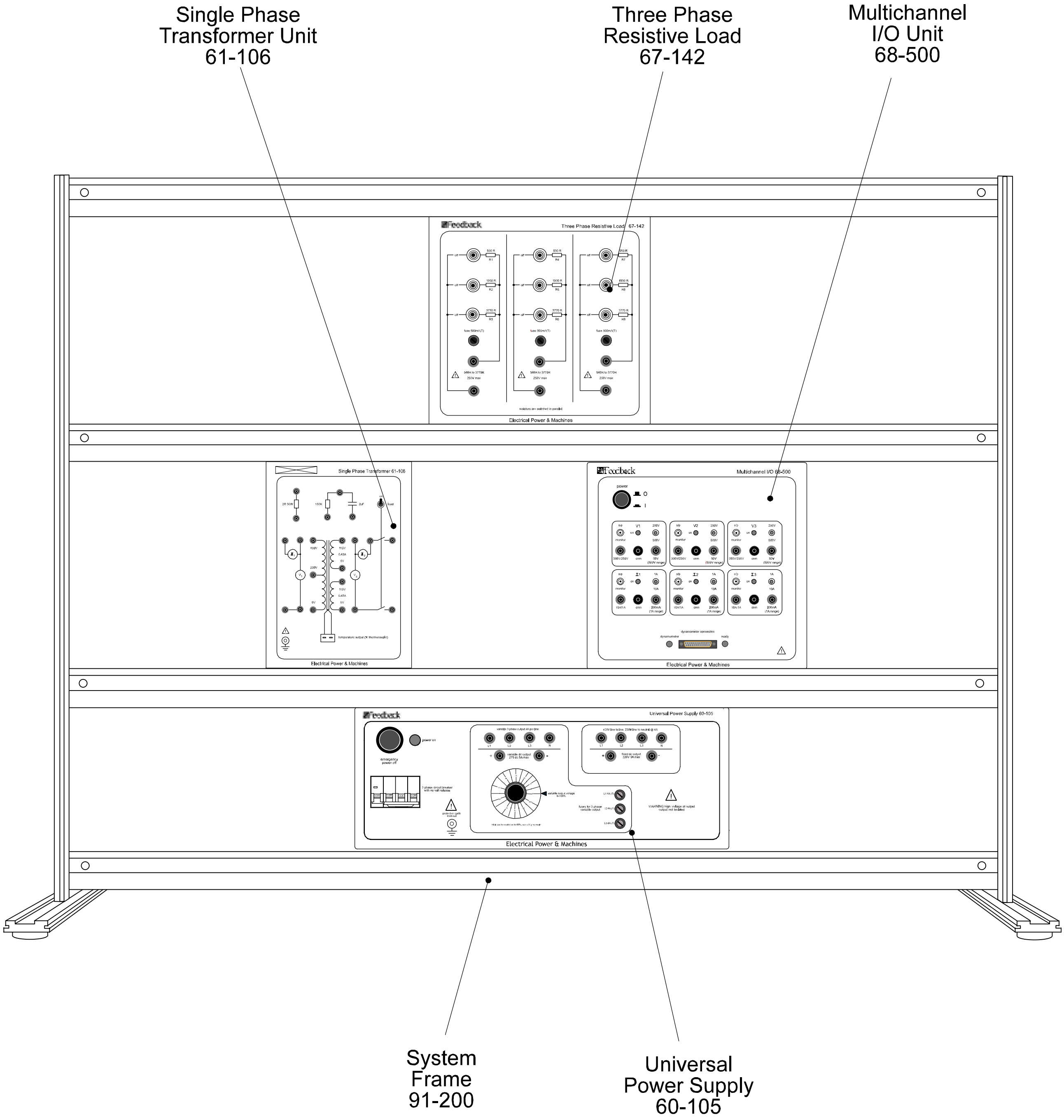


Figure 1-2: Single Phase Transformer Trainer (Virtual Instrumentation Version)

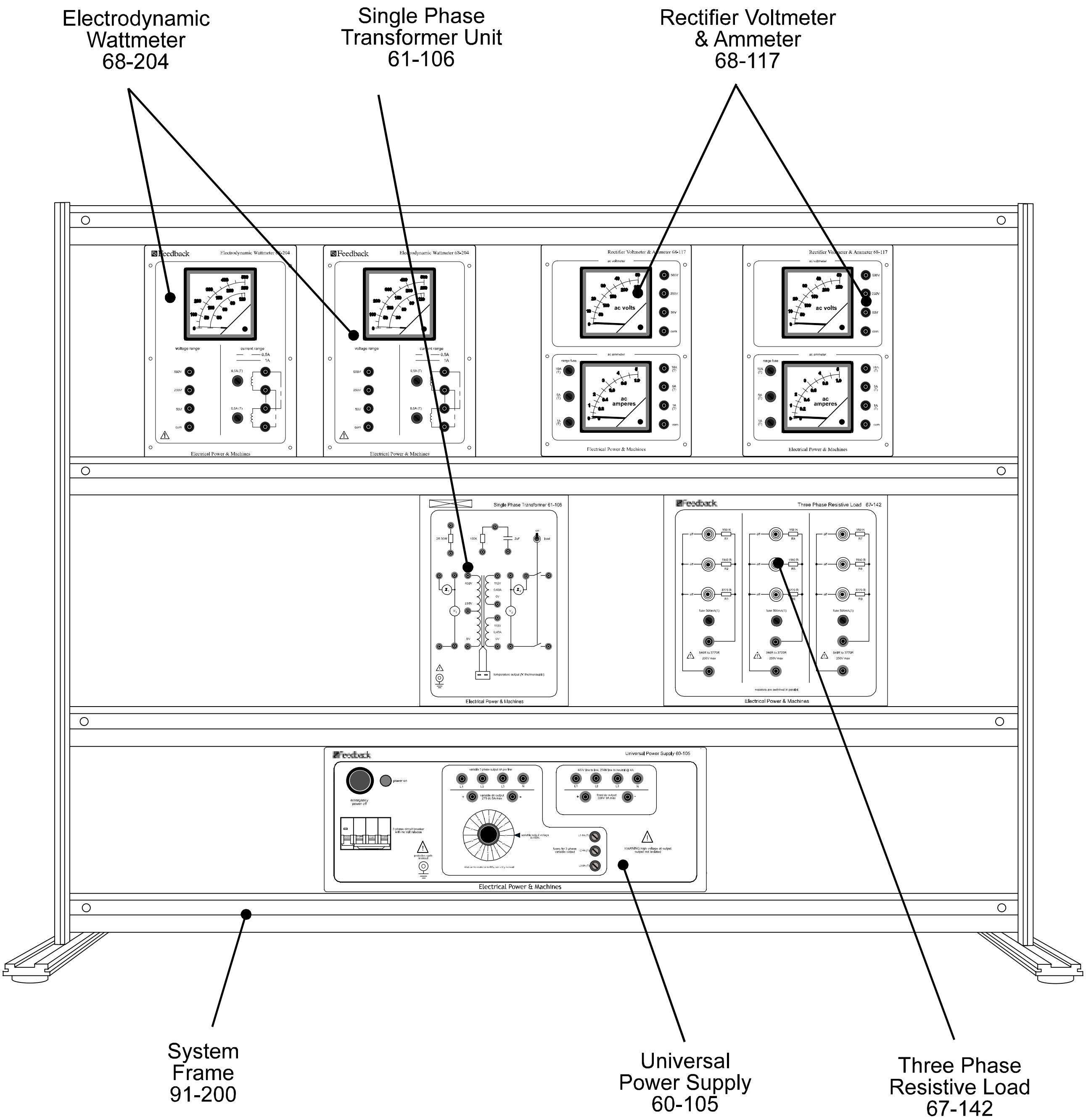


Figure 1-3: Single Phase Transformer Trainer (Conventional Instrumentation Version)

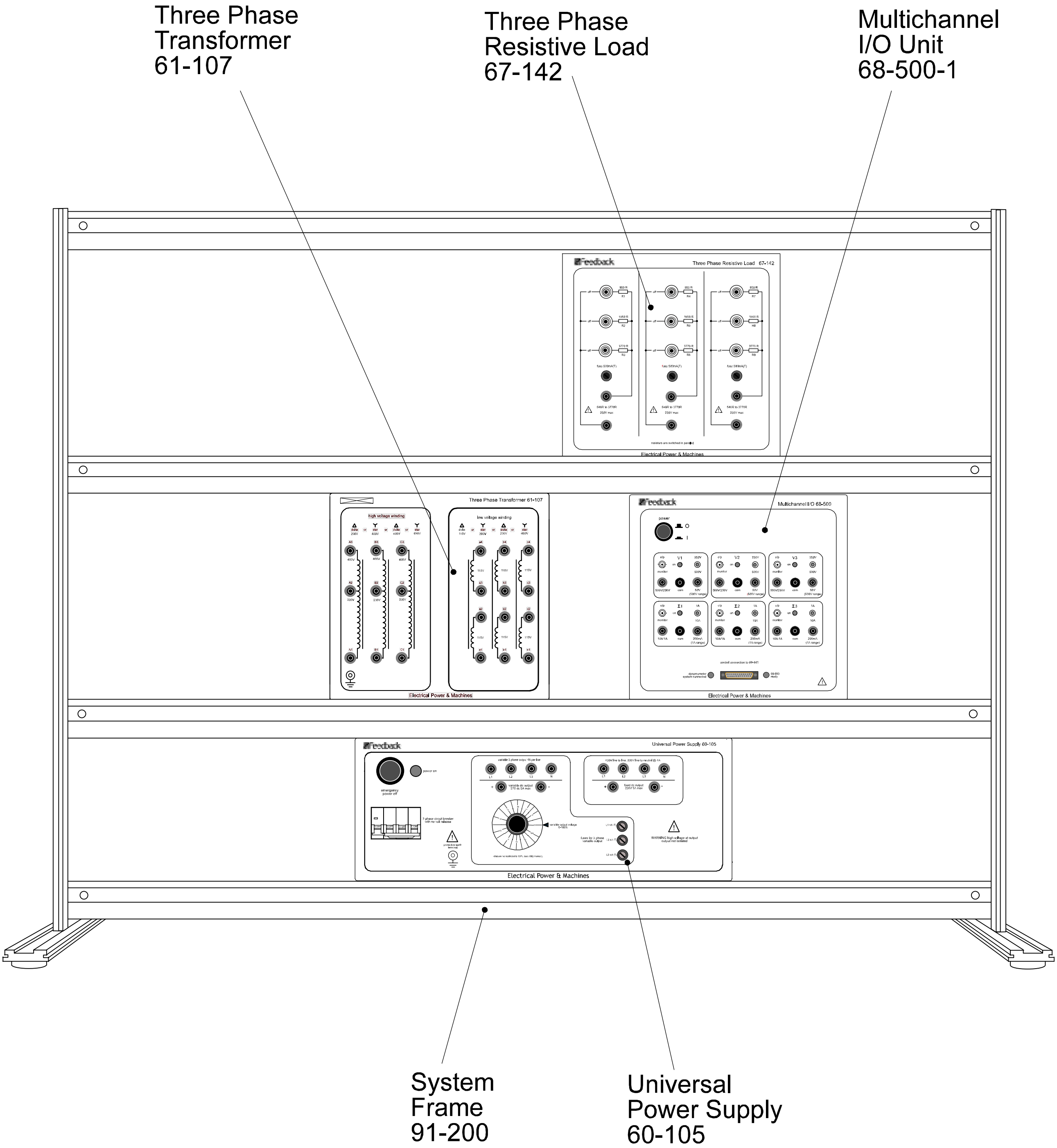


Figure 1-4: Three Phase Transformer Trainer (Virtual Instrumentation Version)

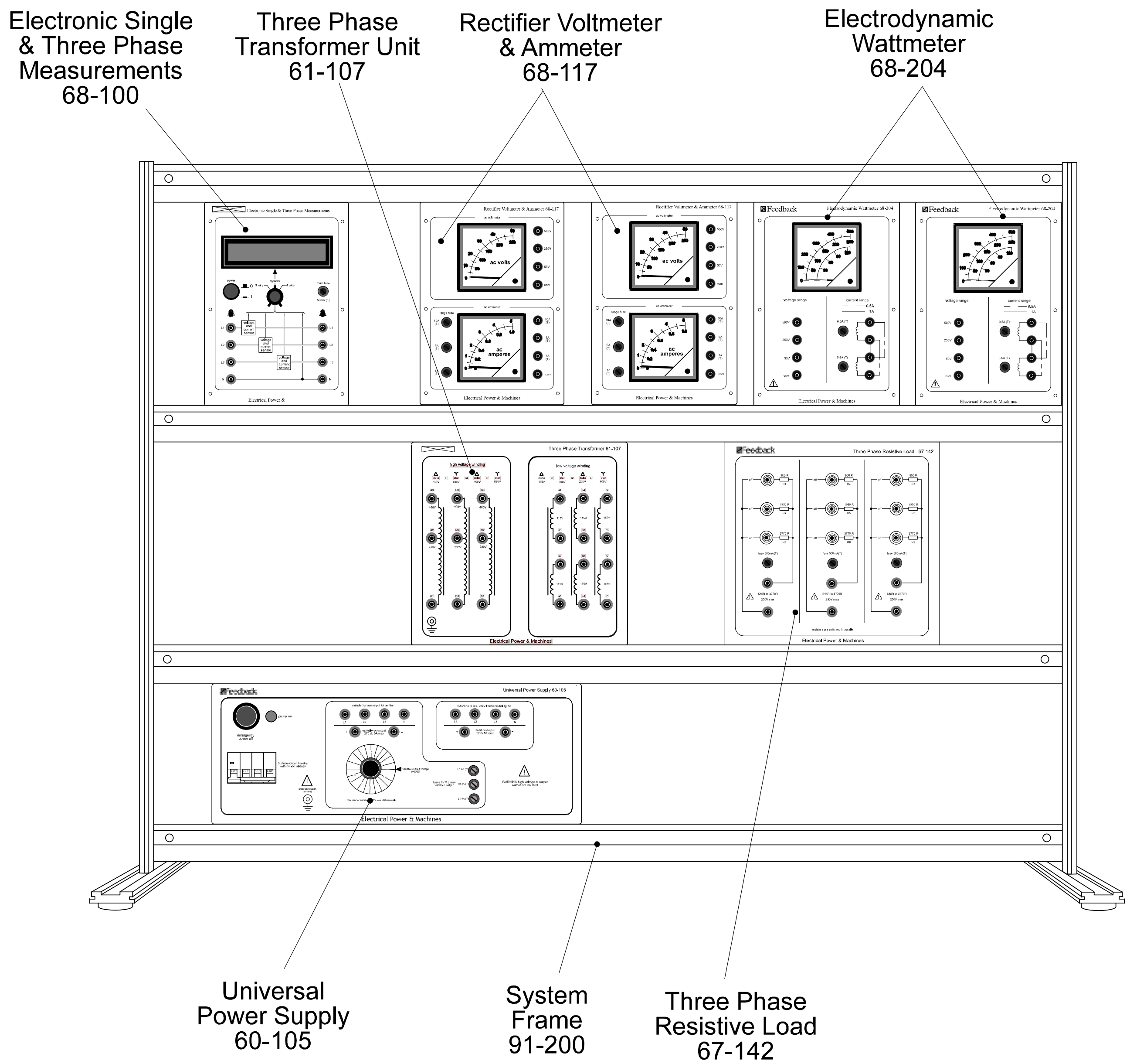


Figure 1-5: Three Phase Transformer Trainer (Conventional Instrumentation Version)

1.4 Main Modules

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

1.4.1 Common Modules

1.4.1.1 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 clock-wise to release) and resetting the lever switches on the circuit breaker to up (on) position.

1.4.1.2 Single Phase Transformer 61-106

The Single Phase Transformer 61-106 unit houses a 100 VA transformer with tapped primary winding input and two secondary windings. Also contained within the unit are two resistors and capacitor which are used for various parameter measuring operations. Additionally, a thermo-couple sensor provides an indication of the core temperature (a multimeter with a K-type thermo-couple input is required), and a toggle switch allows the output of the load to be switched.

All components are connected to a mimic panel on the front of the unit. A representation of the transformers windings is given and shrouded sockets are positioned at appropriate positions to allow inputs and outputs to be connected and various measurements of current and voltage to be taken by virtual or conventional instrumentation.

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

1.4.1.3 Three Phase Transformer 61-107

The Three Phase Transformer 61-107 unit houses a 300 VA 3-phase transformer with three high voltage primaries, and two low voltage secondaries per phase.

All components are connected to a mimic panel on the front of the unit. A representation of the transformers windings is given and shrouded sockets are positioned at appropriate positions to allow inputs and outputs to be connected and various measurements of current and voltage to be taken by virtual or conventional instrumentation.

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

1.4.1.4 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 can be present on 4 mm 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 or instrument casing is connected to the power supply earthing point.

1.4.2 Virtual Instrumentation

1.4.2.1 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 68-500 manual and the Utilities Manual 60-070-UM.

1.4.3 Conventional Instrumentation Packs 60-070-CI1 & 60-070-CI2

1.4.3.1 Rectifier Voltmeter & Ammeter 68-117 (60-070-CI2)

This equipment is used for all 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.

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

1.4.3.2 Electronic Single & Three Phase Measurements (60-070-CI1)

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

1.4.3.3 Electrodynamic Wattmeter 68-204 (60-070-CI2)

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).

1.4.4 Auxiliary Equipment

1.4.4.1 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.

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

1.4.4.2 Digital Storage Oscilloscope 20 MHz (RS232 Communication)

Used for waveform and frequency measurements to provide a steady display of the measured waveforms and a printed or saved copy on the PC through the use of the communications port. However, it is not a specific requirement to do this and a basic dual-input 20 MHz oscilloscope will suffice.

1.4.4.3 Digital Multimeter

A digital multimeter with a type 'k' thermocouple input is required for Assignment 9. This is a low cost instrument and can normally be found in most laboratories.

Notes

2 Preliminary Checks

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 to the main power supply, 60-105, using the earth leads supplied.

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 Single Phase Transformer Assignments

3.1 Introduction

This chapter contains assignments for the Single Phase Transformer. The Three Phase Transformer assignments can be found in Chapter 4. Both sets of assignments form the 60-070-TFM option. The assignments also require the use of equipment from the core system 60-070 of the *Powerframes* range of trainers and instrumentation from option 60-070-VIP or 60-070-CI1 and 60-070-CI2 if conventional instruments are to be used.

The assignments are:

1. Familiarisation
2. Transformer Polarity
3. Series and Parallel Connections
4. The Magnet Circuit
5. Phasor Diagram on No-Load
6. No-Load Losses
7. Open Circuit Test
8. Short Circuit Test
9. The Transformer on Load
10. Using the Equivalent Circuit

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

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, graphs, and answers to all questions are provided in the Reference Manual 60-070-TFM.

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 be 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

1.1 Assignment Information

1.1.1 Objectives

When you have completed this assignment you will know:

- the principles of transformer operation,
- the effect of load on transformer operation.

1.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- 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. Voltage Ratios on No-Load,
2. Voltage and Current Ratios on Load

NOTE:

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

Where parameters specific to an appropriate trainer version is 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

Before we start our study of the transformer in detail, it will be useful to look at what a transformer is and how it works.

The simplest practical transformer consists of two coils placed together and linked by a closed magnetic core which passes through the centre of the coils (see Figure 3-1-1).

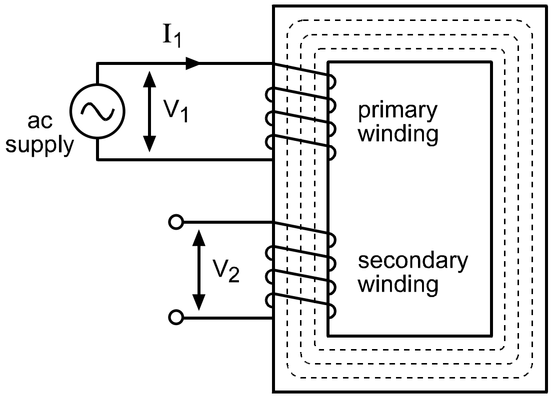


Figure 3-1-1

Each coil consists of insulated copper wire wound round a bobbin and protected by an insulating outer cover. The coils may have many turns of fine wire for low current work or fewer turns of large diameter wire or copper strip capable of passing heavy currents.

In power transformers, one coil or winding will be designated the primary and this will be connected to the ac mains supply. There will be one or more secondary windings, each supplying power to its load at a chosen voltage.

The core of a power transformer is constructed from insulated steel laminations bonded and clamped together. This laminated structure is used to reduce internal heating in the core.

When current flows through the turns of a coil, lines of flux are set up which pass through the centre of the coil and form closed loops outside the coil. Constant current will produce a steady flux, alternating current will produce an alternating flux. If the coil is wound round a close steel core, the flux level will be increased many times and the lines of flux will be confined to the core path. Iron and many of its alloys are ferromagnetic materials and have the valuable property of raising the value of flux produced by a current-carrying coil, and in reducing flux leakage.

As in the simple transformer of Figure 3-1-1, a second coil may be fitted over the core so that the flux links both coils. A steady flux will produce no voltage in the secondary coil but any change of flux will cause a voltage to be induced in it.

When an alternating voltage is connected to the primary winding, a flux is set up in the core which will alternate in direction at the same frequency as the supply voltage. The flux will link with the turns of the secondary winding and cause an ac voltage to be induced in it whose value will depend on the number of turns in the winding and the rate of change of flux in the core.

The effect of the magnetic steel core is to increase the flux produced by current in the primary and keep it within the core path which links the two windings. In Figure 3-1-2(a), two identical coils of a transformer are shown fitted to their core. When one coil is energised from an ac supply, the second coil will produce a voltage equal to the energising voltage.

If the core is removed as in Figure 3-1-2(b), the flux linking the two windings will be much reduced and the secondary voltage will fall to a low value. Separating the coils as in Figure 3-1-2(c) will further reduce the flux linkage and cause the secondary voltage to reduced.

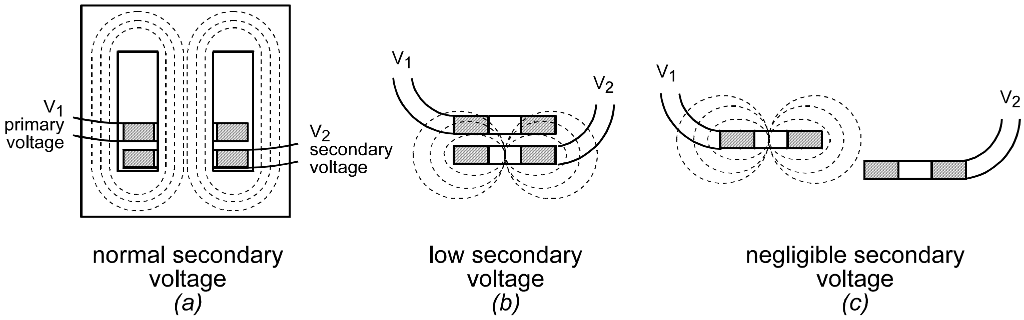


Figure 3-1-2

1.2.2 Voltage Ratio of the Transformer

As previously discussed, the current drawn by the primary winding from the ac supply produces an alternating flux which links all the coils which embrace the core. The voltage induced in the secondary can be measured directly but a voltage will also be induced in the primary winding since its turns are linked by the same flux.

The induced voltage in the primary is referred to as the back EMF. It is almost equal in value to the ac supply voltage and will always act in opposition to it, so tending to reduce the current taken from the supply.

The voltage in each turn of both the primary and secondary windings will be the same; consequently, the value of the voltage induced in the secondary will depend on the ratio of the number of turns in the secondary to those in the primary.

When there are more secondary than primary turns, the transformer is said to be a 'step-up' and the secondary voltage is higher than that of the primary. With fewer secondary than primary turns, the transformer is a 'step-down' and output voltage is lower than the supply. For the same number of turns in each winding, the transformer is a 'one-to-one'.

1.3 Content

The practicals in this assignment familiarise the student with the units and measurement facilities that make up the Single Phase Transformer Trainer.

1.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	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.

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® 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 - Voltage Ratios on No Load

The voltage induced by the alternating flux in any coil wound around the core may be expressed as a given value of volts per turn.

If:

Number of turns in primary = N_1

Number of turns in secondary = N_2

volts per turn = k

Then:

Primary Volts $V_1 = kN_1$

Secondary Volts $V_2 = kN_2$

Since k is constant:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = k \qquad \text{Eq. 1}$$

Load current in the secondary will produce a flux which tends to reduce the main flux. This leads to an increase in primary current sufficient to maintain the flux in the core at its original value.

Hence:

$$I_1N_1 = I_2N_2$$

This can be written as:

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} \qquad \text{Eq. 2}$$

Combining equations 1 and 2:

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} \qquad \text{Eq. 3}$$

So for an ideal transformer:

$$V_1 I_1 = V_2 I_2 \qquad \text{Eq. 4}$$

1.7 Practical 1.1 - Procedure

Procedure	Product Version: 230 V	Product Version: 120 V
Make the connections shown in Figure 3-1-3 (a) and (b) or (c).		
If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 and V2 channels to '500 V' on the Multichannel I/O Unit 68-500. This allows up to 50 V to be monitored when the '50 V' sockets are connected.		
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 primary voltage to 40 V by use of the *'variable output voltage'* control (as read by virtual or conventional instrumentation).		
	Secondary Connections	
Record the secondary voltmeter reading V2, on a copy of the appropriate Practical 1.1 Results Table, in the 'Voltmeter 2' reading column for 'Sec 1'………………………………………………………………………… Be sure to record your results in the appropriate 230 V or 120 V version results table.	*115 V, 0 V*	*62.5 V, 0 V*

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

Repeat the experiment for the other connections as shown in Practical 1.1 Results Table and record the results in the appropriate product version table.

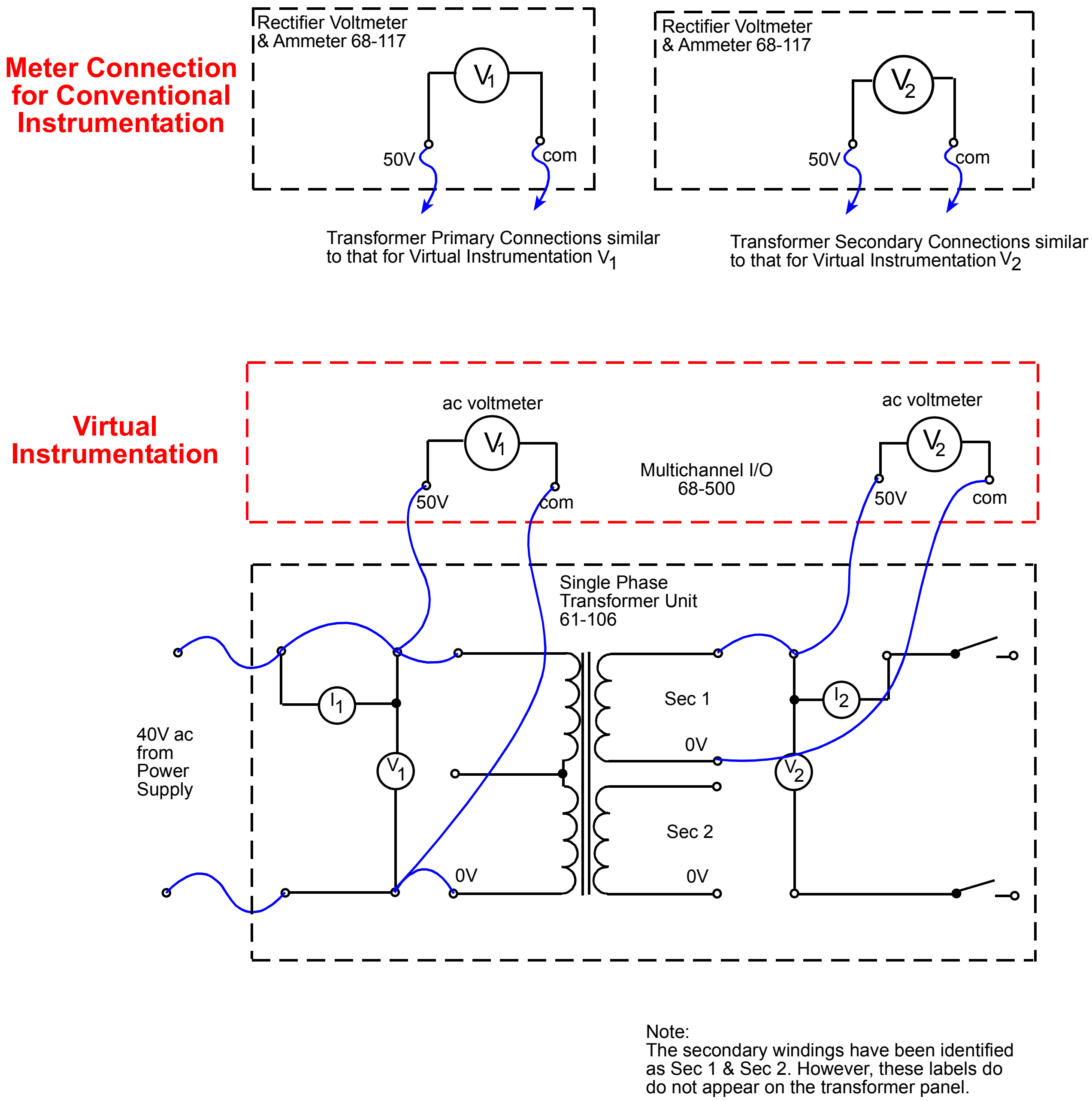


Figure 3-1-3(a): Practical 1.1 Circuit Diagram

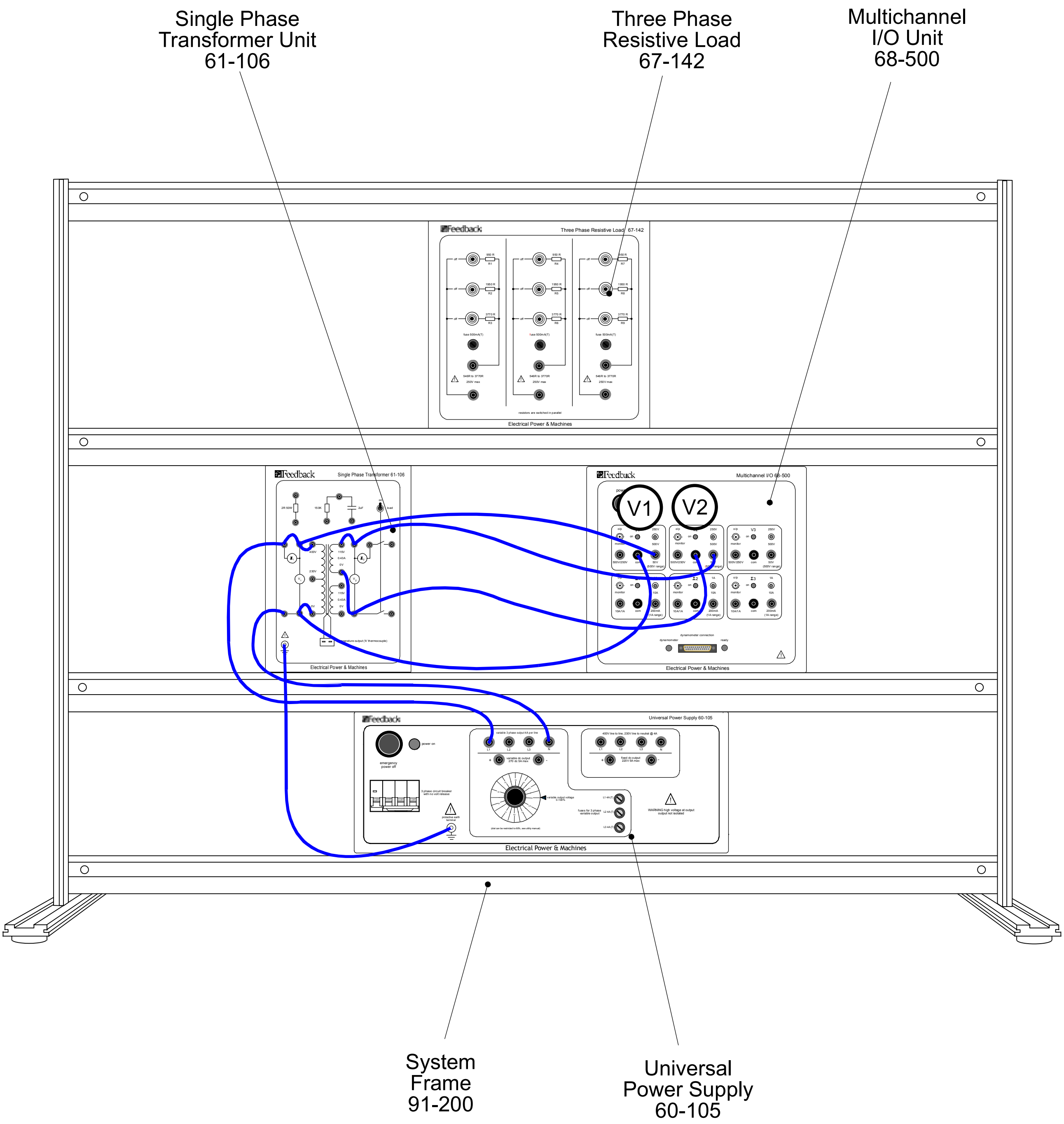


Figure 3-1-3(b): Practical 1.1 Patching Diagram (Virtual Instrumentation)

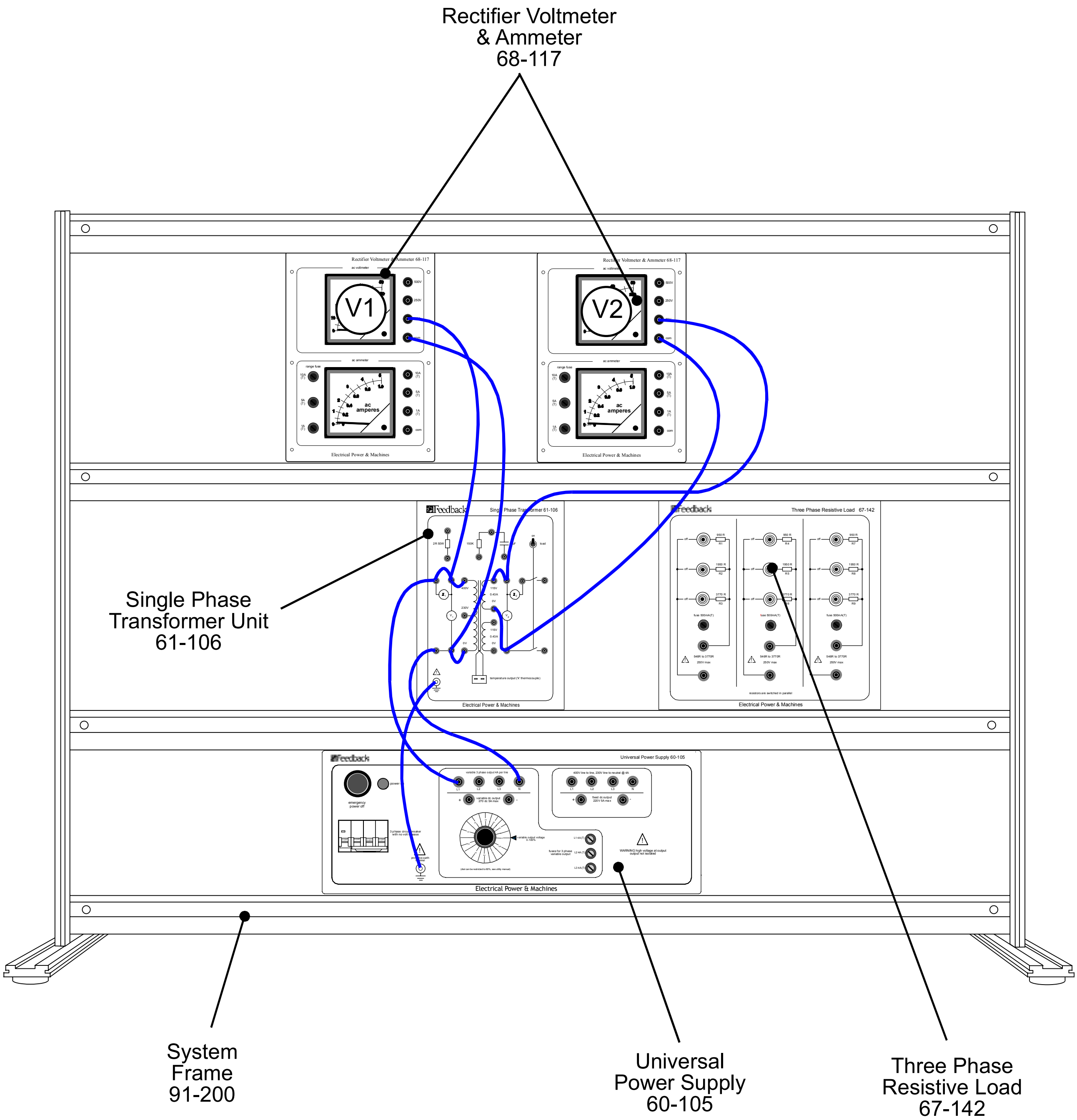


Figure 3-1-3(c): Practical 1.1 Patching Diagram (Conventional Instrumentation)

1.7.1 Exercise 1.1

The test results recorded in Practical 1.1 Results Table give us all the information needed to work out the voltage ratios of the transformer windings on no load. Using this information, draw a transformer diagram similar to that in Figure 3-1-4 and mark in the voltages appearing across each winding for the appropriate product version transformer.

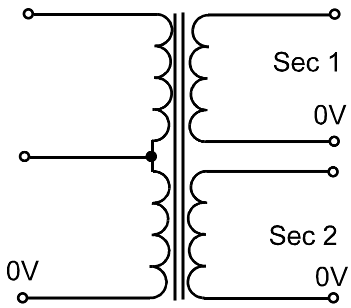


Figure 3-1-4

1.7.2 Questions

Question 1.1

For the transformer primary winding, we are told that there are 1305 turns. What are the approximate number of turns for secondary 2 windings?

Now calculate the ratio of secondary to primary volts to complete each row of Practical 1.1 Results Table for 230 V or 120 V product versions.

Question 1.2

The middle terminal of the primary windings and the 0 V terminal are used as the primary. Terminal 0 V of Sec 1 winding and the top terminal of Sec 2 winding are linked, whilst the top terminal of Sec 1 and 0 V of Sec 2 now form the secondary winding. Would you describe this as a step up or a step down transformer?

1.8 Practical 1.2 - Voltage and Current Ratios on Load

Ensure that the *'variable output voltage'* control on the 60-105 is set to zero and that the supply power is switched off.

Make the connections shown in the circuit diagram Figure 3-1-6 (a) and (b) or (c) depending on whether virtual or conventional instrumentation is available.

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 and I2 to '1 A'. This allows currents 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.

Set the switches on the load unit (Figure 3-1-5) to give a resistance of…. and check that the load switch on the Single Phase Transformer Unit is switched on.

Product Version	
230 V	**120 V**
548 Ω R1, R2, R3 on, rest off	*326 Ω R2, R3 both on, rest off*

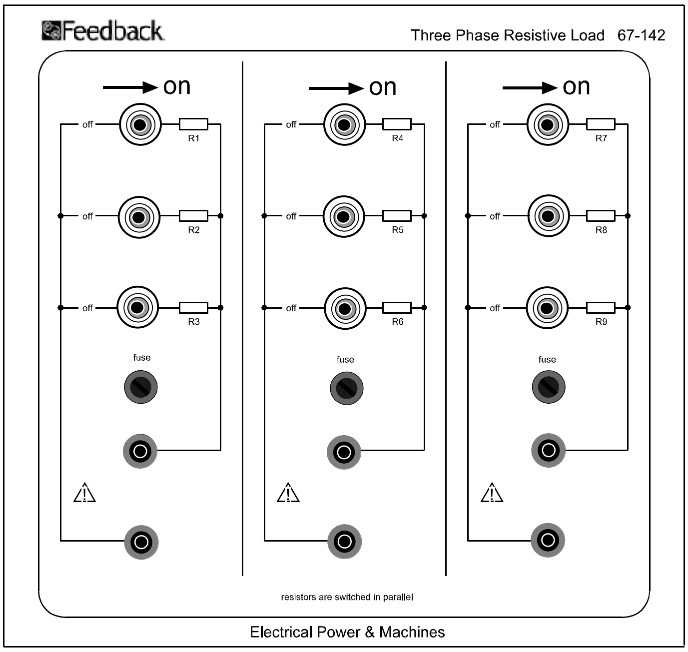
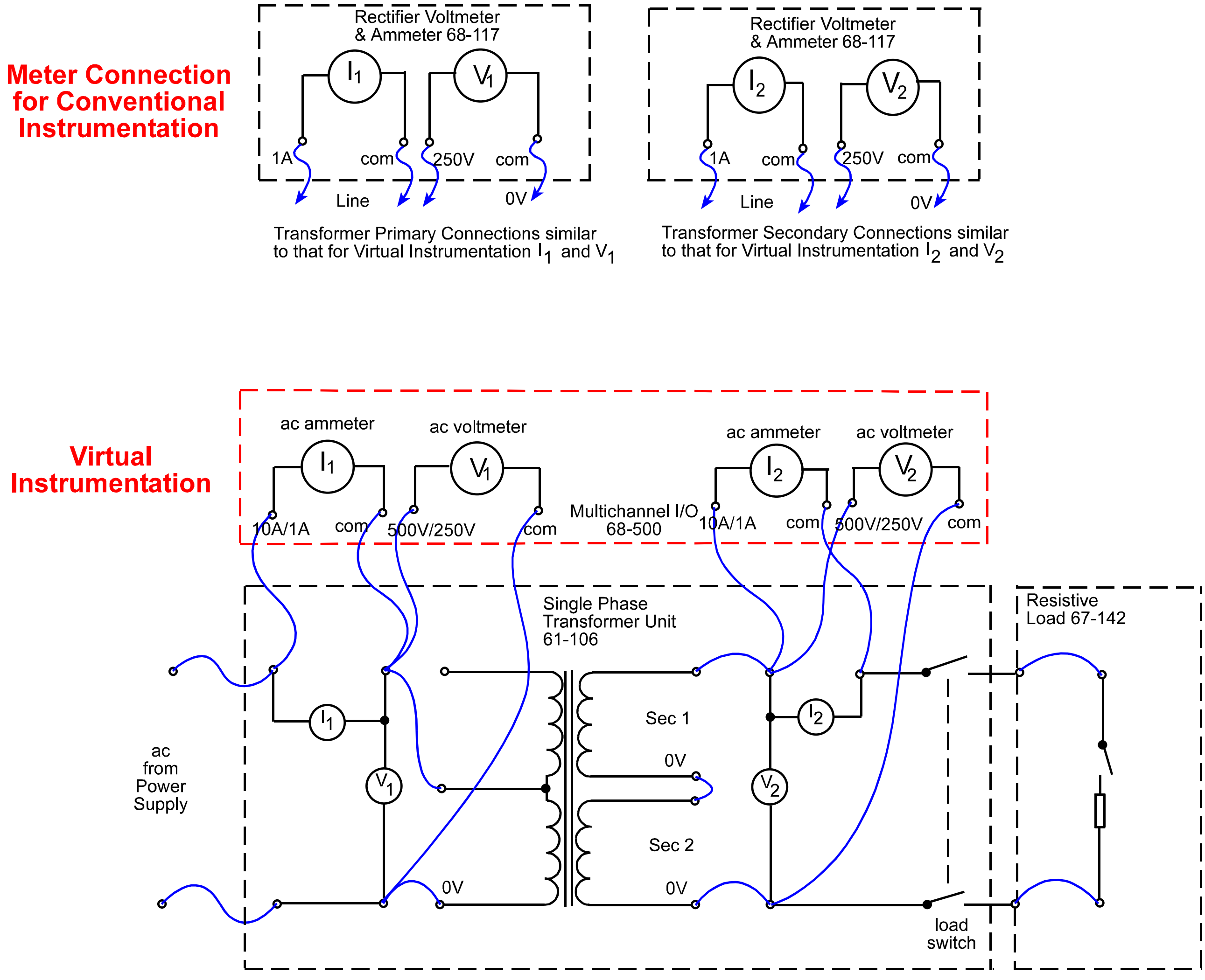


Figure 3-1-5

	Product Version	
	230 V	**120 V**
Switch on the 60-105 power supply and then using the *'variable output voltage'* control, set the primary voltage to ………………………………… as read on virtual or conventional instrumentation meter V1.	*230 V*	*125 V*

Using either virtual or conventional instrumentation (see Figure 3-1-6 (a), measure the primary and secondary voltages and currents and record the results in a copy of Practical 1.2, Results Table in the appropriate product version (230 V or 120 V table).



Note:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

Figure 3-1-6(a): Practical 1.2 Circuit Diagram

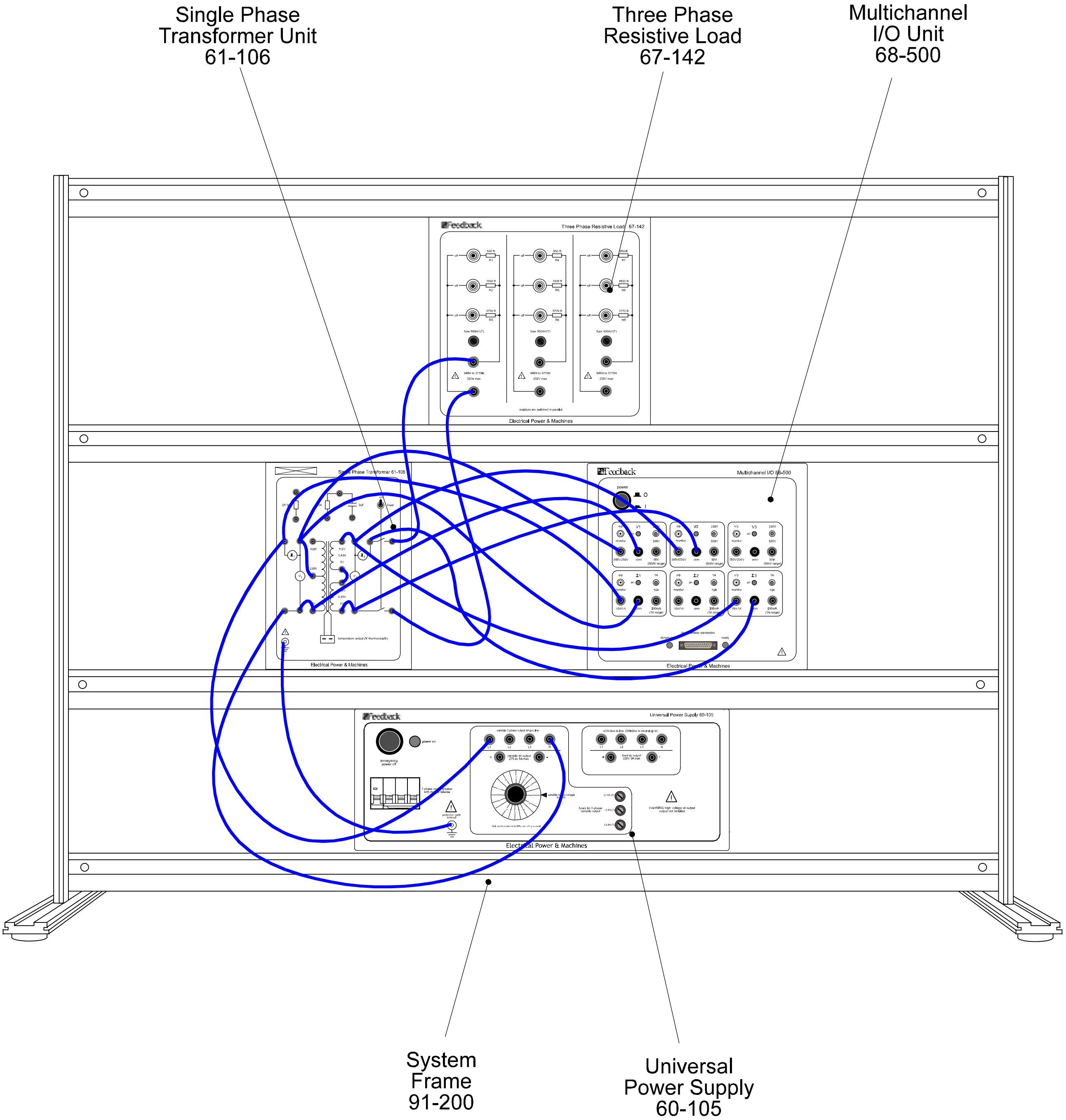


Figure 3-1-6(b): Practical 1.2 Patching Diagram (Virtual Instrumentation)

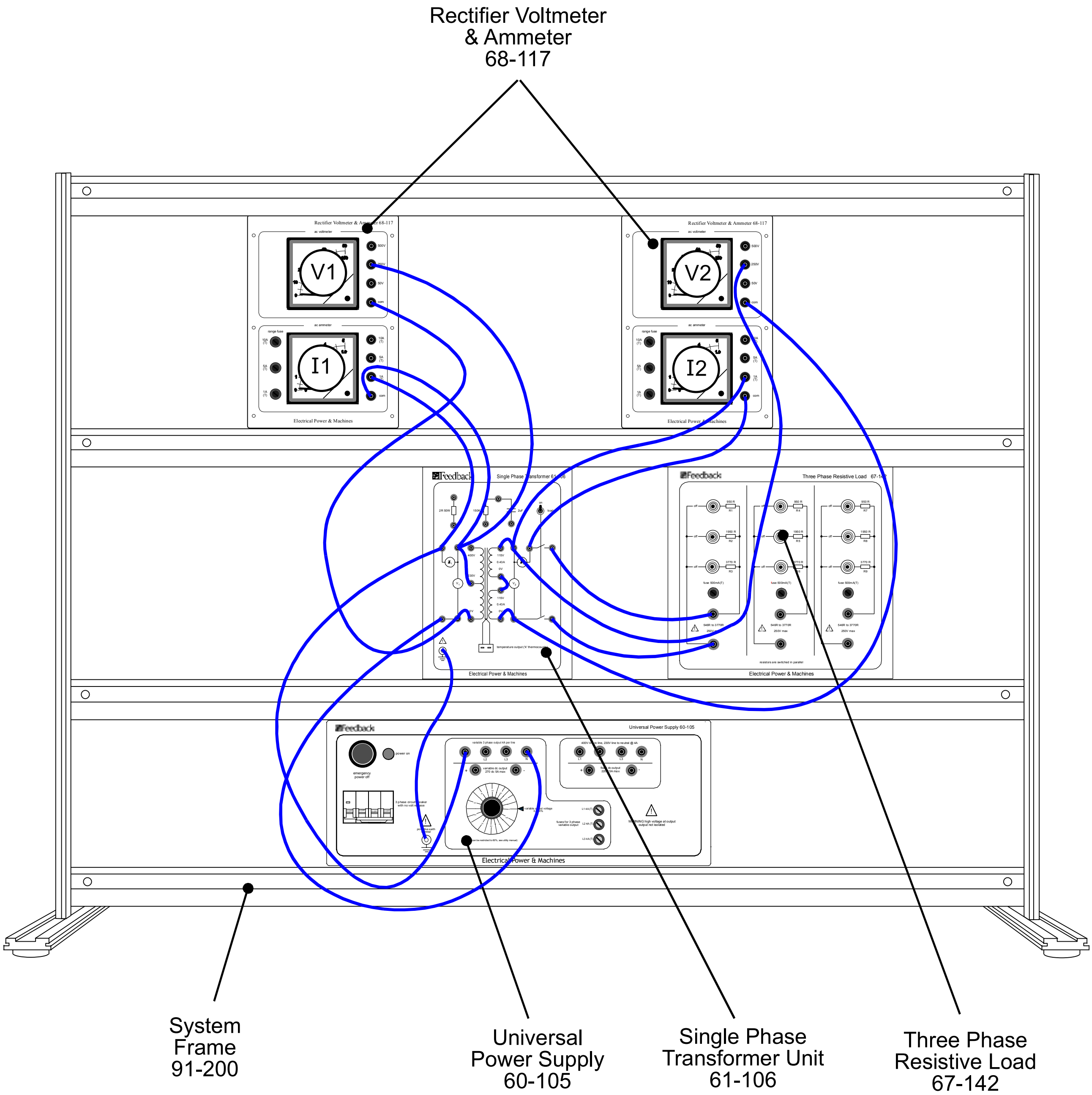


Figure 3-1-6(c): Practical 1.2 Patching Diagram (Conventional Instrumentation)

1.8.1 Exercise 1.2

From the results recorded in Table 1-2 calculate:

a) The Voltage Ratio $\frac{V_2}{V_1}$

The Current Ratio $\frac{I_1}{I_2}$

b) The primary and secondary volt/amperes:

V_1I_1 and V_2I_2

In an ideal transformer, primary and secondary volt/amperes would be equal, but in practise this is not the case due to losses within the transformer. This will be discussed in later assignments

1.8.2 Exercise 1.3

With a transformer energised and supplying the load, disconnect the load using the switch on the front panel of the Single Phase Transformer unit.

Look at the primary and secondary voltmeters while switching off the load (using the load switch on the Transformer Unit). You will see that both rise to higher voltages. Again, this is due partly to losses within the transformer, and also due to a very small change in supply voltage when the transformer is on load. Repeat the test but, this time, adjust the output of the power supply, after operating the load switch, to keep a constant supply voltage on the primary voltmeter.

Any change in the secondary voltage after switching in the load is now due to the transformer itself. The effect is well known in transformer design. It is called 'regulation' and is dealt with in more detail in a later assignment.

1.8.3 Questions

Question 1.3 — *If a manufacturer describes a power supply transformer as providing a secondary voltage of 24 volts when connected to the mains supply, do you think they are referring to the full load or no load secondary voltage?*

1.9 Practical Aspects

Most power transformers are used to provide either a step up or a step down of the primary voltage. If the secondary voltage is greater than the primary then it is a step up, whereas if the secondary voltage is less than the primary then it is a step down.

Large electricity supply transformers are used to change the relatively low voltage produced by the power station generators to a much higher level for transmission of power over long distances; eg, power may be generated at 11 kV and transmitted at 27.5 kV.

At a substation, situated near to a town or city where the electricity will be used, several step down transformers will be connected between the transmission lines and the distribution system. Further step down transformers reduce the mains supply to the nominal value specified by the supply authorities to, for example, domestic and light industry applications.

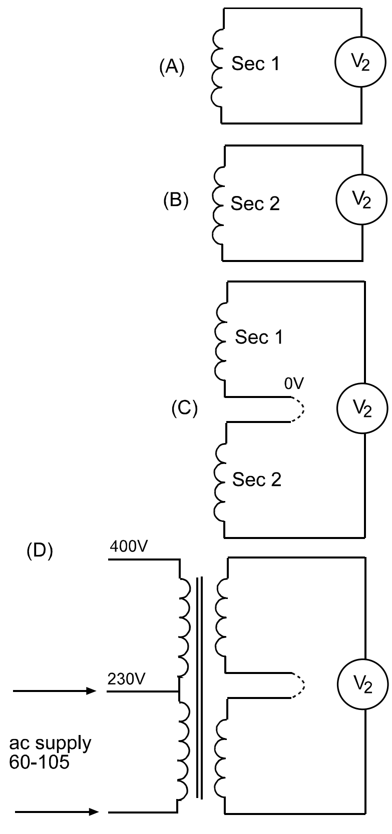
In many types of electrical equipment such as industrial electronics instruments, step down transformers are used to provide the low voltage power supplies required for transistors and integrated circuits.

Stepped ratio transformers enable a small motor or possibly a heating element to be powered from a range of different supply voltages. In these cases, a mains voltage selector switch may be connected to tapping points on the primary winding for 100, 120, 200, 240 volts or other supply voltage levels.

Notes

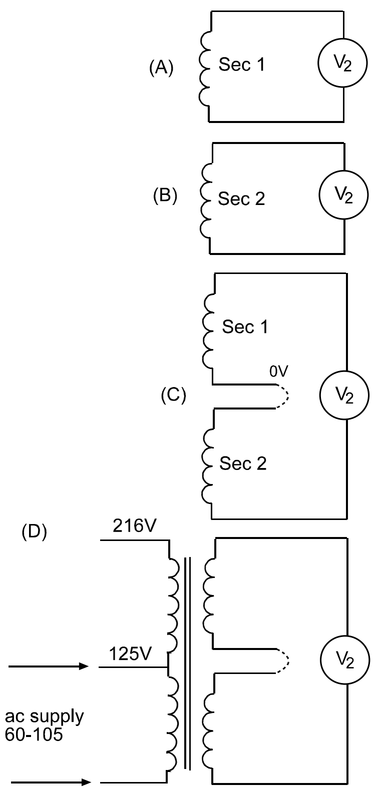
1.10 Practical 1.1 - Results Tables (230 V Product Version)

Voltmeter 1		Voltmeter 2		Voltmeter Ratio on No-Load (Primary Reading/Secondary Reading)
Primary Connections	**Reading**	**Secondary Connections**	**Reading**	
400 V, 0 V	40	**(A)** 115 V, 0 V (Sec 1)		
400 V, 0 V	40	**(B)** 115 V, 0 V (Sec 2)		
400 V, 0 V	40	**(C)** 115V (Sec 1), 0 V (Sec 2) [0 V (Sec 1) & 115 V (Sec 2) linked]		
230 V, 0 V	40	**(D)** 115 V (Sec 1), 0 V (Sec 2) [0 V (Sec 1) & 115 V (Sec 2) linked]		



1.11 Practical 1.1 - Results Tables (120 V Product Version)

Voltmeter 1		Voltmeter 2		Voltmeter Ratio on No-Load (Primary Reading/Secondary Reading)
Primary Connections	**Reading**	**Secondary Connections**	**Reading**	
216 V, 0 V	40	**(A)** 62.5 V, 0 V (Sec 1)		
216 V, 0 V	40	**(B)** 62.5 V, 0 V (Sec 2)		
216 V, 0 V	40	**(C)** 62.5V (Sec 1), 0 V (Sec 2) [0 V (Sec 1) & 62.5 V (Sec 2) linked]		
125 V, 0 V	40	**(D)** 62.5 V (Sec 1), 0 V (Sec 2) [0 V (Sec 1) & 62.5 V (Sec 2) linked]		



1.12 Practical 1.2 - Results Tables (230 V Product Version)

Primary Voltage (V_1)	Primary Current (I_1)	Secondary Voltage (V_2)	Secondary Current (I_2)	Load Resistance (Ω)
230 V				548

1.13 Practical 1.2 - Results Tables (120 V Product Version)

Primary Voltage (V_1)	Primary Current (I_1)	Secondary Voltage (V_2)	Secondary Current (I_2)	Load Resistance (Ω)
125 V				326.7

Notes

2 Transformer Polarity

2.1 Assignment Information

2.1.1 Objectives

When you have completed this assignment you will:

- know how to establish the polarity of a transformers windings.

2.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have read or completed 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. Winding Polarity.

NOTE:

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

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.

2.2 Theory

2.2.1 Introduction

A simple transformer with two separate windings is shown in Figure 3-2-1(a). To illustrate the principles involved, the same transformer is re-drawn in Figure 3-2-1(c) with the primary and secondary coils wound in the same direction on a common core, and with the 'start' and 'finish' wires of each coil labelled.

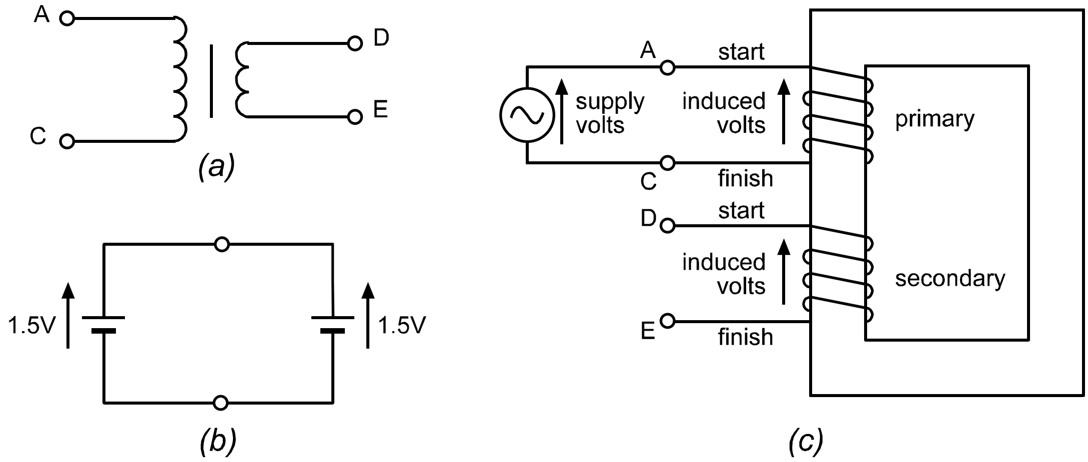


Figure 3-2-1

If an alternating voltage is now connected to coil A–C, the resulting current flow will set up an alternating flux in the magnetic core. This causes an induced voltage to be produced in coil A–C which acts to reduce the flow of current through that coil. This induced voltage is called the 'back EMF' or 'counter EMF'.

The relationship between the supply voltage and the back EMF in the primary can be likened to that of two cells connected positive to positive, negative to negative, as shown in Figure 3-2-1(b). They have the same polarity, but it should be noted that their terminal voltages are in opposition to one another and as a result no current flows between them. In the transformer we can say that the polarity of the back EMF in the primary winding is the same as that of the supply voltage, again the two voltages oppose one another. The effect of the back EMF is to reduce the flow of current into the transformer.

The secondary winding is wound around the same core as the primary and consequently an induced voltage will also be set up within its windings. This is the output voltage of the transformer - its frequency is the same as the supply voltage frequency and its magnitude will depend on the number of turns in its winding. Referring to Figure 3-2-1(c), the polarity of the induced secondary voltage across terminals D–E will be the same as the polarity of the primary voltage across terminals A–C.

The polarity of the secondary coil can be reversed by reversing the connections to its terminals. During manufacture, it is probable that all coils in the transformer will be wound in the same direction of rotation, clockwise or anticlockwise. If this is so then the start of winding leads will always have the same polarity.

2.2.2 Establishing the Polarity of a Transformer Winding

If the transformer winding details are not given, we can carry out a test to establish their polarity. In this test, one of the primary coil terminals is made common with one of the secondary coil terminals. A low ac voltage is applied to the primary and the voltage difference between the two non-common terminals is measured. We can then work out the relative polarity of the two windings.

The connection that gives minimum voltage across the windings is that which gives equivalent polarity. If the voltage ratio of the two windings is one-to-one, the voltage across the windings is zero when their polarities are the same. For other ratios, the voltage across the windings is the difference between the individual winding voltages (same polarity) or the sum of the individual voltages (opposite polarity).

Where a transformer has more than one secondary, the same test can be extended to identify the polarity of all the windings.

The circuits used for ac polarity tests are given in Figure 3-2-2.

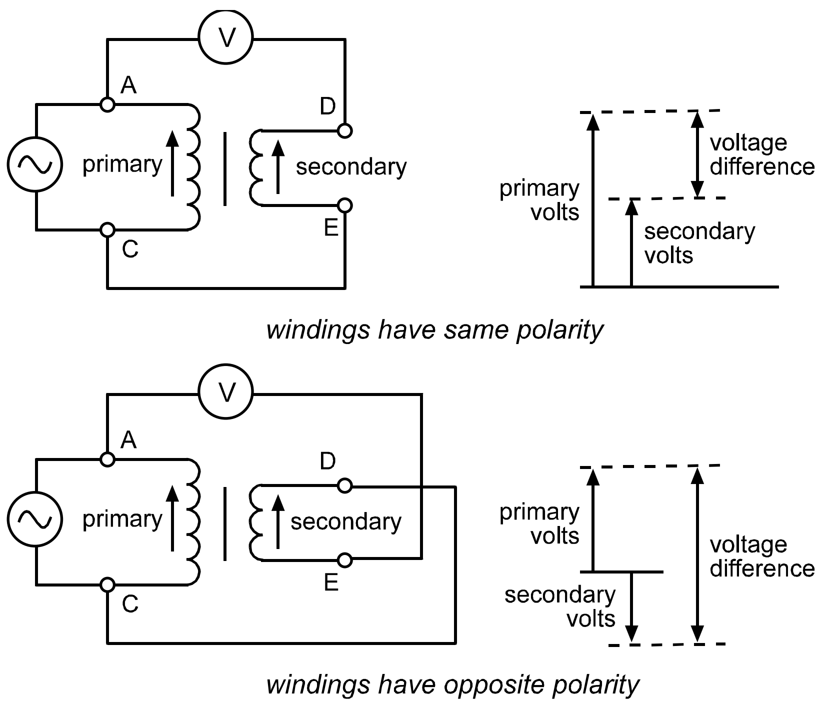


Figure 3-2-2

2.3 Content

The practical in this assignment will clarify the term polarity and demonstrate how polarity of windings is established.

2.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	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.

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.

Make all connections as shown in Figure 3-2-3.

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).*

2.6 Practical 2.1 - Winding Polarity

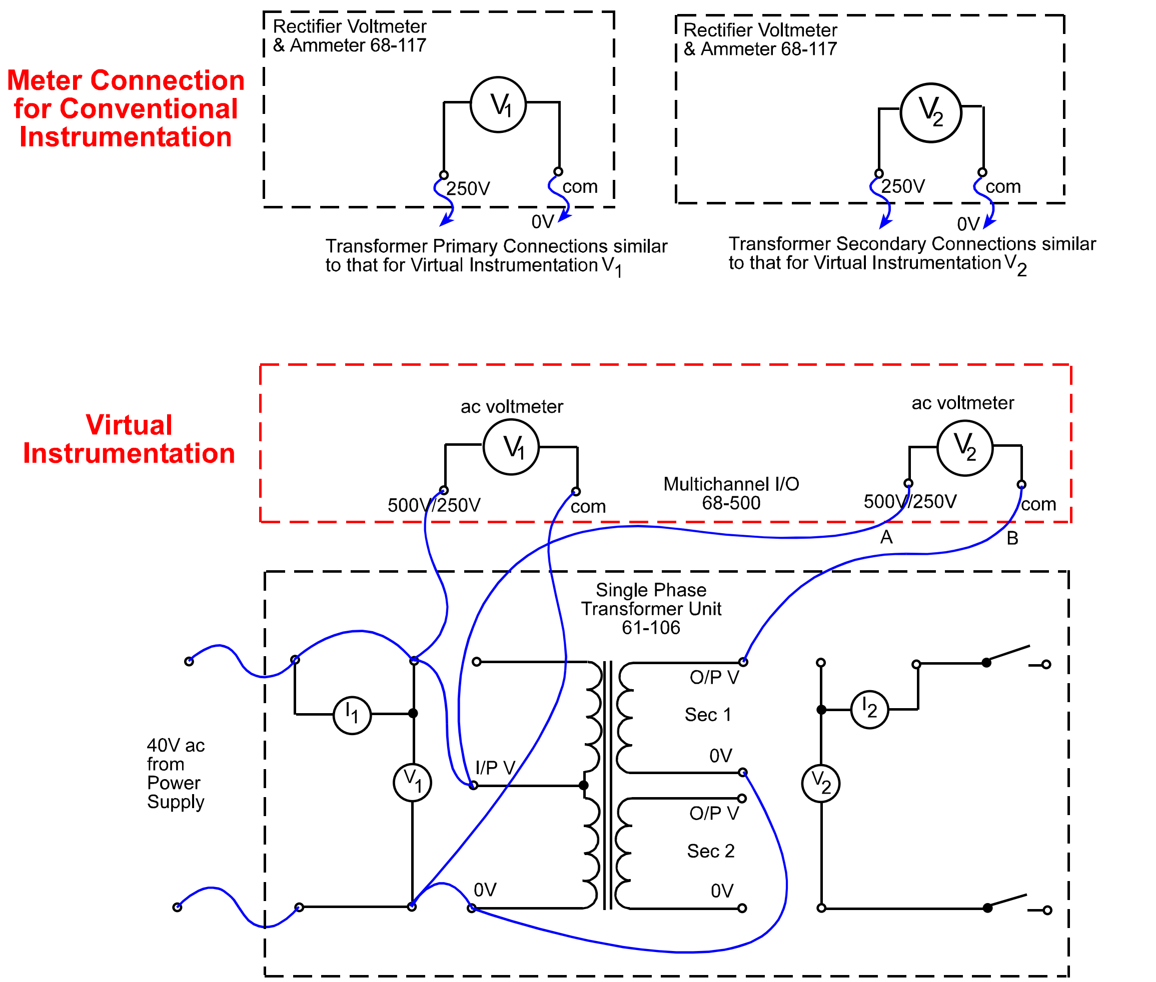
	Product Version	
	230 V	**120 V**
If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 and V2 channels to '500 V' on the Multichannel I/O Unit 68-500. This allows up to 50 V to be monitored when the '50 V' sockets are connected and selected in the software. On the Universal 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.		
	Primary Connections	
Set the primary voltage to 40 V by use of the *'variable output voltage'* control. This is the voltage applied to the primary connection ……………… and is read on virtual or conventional instrumentation V1.	*0-230 V*	*0-125 V*

Record the secondary voltmeter reading, on a copy of the appropriate Practical 2.1 Results Table (depending on the product version 230 V or 120 V). The secondary voltmeter V2 connection and the link between the primary and secondary shown in Figure 3-2-3 correspond with the first entry in you table.

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

Repeat the experiment for the other connections listed in Practical 2.1 Figure 3-2-3 Table (a) and record the values in the appropriate results table.

We now have all the information needed to establish the polarity of the primary and two secondary windings of the transformer.



Notes:

1 The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

2 The connections shown are for the first measurement as shown above For further measurements, make patching connections as given in the table.

Table (a)

Link between windings		Monitoring terminals	
Primary	**Secondary**	**'A'**	**'B'**
0V	0V (Sec 1)	I/P V	O/P V (Sec 1)
0V	O/P V (Sec 1)	I/P V	0V (Sec 1)
0V	0V (Sec 2)	I/P V	O/P V (Sec 2)
0V	O/P V (Sec 2)	I/P V	0V (Sec 2)
Secondary	**Secondary**		
0V (top)	0V (Sec 2)	O/P V (Sec 1)	O/P V (Sec 2)
0V (top)	O/P V (Sec 2)	O/P V (Sec 2)	0V (Sec 2)

Figure 3-2-3: Practical 2.1 Circuit Diagram

2.6.1 Exercise 2.1

Complete the column headed 'polarity' in your version of Practical 2.1 Results Table. Draw the transformer circuit diagram and indicate with arrows the polarity of all three windings.

2.6.2 Questions

Question 2.1 *Would you expect the polarity of the primary windings ……..*

to be the same as……………………………………………?

Explain how you would check this.

2.7 Summary

In the first two tests, the minimum voltage across the windings occurs when the connections 0 V (primary) and 0 V (Sec 1) are commoned. Therefore, the secondary connections…………………………………………………………… (Sec 1) to 0 V (Sec 1) have the same polarity as the primary connections……. to 0 V.

Product Version	
230 V	**120 V**
230-0 V	*125-0 V*
400-0 V	*216-0 V*
115 V	*62.5 V*
400 V	*216 V*

2.8 Practical Aspects

In most transformer applications, it is not necessary to know the polarity of the windings. However, when two transformers are required to be connected in parallel, it is essential to establish correct polarity, otherwise destructively large currents would circulate in the secondary windings. This is of particular importance in power distribution systems.

In most transformers supplying industrial loads, e.g. motors, heaters etc., two or more secondaries may be connected in series or in parallel to provide a range of voltage and current levels. Again, the polarity of the secondary winding must be known.

Notes

2.9 Practical 2.1 - Results Tables (230 V Product Version)

Primary Voltage (V)		**Link between windings**		**Voltage (V)**		**Polarity same/ opposite**
Connection	**Reading**	**Primary**	**Secondary**	**Connection**	**Reading**	
230 V, 0 V	40	0 V	0 V (Sec 1)	230 V, 115 V (Sec 1)		
230 V, 0 V	40	0 V	115 V (Sec 1)	230 V, 0 V (Sec 1)		
230 V, 0 V	40	0 V	0 V (Sec 2)	230 V, 115 V (Sec 2)		
230 V, 0 V	40	0 V	115 V (Sec 2)	230 V, 0 V (Sec 2)		
		Secondary	**Secondary**			
230 V, 0 V	40	0 V (Sec 1)	0 V (Sec 2)	115 V (Sec 1), 115 V (Sec 2)		
230 V, 0 V	40	0 V (Sec 1)	115 V (Sec 2)	115 V (Sec 1), 0 V (Sec 2)		

2.10 Practical 2.1 - Results Tables (120 V Product Version)

Primary Voltage (V)		Link between windings		Voltage (V)		Polarity same/ opposite
Connection	**Reading**	**Primary**	**Secondary**	**Connection**	**Reading**	
125 V, 0 V	40	0 V	0 V (Sec 1)	125 V, 62.5 V (Sec 1)		
125 V, 0 V	40	0 V	62.5 V (Sec 1)	125 V, 0 V (Sec 1)		
125 V, 0 V	40	0 V	0 V (Sec 2)	125 V, 62.5 V (Sec 2)		
125 V, 0 V	40	0 V	62.5 V (Sec 2)	125 V, 0 V (Sec 2)		
		Secondary	**Secondary**			
125 V, 0 V	40	0 V (Sec 1)	0 V (Sec 2)	62.5 V (Sec 1), 62.5 V (Sec 2)		
125 V, 0 V	40	0 V (Sec 1)	62.5 V (Sec 2)	62.5 V (Sec 1), 0 V (Sec 2)		

3 Series and Parallel Connections

3.1 Assignment Information

3.1.1 Objectives

When you have completed this assignment you will:

- know the effect on power output when the secondary windings are connected in series.
- know the effect on power output when the secondary windings are connected in parallel.

3.1.2 Knowledge Level

Before you start this assignment:

- you should have completed or read Assignment 1 Familiarisation.
- you should have completed or read Assignment 2 Transformer Polarity.
- 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. Check on Voltage Ratio and Polarity
2. Parallel Connection
3. Series Connection

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.

3.2 Theory

3.2.1 Introduction

In Assignments 1 and 2, tests were carried out to find the ratio and polarity of a transformer. These tests and the principles involved are applicable to power transformers which have two or more secondaries of the same voltage ratio. In this assignment, we will make use of the information obtained and extend it to show that, by connecting the secondaries in series or in parallel, we can change the output voltages and currents.

The information gained from series or parallel connection of the secondaries of a single transformer also applies where two or more transformers of appropriate voltage ratio are connected to a common power supply.

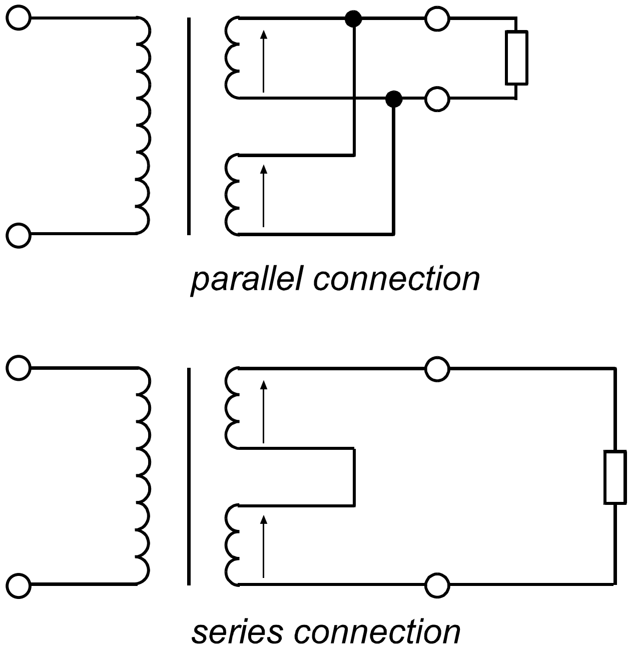


Figure 3-3-1

Figure 3-3-1 shows the principle used in the tests which follow. If the two secondary windings are to be connected in parallel, we must first ensure that they:

a) have the same voltage ratio. Otherwise a circulating current will flow through the windings, even if their polarities are the same.

b) have the same polarity. This is essential to avoid the flow of a destructively heavy current through the windings.

Both these requirements are met by an initial check on the voltage across the open ends of the secondary windings when their other terminals are connected together. If this voltage is zero, the two windings have the same voltage ratio and the same polarity.

3.3 Content

The effect on output voltage of connecting the secondary windings of a transformer in series and parallel is investigated.

3.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	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.

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® 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 - Check on Voltage Ratio and Polarity

	Product Version	
	230 V	**120 V**
Make all connections as shown in Figure 3-3-2. 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. 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 voltage to ………………………………………………………….. using the *'variable output voltage'* control. This is the voltage applied to the primary and is read on virtual or conventional instrumentation meter V1.	*230 V*	*125 V*
Check that the secondary voltage V2 reads approximately………………	*115 V*	*62.5 V*
Switch off the power supply.		
Change the connections of the secondary voltmeter V2 from Sec 1 to Sec 2, switch on the power supply and check that the secondary voltage reads approximately …………………………………………………………	*115 V*	*62.5 V*
Switch off the power supply. Connect the 0 V on Sec 1 to the 0 V on Sec 2.		
Change the connections of the secondary voltmeter from Sec 2 to ……… terminals of each secondary winding, switch on the power supply and check that the voltage reads zero. This shows that the secondaries have the same output voltage and correct polarity.	*115 V*	*62.5 V*

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 the connection between Sec 1, 0 V, and Sec 2, 0 V.

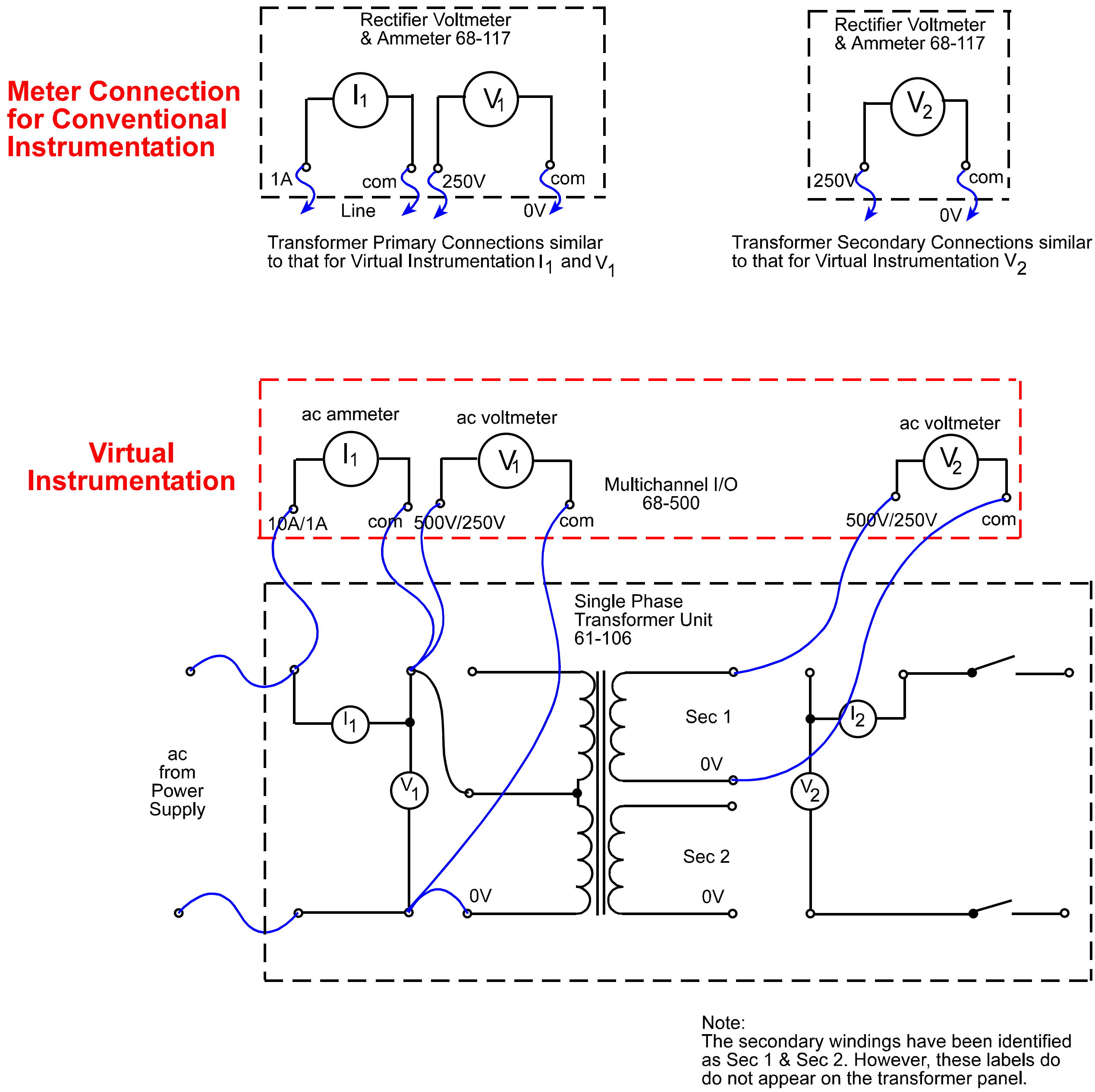


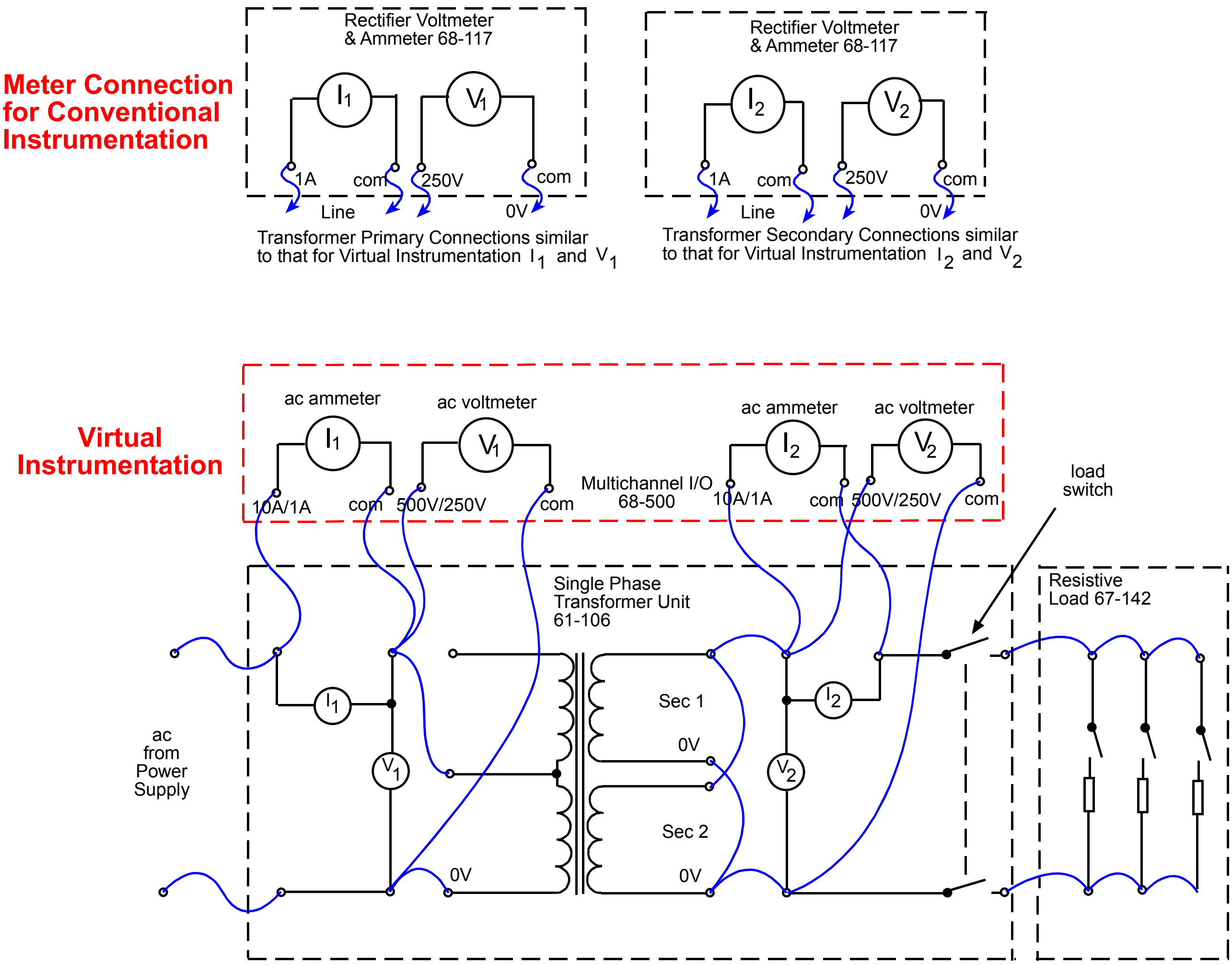
Figure 3-3-2: Practical 3.1 Patching Diagram

3.7 Practical 3.2 - Parallel Connection

	Product Version	
	230 V	**120 V**
Make all connections as shown in Figure 3-3-3. 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 and I2 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 Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0%.		
Set the switches on the Resistance Load 67-142 to give a resistance of… and check that the load switch on the Single Phase Transformer Unit is switched off.	*182 Ω Connect all 'R's in parallel*	*47 Ω connect all 'R's in parallel*
Switch on the power supply, set the primary voltage to …………………… using the *'variable output voltage'* control (read on virtual or conventional instrumentation).	*230 V*	*125 V*
Switch on the load switch on the Single Phase Transformer Unit and re-adjust the primary voltage (V1) to read……………………………………	*230 V*	*125 V*

Record the corresponding values of primary current (I1), secondary voltage (V2) and secondary current (I2) in a copy of Practical 3.2 Results Table for the appropriate product version (230 V or 120 V).

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



Note:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

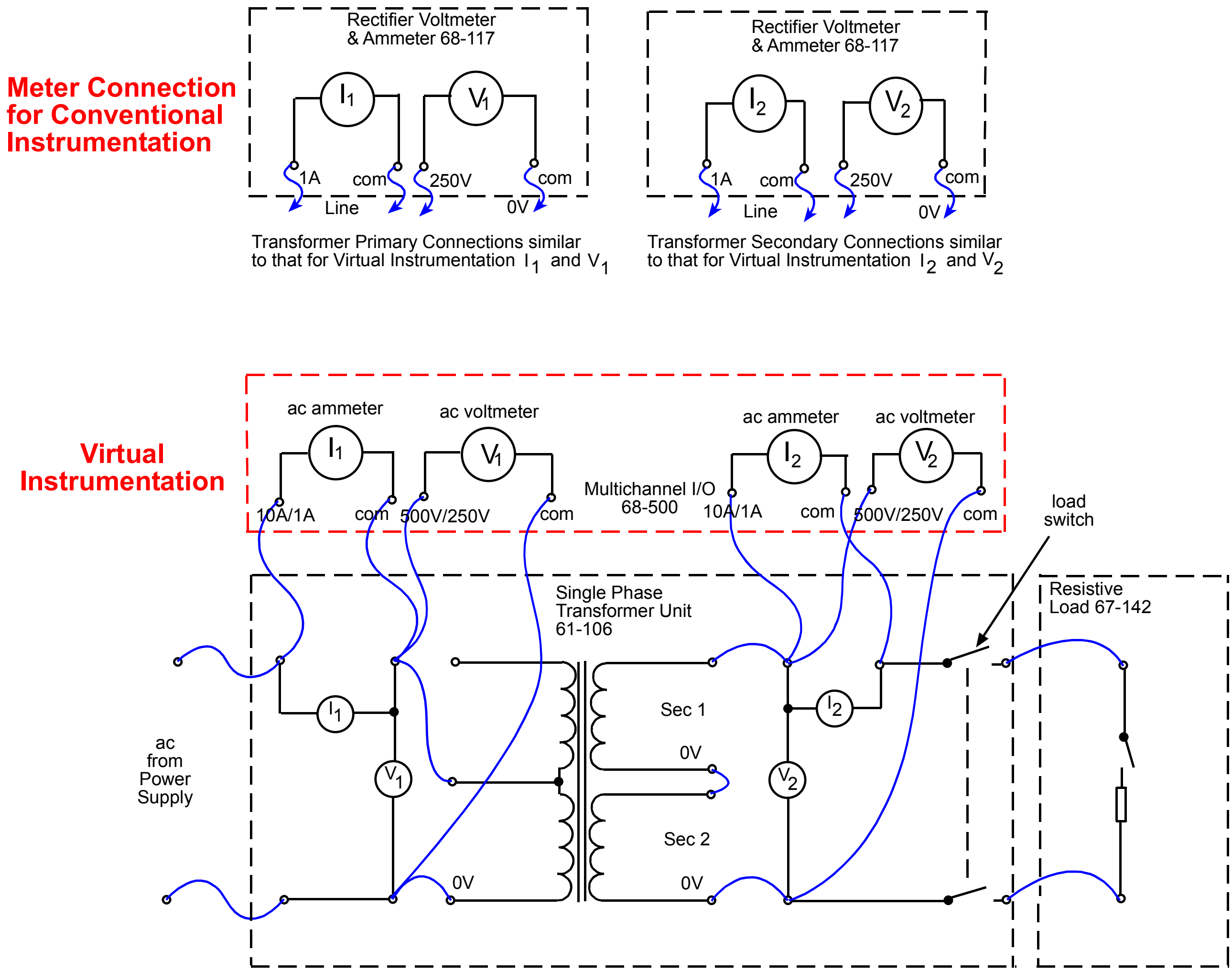
Figure 3-3-3: Practical 3.2 Patching Diagram

3.8 Practical 3.3 - Series Connection

	Product Version 230 V	Product Version 120 V
On the Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0%. 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 and I2 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. Make all connections as shown in Figure 3-3-4.		
Set the switches on the Resistance Load 67-142 to give a resistance of… and check that the load switch on the Single Phase Transformer Unit is switched off.	*640 Ω R1, R2 on, all others off*	*196 Ω R1, R3 on, all others off*
Switch on the power supply, set the primary voltage V1 to …………….. using the *'variable output voltage'* control (read on virtual or conventional instrumentation).	*230 V*	*125 V*
Switch on the load switch on the Single Phase Transformer Unit and re-adjust the primary voltage to read………………………………………..	*230 V*	*125 V*

Record the corresponding values of primary current, secondary voltage and secondary current in a copy of Practical 3.3 Results Table for the appropriated product version (230 V or 120 V).

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



Note:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

Figure 3-3-4: Practical 3.3 Patching Diagram

3.9 Exercise 3.1

From the information recorded in Practical 3.3 and 3.4 Results Tables for product versions (230 V or 120 V), calculate the power output of the transformer when the secondaries are connected:

a) in parallel

b) in series

In this case,

Power Output = Secondary Voltage (V2) x Secondary Current (I2)

3.10 Questions

Question 3.1 *Referring to the parallel connection test, we could disconnect one of the secondary windings and still supply power to the two banks of load resistors. The voltage and current would be only a little less than those obtained with both windings connected. What would be wrong with doing this?*

3.11 Practical Aspects

In a transformer supplying industrial loads, e.g. motors, heaters etc; two or more secondaries may be connected in series or in parallel to provide a range of voltage and current levels.

A test procedure similar to that given in this assignment is necessary to ensure correct polarity and to check the final voltage and current on load so that the transformer output rating is not exceeded.

3.12 Practical 3.2 - Results Tables (230 V Product Version)

Primary Voltage (V)	Primary Current (A)	Secondary Voltage (V)	Secondary Current (A)	Load (Ω)
230				182

3.13 Practical 3.3 - Results Tables (230 V Product Version)

Primary Voltage (V)	Primary Current (A)	Secondary Voltage (V)	Secondary Current (A)	Load (Ω)
230				640

3.14 Practical 3.2 - Results Tables (120 V Product Version)

Primary Voltage (V)	Primary Current (A)	Secondary Voltage (V)	Secondary Current (A)	Load (Ω)
125				46.7

3.15 Practical 3.3 - Results Tables (120 V Product Version)

Primary Voltage (V)	Primary Current (A)	Secondary Voltage (V)	Secondary Current (A)	Load (Ω)
125				196

4 The Magnetic Circuit

4.1 Assignment Information

4.1.1 Objectives

When you have completed this assignment you will understand:

- the effect of magnetic flux on the circuit.

4.1.2 Knowledge Level

Before you start this assignment:

- you should have some knowledge of transformer construction as covered in Appendix A General Information.
- 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. Primary Current and Voltage Transformer on No-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.

4.2 Theory

4.2.1 Introduction

In earlier assignments, we have looked mainly at the voltage relationship between the primary and secondary windings of the transformer and only briefly at the magnetic path taken by the flux which links those windings. In this assignment, we shall study the magnetic circuit in more detail.

A simple transformer with two coils wound on a common magnetic core is shown in Figure 3-4-1. If we connect the primary coil to an electrical supply, the flow of current through its windings will set up a magnetic field which produces a flux in the core.

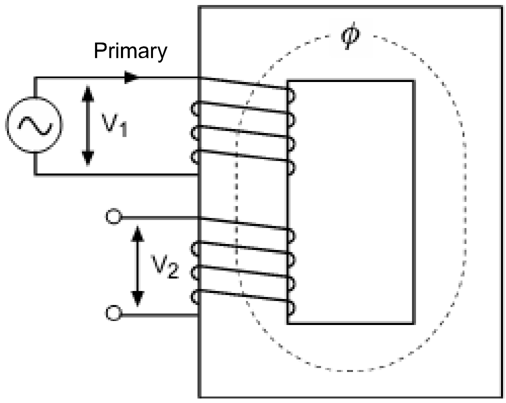


Figure 3-4-1

There is an important law of electromagnetism which states 'whenever the flux through a circuit changes, an EMF is induced in that circuit'. If the primary winding of this simple transformer is connected to an alternating current source, the flux through the magnetic core will alternate at the same frequency as the source. This will cause voltages to be induced in both the primary and secondary windings. In the primary winding, this voltage is called the back EMF. It opposes the supply voltage and reduces the current flowing in the primary.

The voltage induced in the secondary has the same frequency as the supply voltage and its value will depend on the turns ratio of the primary and secondary windings, assuming that all the flux which links the primary will also link the secondary. In practice, there is always some flux leakage, and this will be considered more fully in a later assignment.

The action of the transformer is, therefore, seen to depend on the magnetic flux which links the two windings. The strength of this flux will itself depend on four main factors which are taken into account when deriving the magnetic circuit:

- the value of current flowing in the primary
- the number of turns in the primary
- the dimensions of the magnetic core
- the materials which form the magnetic core

4.2.2 The Magnetic Circuit

The path taken by the flux in an electrical machine is called the magnetic circuit. Transformers, motors and generators, solenoids and relays all obey similar rules and are made up from similar magnetic materials. By understanding the principles of the magnetic circuit of a transformer, we can extend our knowledge of other electrical machines.

Definitions of the terms used in this section are set out in Appendix C.

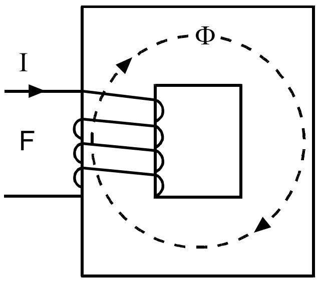
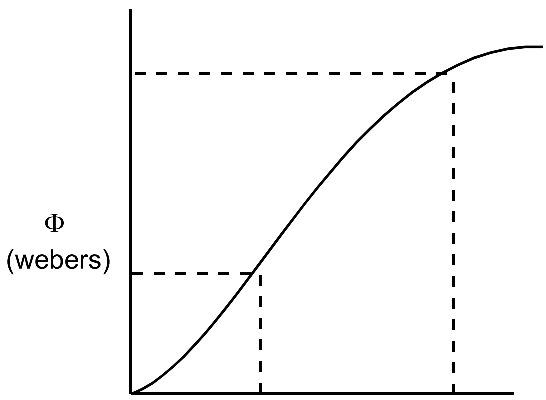


Figure 3–4–2

In the magnetic circuit shown in Figure 3–4–2, a coil is wound around one section of a magnetic core. When there is current I flowing in the coil, it will produce a magnetic field and this will cause a flux Φ to be set up in the magnetic material which forms the core.

We say that current flowing through the turns of the coil produces a magnetomotive force (MMF, expressed in ampere-turns) and that the field strength due to this is H (ampere-turns per metre of the flux path length). The relationship between flux Φ (expressed in weber) and MMF is similar to that between current and voltage in an electrical circuit with resistive elements. However, there is one basic difference; in the electrical circuit, the graph of current against voltage is a straight line through the origin, whereas in a magnetic circuit, the graph of flux against MMF is not linear (see Figure 3–4–3).



F (ampere turns)

reluctance = $^{F}/_{\Phi}$ (not constant)

Figure 3–4–3

4.2.3 Magnetic Reluctance

Magnetic reluctance is the resistance of a material to a magnetic field. It is defined as the ratio of magnetomotive force to magnetic flux.

The definition can be expressed as:

$$R_m = \frac{MMF}{\Phi}$$

where R_m is the reluctance of the magnetic circuit expressed as ampere-turns per weber. This is analogous to Ohm's Law with resistance replaced by reluctance, voltage by MMF and current by magnetic flux.

Although reluctance corresponds approximately to resistance in the electrical circuit, the ratio MMF:Φ is not a constant; the reluctance in the magnetic circuit decreases as the flux in the core approaches saturation.

Question 4.1 *We are told that the primary coil of the transformer shown in Figure 3-4-1 has 270 turns and requires a magnetizing current of 0.2 A to produce a flux in the core of 1.3 milliweber. What is the reluctance of the magnetic path at that flux level?*

4.2.4 Transformer with no Secondary Load

When an ac voltage is applied to the primary of a transformer and there is no load on the secondary, the current which flows is limited by the impedance of the primary. There is a small voltage drop due to the resistance of the winding and a much larger drop due to the induced voltage in the primary.

The induced voltage is caused by the changing flux in the core and always opposes the applied voltage. This is a direct application of Lenz's Law, 'induced voltages act in such a direction as to oppose the action by which they are due'. Here the applied alternating voltage causes current to flow in the primary coil which produces an alternating flux in the core. The voltage induced in the primary will be proportional to the rate of change of flux in the core. Therefore, sufficient current must flow in the primary to produce the required value of flux.

4.2.5 Phase Relationship between Core Flux and Induced Voltage

We can show that the rate of change of any sine wave can be represented by another sinusoidal curve, but displaced by 90°.

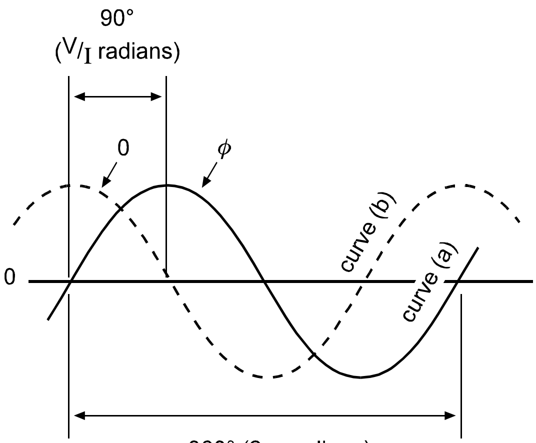


Figure 3–4–4

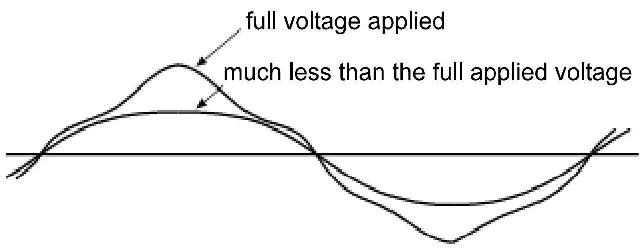
In the full-line sine curve of Figure 3-4-4 (a), the rate of change or slope is a maximum where the curve crosses the zero axis and is a minimum at the crests of the sine wave. The broken line curve, Figure 3-4-4 (b), represents the rate of change of the sine curve and is itself sinusoidal (it is a cosine curve) and leads by $\pi/2$ radians or 90°.

If curve (a) represents flux Φ in the core and curve (b) the induced voltage EMF in either the primary or secondary due to the rate of change of flux, we can see that the flux will lag the voltage by 90°. The magnetizing current is in phase with the flux which it produces and also lags the induced voltage by 90°.

4.2.6 Magnetizing Current Waveform

We have seen in Figure 3-4-3 that the curve of flux Φ against magnetomotive force (MMF) is not linear. In this curve, if the flux is progressively increased then the magnetomotive force required to produce that flux will increase in greater proportion. From this we can see that as the voltage applied to the primary is increased, the core flux will have to increase by the same amount to maintain equality between the induced voltage and the applied voltage. This will require a proportionately greater increase in magnetomotive force and hence in the current flowing in the primary, particularly as the core approaches saturation.

The applied alternating voltage has a sinusoidal waveform and the flux in the core will also be sinusoidal, but the current producing that flux will have a waveform which will depend on how near the core is to saturation (see Figure 3-4-5).



primary current waveform - transformer on no-load

Figure 3–4–5

4.3 Content

The principal terms used in the study of the magnetic circuit of a transformer are introduced to the student.

4.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter	68-117
Auxiliary Equipment	• Differential Voltage Probe	68-151
	• Oscilloscope, two channel 20 MHz	

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® 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 - Primary Current and Voltage Transformer on No-Load

In the test which follows, the current taken by the primary will be measured, with the secondary on no-load, for increasing values of applied voltage. Using an oscilloscope and voltage isolation we can look at the shape of the current waveform and note how it develops a peak in each half cycle as the applied voltage is increased.

Make all connections shown in Figure 3-4-6.

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 200 mA to be monitored when the 200 mA socket is connected.

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.

Leave the oscilloscope switched off.

Instruction	Product Version: 230 V	Product Version: 120 V
On the Universal Power Supply 60-105 , set the *'3 phase circuit breaker'* to the on position and then increase the voltage from 0 V to a maximum of If the 240 V or 125 V setting cannot be attained then record the maximum voltage available and the primary current value.	*240 V in steps of 50 V*	*125 V in steps of 25 V*

At each voltage step, record the primary current in a copy of Practical 4.1 Results Table for the appropriate product version (230 V or 120 V).

Reduce the voltage supplied from the power supply to zero and switch on the oscilloscope.

If conventional instrumentation is being used, switch on the differential probe and ensure that the attenuation ratio is set to 1:20. The Y_1 input to the oscilloscope is measured, via the differential probe, across a 2 ohm resistor connected in series with the primary winding; the voltage drop across the resistor is directly proportional to the primary current.

Set the time base to 5 ms/div

Set the Y amplifier to 10 mV/div.

Increase the voltage using the power supply dial from zero up to a maximum of the available supply but no more than…………………………... and observe the change in current waveform as the voltage is increased.	*300 V*	*160 V*

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

Q 4.2 *Why does the current waveform develop peaks as the voltage is increased?*

4.6.1 Exercise 4.1

Plot the results from Practical 4.1 Results Table for the appropriate version (230 V or 120 V). The resulting curve should have a similar shape to the Φ/MMF curve in Figure 3-4-3. The suggested graph axes are given with the Results Table.

4.7 Practical Aspects

Working flux level

One of the most important points in the design of a transformer is to fix the working flux level since the current taken from the supply on load and off load depends upon this. If the working flux is too high and the core becomes saturated, the input current will be high and the transformer will overheat. If the working flux is low, the transformer will be larger and more costly than it need be.

The designer makes a compromise, usually fixing the working flux at a point just beyond the linear part of the Φ/MMF curve.

When a transformer has to cover a wide range of applied voltages, tappings are provided on the primary winding so that saturation of the core is avoided.

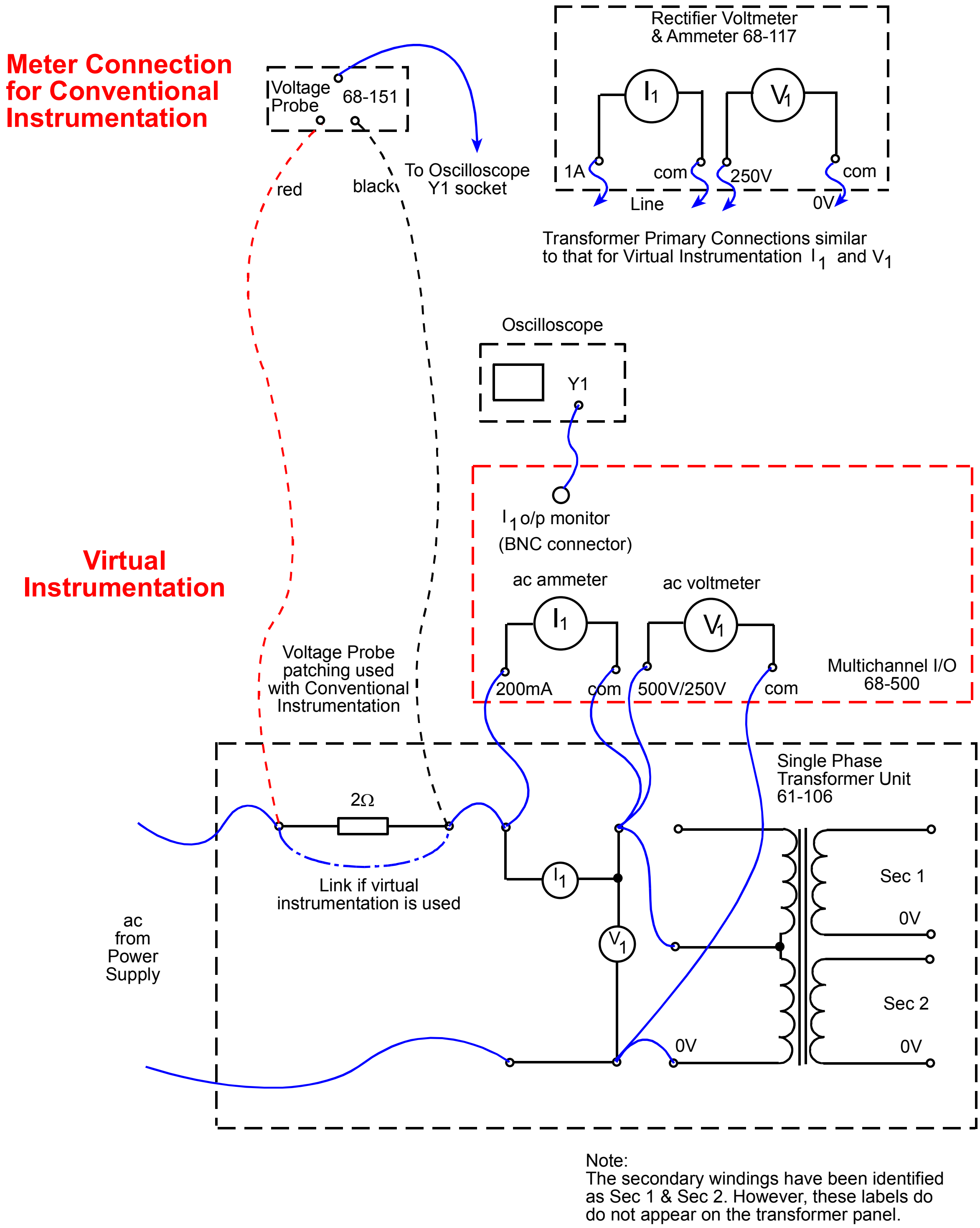
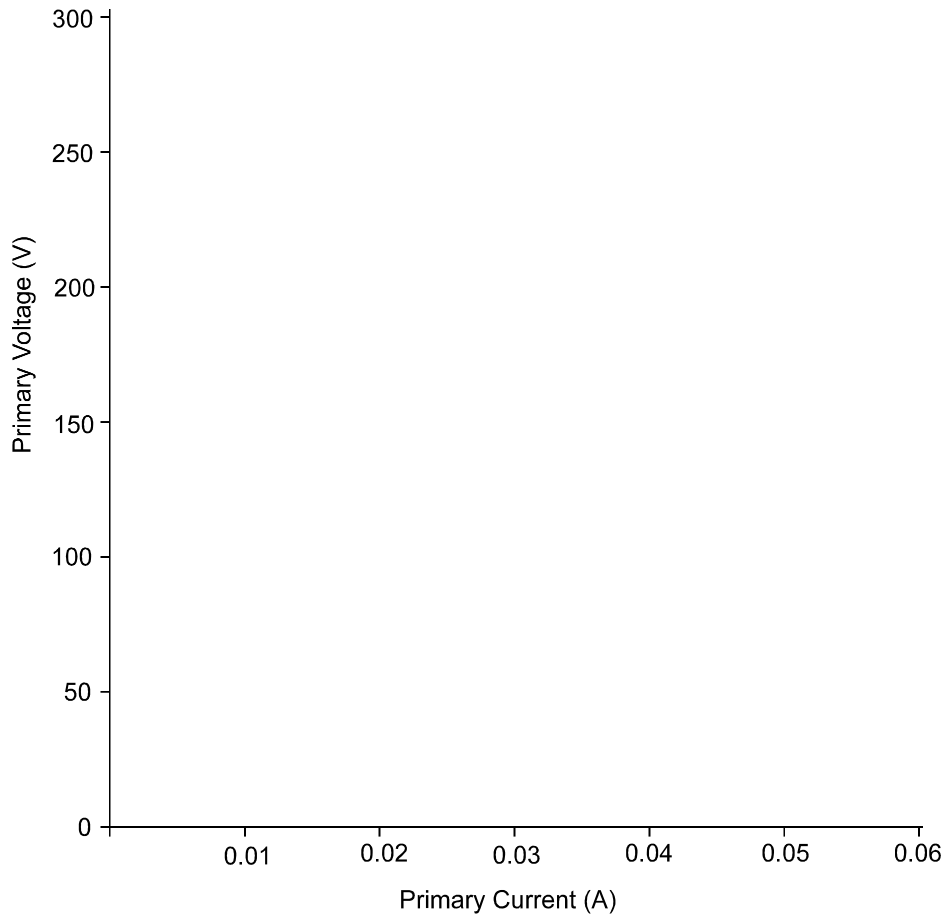


Figure 3-4-6: Practical 4.1 Circuit Diagram

Notes

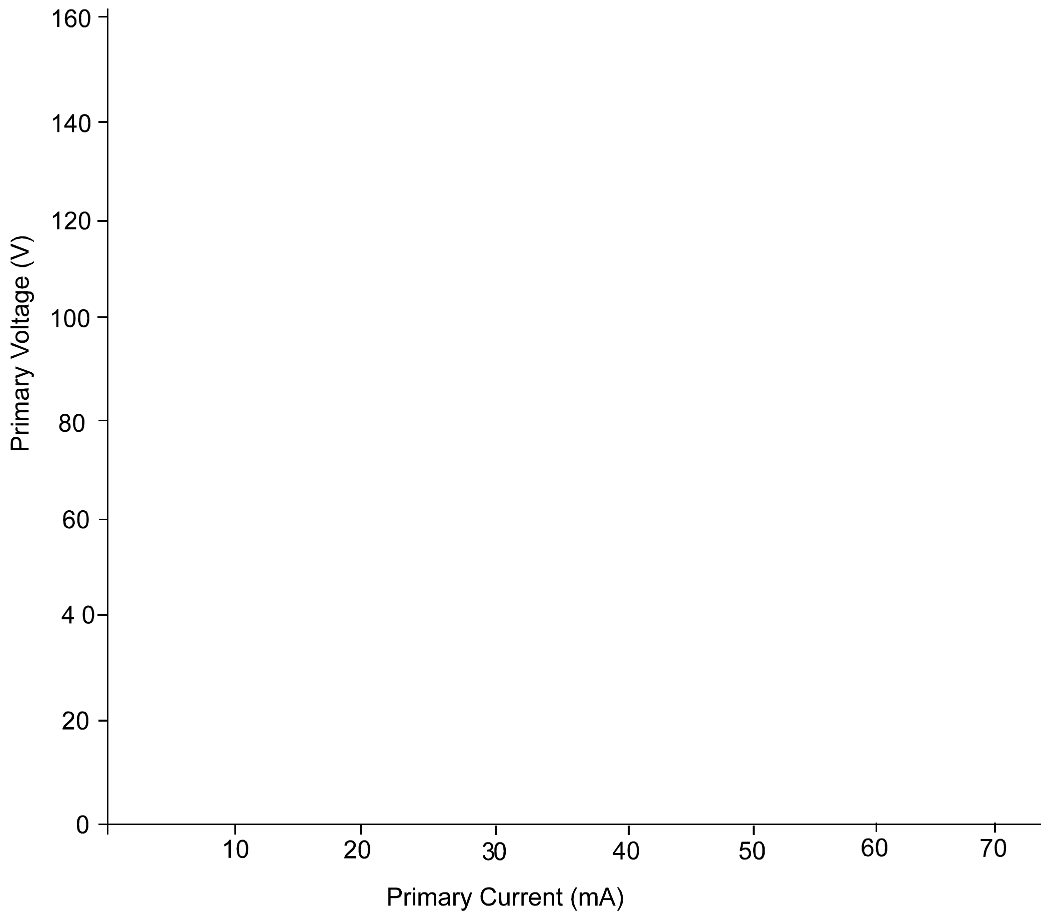
4.8 Practical 4.1 - Results Tables and Graphs (230 V Product Version)

Primary Voltage (V)	0	50	100	150	200	240
Primary Current (A)						



4.9 Practical 4.1 - Results Tables and Graphs (120 V Product Version)

Primary Voltage (V)	0	25	50	75	100	125	150	160
Primary Current (A)								



5 Phasor Diagram on No-Load

5.1 Assignment Information

5.1.1 Objectives

When you have completed this assignment you will know:

- the phase relationship between terminal voltage, current, and flux in a transformer under no-load conditions.
- how to draw the phasor diagram of a transformer under no-load conditions.

5.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information,
- you should have completed or read Assignment 4, The Magnetic Circuit,
- 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

1. Phase Relationship of Primary and Secondary Voltages
2. Phase Relationship of Primary Current and Secondary Voltage

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 all alternating current electrical machines, knowledge of the phase relationship between the voltage, current and magnetic flux waveforms is essential to the designer and of considerable assistance to the users in furthering their understanding of the machine. Fortunately, in power transformers we are mainly concerned with sinusoidal waveforms. These are more easily analysed and measured than the complex waveforms encountered in, for example, a pulse transformer.

It is often useful to draw the required waveforms in full, showing amplitude and phase for one or more cycles, but where a number of sine waves is involved, it is more convenient to use a phasor diagram. The phasor diagram is one method by which we can show the relationship between alternating currents or voltages in an electrical circuit. It is necessary to show their amplitudes and how they lead or lag one another in time. By constructing a phasor diagram, the accuracy of a calculation can be checked or the circuit to which it applies may be more easily understood.

5.2.2 Phasor Diagrams

A rod, pivoted at one end and rotating at uniform velocity will have a vertical projection which increases to a maximum twice in each revolution (see Figure 3-5-1).

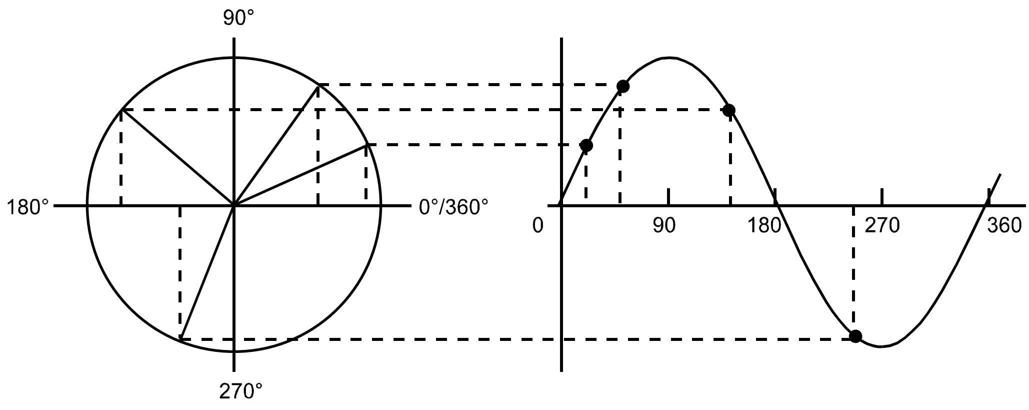


Figure 3-5-1

If the length of these projections is measured at intervals throughout one revolution and the measured values plotted against angular position, a sine curve will be obtained, as in Figure 3-5-1(b), whose amplitude corresponds to the length of the rod.

Therefore, any sine wave can be represented by a line which is assumed to rotate at a constant angular velocity determined by frequency. Two or more sine waves, which may correspond to voltage, current or flux can be represented by radial lines, or phasors, whose lengths are proportional to amplitude and whose angular positions correspond to phase angle.

Figure 3-5-2(a) shows a phasor diagram for the voltage across a pure inductance and the current flowing through it. In this case, the current lags the voltage by 90° in phase.

The phasor diagram provides useful information in a concise form which can often be an aid to understanding the behaviour of an electrical circuit. In some circuits, it is necessary to obtain the resultant of two sinusoidal quantities; this can be readily carried out by means of a phasor diagram. Figure 3-5-2(b) shows the phasor addition of two ac voltages.

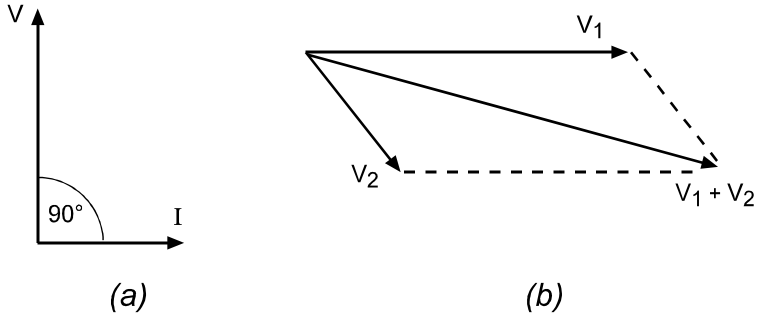


Figure 3-5-2

5.2.3 Phasor Diagram for Transformer on No-Load

Most of the information needed to construct the phasor diagram has now been obtained. The flux in the core has not been measured, since this would require special instruments, but we can say that it has a sinusoidal waveform and is in phase with the primary current.

Using this information, the phasor diagram can be drawn as shown in Figure 3-5-3(b). The current waveform is not sinusoidal due to the onset of core saturation at the applied voltage peaks. It is therefore not strictly correct to include this in a simple phasor diagram but for the present purpose the primary current can be treated as a sine wave.

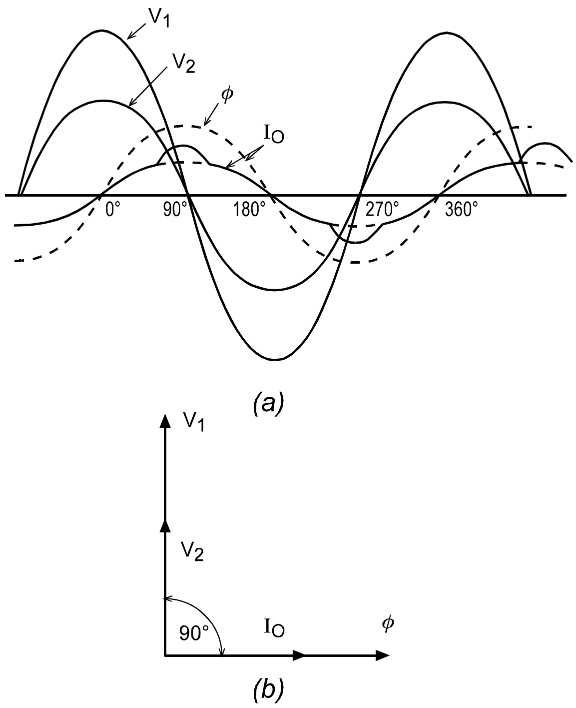


Figure 3-5-3

An oscilloscope will first be used to examine the waveform and phase relationship between:

- the primary terminal voltage V_1,
- the secondary terminal voltage V_2,
- the primary current I_1.

and from observation the phasor diagram can be drawn.

For this test, an oscilloscope will be used to check the phase relationship between the primary and secondary terminal voltages, with the start and finish of each winding connected to give the same polarity. The phase relationship between the secondary voltage and primary current will then be checked and, at the same time, the waveform of the primary current can be observed. Figure 3-5-4 shows the circuit diagram used for this test. The secondary voltage is used as a reference in both tests to avoid connection difficulties where the Y_1 and Y_2 inputs on the oscilloscope have the same common terminal.

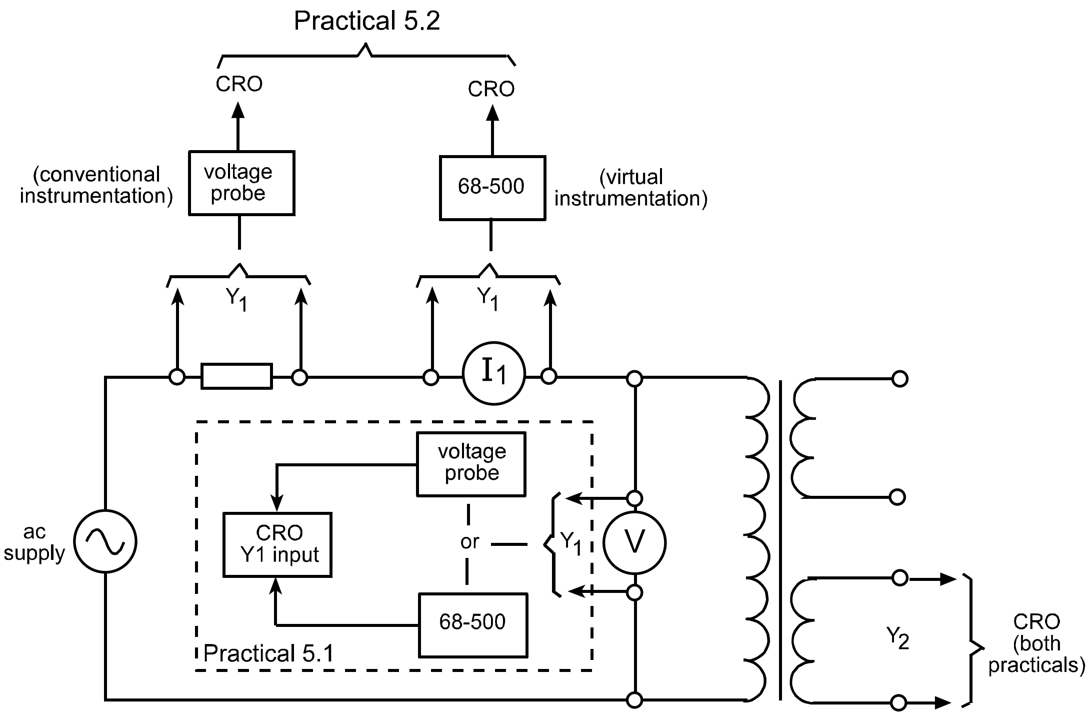


Figure 3-5-4

5.3 Content

The phase relationships between terminal voltage, current and flux in a transformer are examined under no-load conditions.

5.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit • Software Pack CD	68-500 68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter	68-117
Auxiliary Equipment	• Differential Voltage Probe • Oscilloscope	68-151

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® 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).*

5.6 Practical 5.1 - Phase Relationship of Primary and Secondary Voltage

Instruction	Product Version	
	230 V	**120 V**
Make all connections shown in Figure 3-5-5. 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. 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 primary voltage to ……………………………………………………….. by use of the *'variable output voltage'* control (as read by virtual or conventional instrumentation meter V1).	*230 V*	*125 V*

Switch on the oscilloscope and set the timebase to 5 ms/div, and the Y1 and Y2 amplifier to 2 V/div.

If conventional instrumentation is used, switch on the Differential Probe and set the 'Attenuation Ratio' to 1/200 and the oscilloscope Y1 input to 1 V/div. Secondary 2 (Y2) is measured using an oscilloscope probe set to X10 and the oscilloscope Y2 input set to 10 V/div.

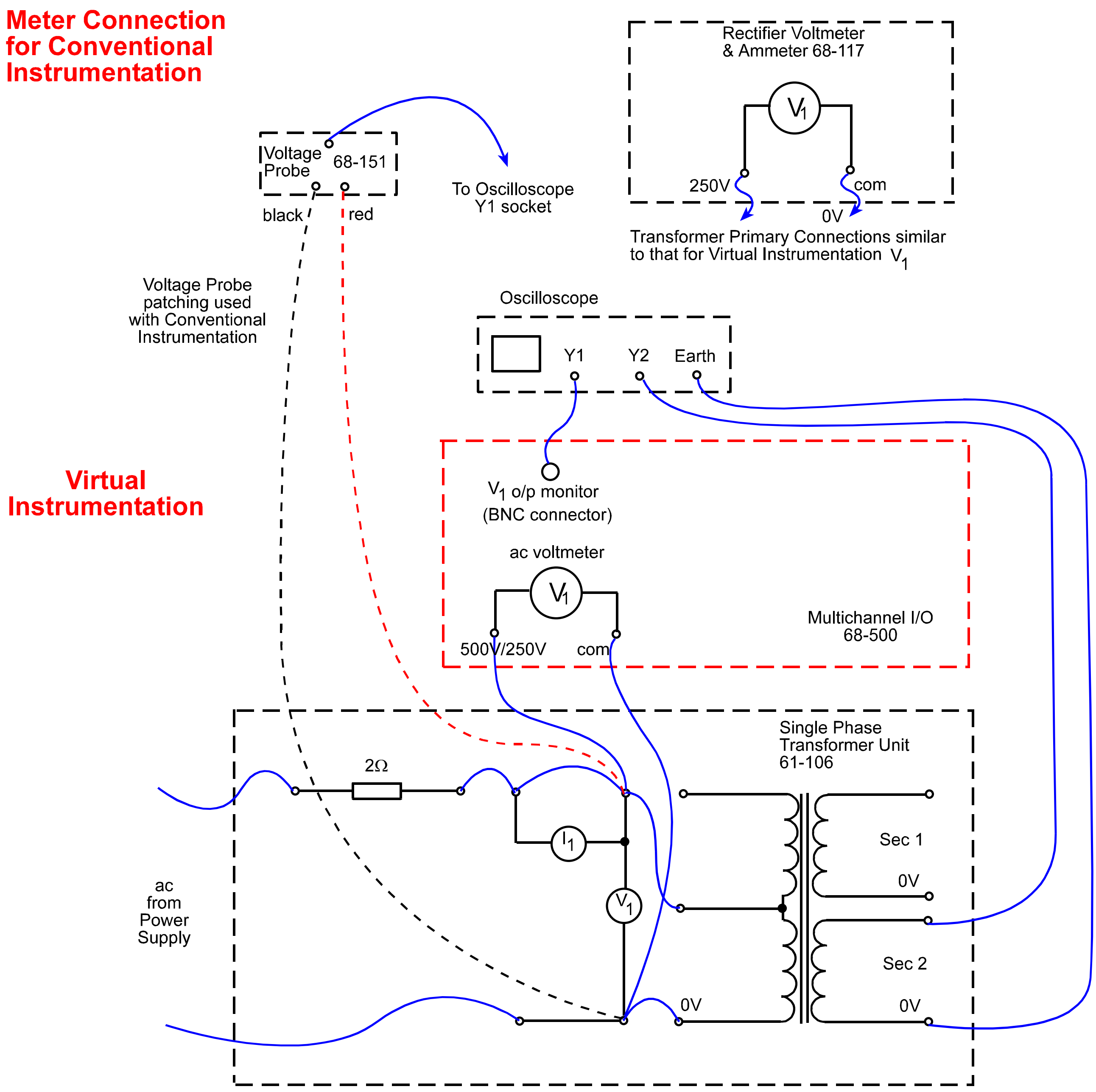
Observe that the primary and secondary voltages are sine waves and that they are not in phase with one another. Draw a diagram of the two waveforms from the oscilloscope traces. Note on your sketches the peak value of the voltages; this is calculated by multiplying the peak value noted on the oscilloscope by a factor of 200 when using the Differential Probe.

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

5.6.1 Questions

Question 5.1 — *Do you remember and can you explain the phase relationship between the voltage applied to the primary winding and the current in it?*

Question 5.2 — *Can you predict the phase of the secondary voltage relative to the primary current?*



Note:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

Figure 3-5-5: Practical 5.1 Circuit Diagram

5.7 Practical 5.2 - Phase Relationship of Primary Current and Secondary Voltage

Change the oscilloscope connections to monitor the secondary voltage and primary current as shown in Figure 3-5-6.

If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 to '250 V' on 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 I1 to '1 A'. This allows currents 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. The primary current (Y1 input) to the oscilloscope is measured, via the differential probe, across a 2 ohm resistor connected in series with the primary winding; the voltage drop across the resistor is directly proportional to the primary current. Set the oscilloscope Y1 input to 10 mV/div and the Y2 input to 10 V/div. An oscilloscope probe must be used with Y2, set this to the X10 position.

	Product Version: 230 V	Product Version: 120 V
On the Universal Power Supply 60-105, set the *'3 phase circuit breaker'* to the on position and, if necessary, re-adjust the voltage to ………………	*230 V*	*125 V*
Observe that the primary current waveform is not sinusoidal if the voltage is increased above ………………………………………………………….. and that it lags the secondary voltage by approximately 90°.	*230 V*	*125 V*

The word 'phase' has exact meaning only in relation to a true sine wave, but it will suffice for the moment to talk of the phase of the current while ignoring its peaky wave shape.

Sketch the current waveform with respect to the secondary voltage waveform and record its peak value.

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

5.7.1 Exercise 5.1

Using a copy of Figure 3-5-7, draw the waveforms which were displayed on the oscilloscope, similar to those shown in Figure 3-5-3(a).

Construct the phasor diagram, firstly as shown in Figure 3-5-3(b) and then redraw, this time assuming the polarity of the secondary winding has been reversed.

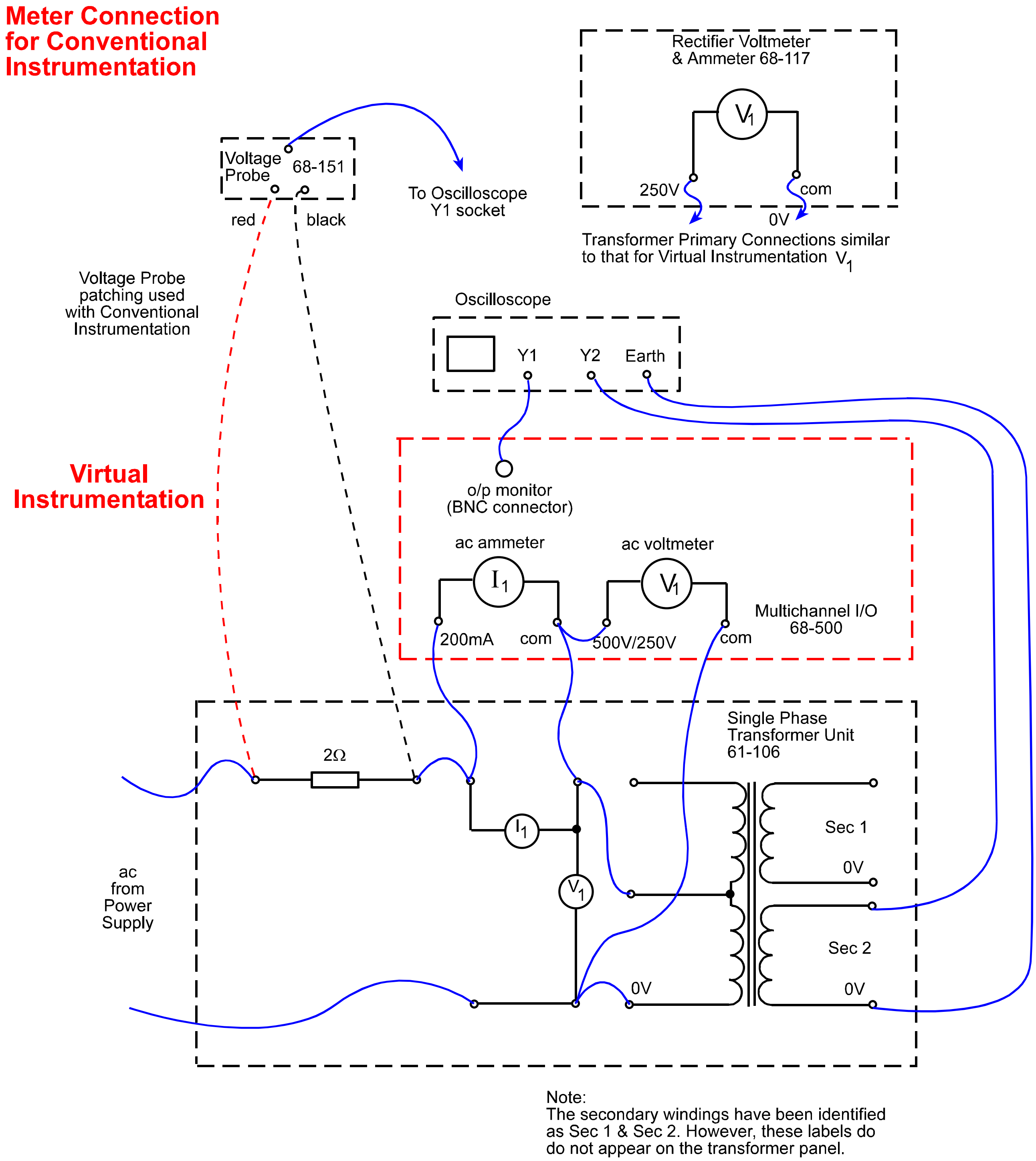


Figure 3-5-6: Practical 5.2 Circuit Diagram

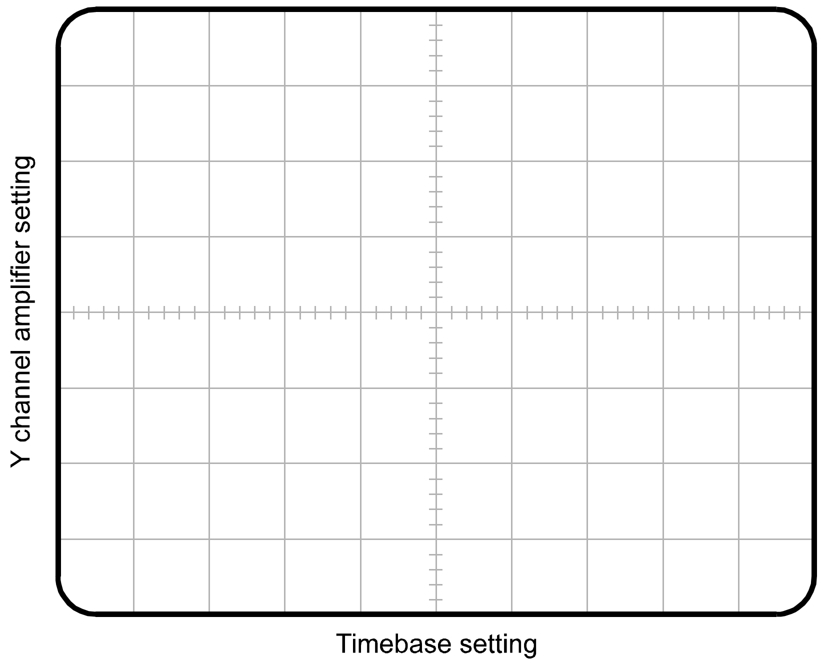
5.8 Practical Aspects

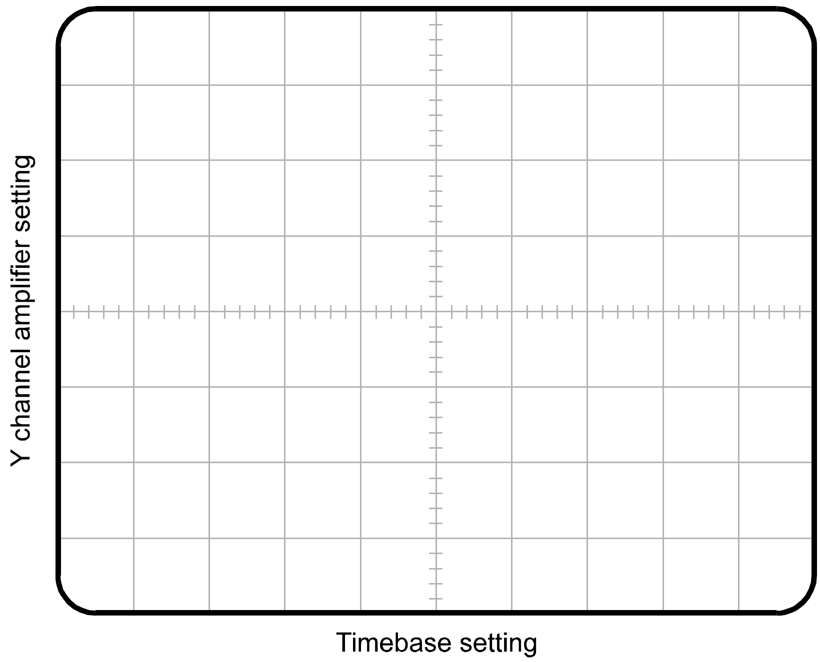
We have seen that the phasor diagram enables us to show in a concise way several important points relating to a transformer:

- The secondary voltage on no-load is in phase with the primary voltage.
- The amplitude of each secondary voltage is approximately half that of the primary voltage for the transformer tested.
- The primary current on no-load lags the primary voltage by about 90° (this shows that on no-load the transformer behaves as an inductor with low series resistance).

At this stage, the phasor diagram is not complicated and can easily be extended to show, for example the relationship between the components of primary current and primary voltage when the transformer is supplying power to an external load. This is dealt with in Assignment 7.

5.9 Exercise 5.1 Graphical Results (230 V version)





Exercise 5.1 (230V version)

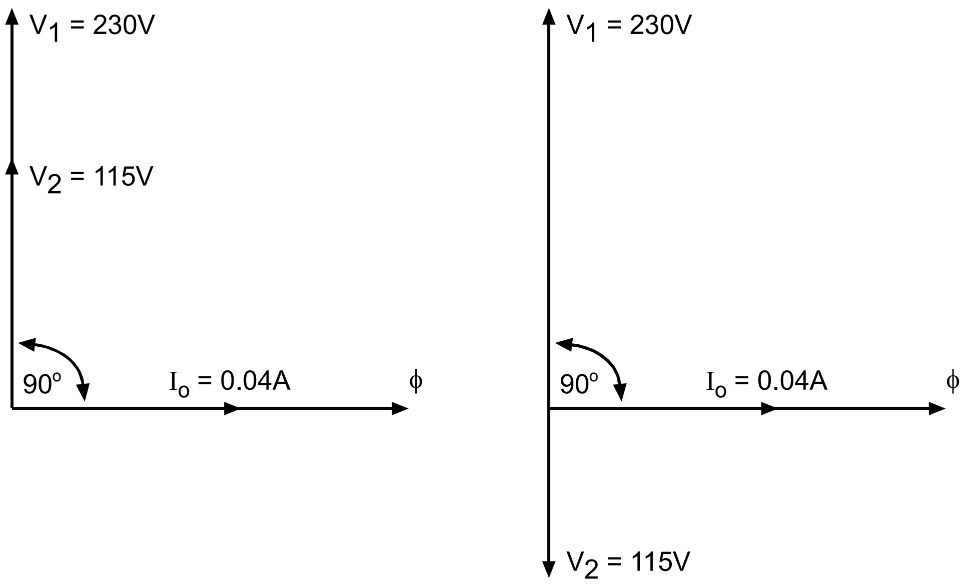


Figure 3-5-9

Exercise 5.1 (120V version)

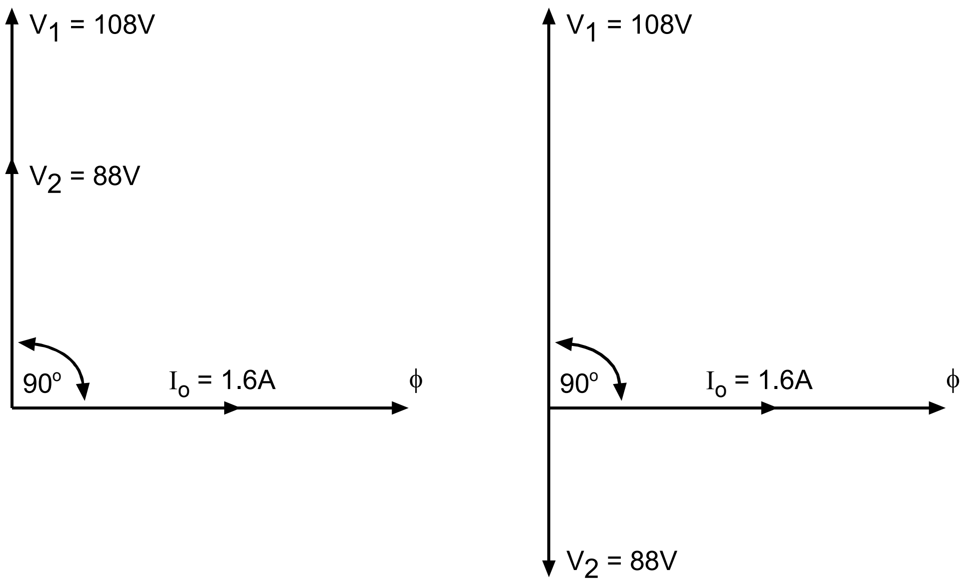


Figure 3-5-10

6 No-Load Losses

6.1 Assignment Information

6.1.1 Objectives

When you have completed this assignment you will understand:

- the effect of supply voltage on core loss.

6.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have read or completed Assignment 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. Core-loss Loop

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.

6.2 Theory

6.2.1 Introduction

In the work carried out so far, it has been seen how a transformer produces a voltage at its secondary terminals which is dependent on the turns ratio and how the current taken from the supply is affected by the magnetic properties of the core. We have not previously taken into account the power dissipated in the transformer itself.

All machines, electrical or mechanical, are less than 100% efficient; they take more power from the source than they give out to their load. The difference is a power loss which is dissipated as heat or noise by the machine.

There are two ways in which power is lost in the transformer; copper loss due to current flow in the windings and iron or core loss due to the alternating flux in the core. These losses cause the temperature of the windings and core to rise so that power is dissipated by thermal radiation and convection. Copper loss varies with load current and core loss with applied voltage. As the electrical supply voltage is usually fixed, the core loss is almost independent of load.

In later assignments, we shall measure the iron and copper losses separately. In this assignment, we will make a preliminary study of the cause of power loss in the transformer core and display the total no-load loss curve of a transformer on an oscilloscope.

6.2.2 No-Load Current

When a transformer is connected to an ac supply with no-load applied to its secondary, the current in the primary will have two components.

The magnetizing current.

This produces the magnetomotive force (MMF) which sets up the working flux in the transformer core. This current, as we have seen in Assignment 5, lags the primary voltage by almost 90°. When an alternating voltage and current in the same circuit are 90° out of phase (in quadrature), there is no real power consumed, only apparent power (volts-amperes).

The core-loss current

This is in phase with the applied voltage and causes power to be lost, which is dissipated as heat in the core. This power loss is due to the behaviour of a ferromagnetic material when carrying an alternating flux. In this assignment, we will look at the two principal effects hysteresis and eddy current losses.

6.2.3 Hysteresis Loss

If a coil linking a ferromagnetic core is supplied from a dc source and the current through it is progressively increased to a given maximum, the field strength H will increase proportionately. The curve relating flux density B and field strength H will be nearly linear until the core approaches saturation, as shown by the dotted line in Figure 3-6-1.

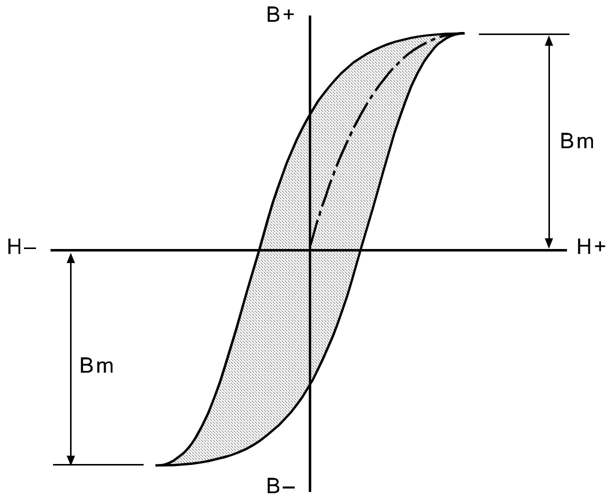


Figure 3-6-1

If the current through the coil is now reduced through zero to the given maximum in the reverse direction, the resulting B/H curve will not follow the original curve but that shown as a full line in Figure 3-6-1. Again, taking the current through zero to its maximum in the forward direction causes B to complete its cycle. Repeating the cycle of current reversals will cause the same B/H loop to be retraced. This is known as the hysteresis loop; different types of magnetic material will have different forms of hysteresis loop.

The hysteresis loop provides useful information on one of the principal sources of power loss in the core. When the core is carrying an alternating flux, as is the case in most transformers and many other electrical machines, there will be a power loss proportional to the area enclosed by the hysteresis loop and the number of times per second that the loop is traced out. In a transformer, the loop will be completed once per cycle of the ac supply voltage.

The area enclosed by the hysteresis loop can be expressed in terms of a power of B_m, leading to the empirical formula:

$$P_h = K_h f B_m^{1.6}$$

where P_h is the hysteresis loss per unit volume of core:

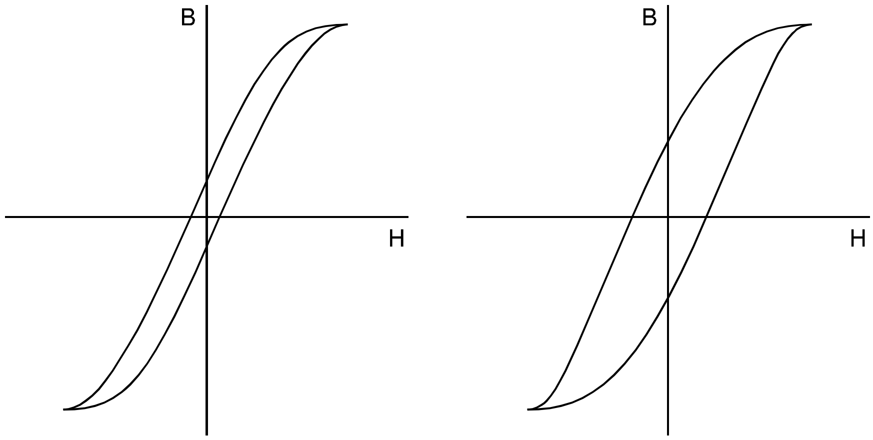
K_h is a constant for a given core material,

f is the frequency of the supply,

B_m is the maximum flux density.

The area enclosed by the hysteresis loop is dependent on how far the core is taken into saturation in each cycle and on the properties of the ferromagnetic material which forms the core.

A power transformer will be designed to have a working flux which will approach but not reach saturation when the flux density is at its maximum value so reducing the width of the hysteresis loop. Also, the laminations which form the core will be chosen from a range of steels which have an inherently low hysteresis loss. Steel alloys with up to 3% silicon content are frequently used since they have a narrow hysteresis loop as compared, for instance, with mild steel. The hysteresis curves for silicon steel and mild steel are shown in Figure 3-6-2.



(a) Silicon steel (b) Mild steel

Figure 3-6-2

6.2.4 Eddy Current Loss

We have previously seen that a coil linked by a changing flux will have a voltage induced in it. The steel which makes up the core of the transformer is itself a conductor and, when carrying an alternating flux, will act as a single-turn coil closed upon itself. As a result, circulating currents will flow in the core material (see Figure 3-6-3(a)). These are known as eddy currents and if the magnetic core were to be made from solid steel, there would be a substantial power loss and temperature rise due to this effect. To reduce eddy current loss, the core of a power transformer is built up from laminated steel punchings insulated from one another and held together as a stack of rivets, bolts or by resin impregnation.

Eddy current flow in a laminated core will be reduced by the substantial increase in resistance of each current path, Figure 3-6-3(b). For an operating frequency of 50 or 60 Hz, a lamination thickness of 0.3 mm will normally be used, and for a frequency of 400 Hz, the lamination thickness will be around 0.1 mm.

Eddy current loss per unit volume is given by the formula:

$$P_e = K_e \; f^2 \, B_m{}^2$$

where K_e is a constant, proportional to the square of lamination thickness and inversely proportional to resistivity.

f is the supply frequency,

B_m is the maximum flux density

A further advantage in the use of silicon steel is that the resistivity of this material is greater than that of mild steel. As a result, the magnitude of the eddy currents is reduced and losses are lower.

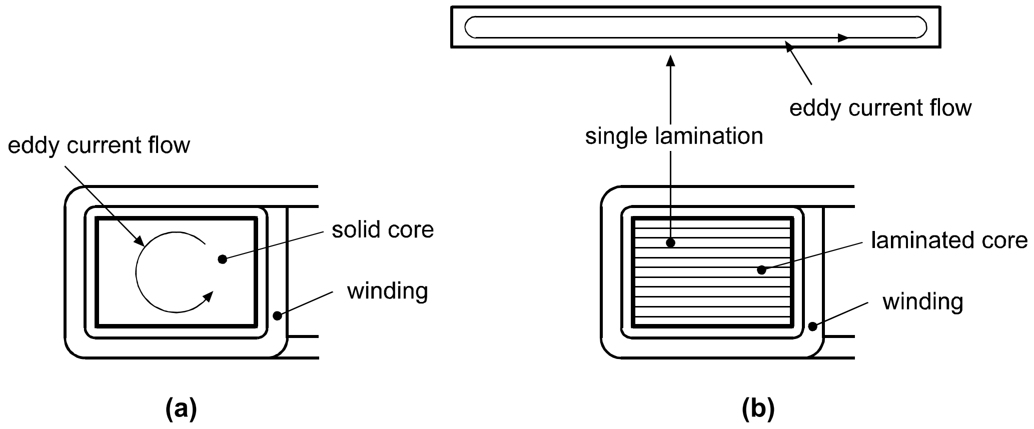


Figure 3-6-3

Question 6.1 *Why are thinner steel laminations used at high supply frequencies?*

6.2.5 Core Loss Loop

An oscilloscope can be used to display the total core-loss loop of the transformer when operating on no-load but with a rated supply voltage applied to its primary windings.

A low value resistor is connected in series with the primary winding and the voltage drop across it, which is directly proportional to primary current, is applied to the X amplifier of the oscilloscope.

The secondary winding is connected to the Y amplifier of the oscilloscope via an RC integrating circuit. The voltage across the secondary winding is proportional to the rate of change of flux in the transformer core and the integral of this voltage therefore represents the flux directly.

By this means, we can display the relationship between flux in the core (integral of secondary voltage - Y axis) and the primary current (mainly magnetizing current - X axis), and from these the loss in the core can be calculated. If the dimensions of the core are known, it is possible to scale the resulting loop in terms of flux density B and field strength H, from which one can calculate the core loss per unit volume, which can then be used as design data for other cores made of the same material. However, loss measurements based on the loss loop are not very accurate, and it is better to measure the losses directly using a wattmeter (as described in Assignment 8).

The shape of the core-loss loop is very dependent on the level of voltage applied to the primary from the ac source. At the higher values of applied voltage, the peak flux density in the core approaches saturation in each half cycle. In the practical which follows, the supply voltage is raised from below to above the rated value and the effect on the core-loss loop can be observed. Figure 3-6-4 shows the circuit diagram used in this practical.

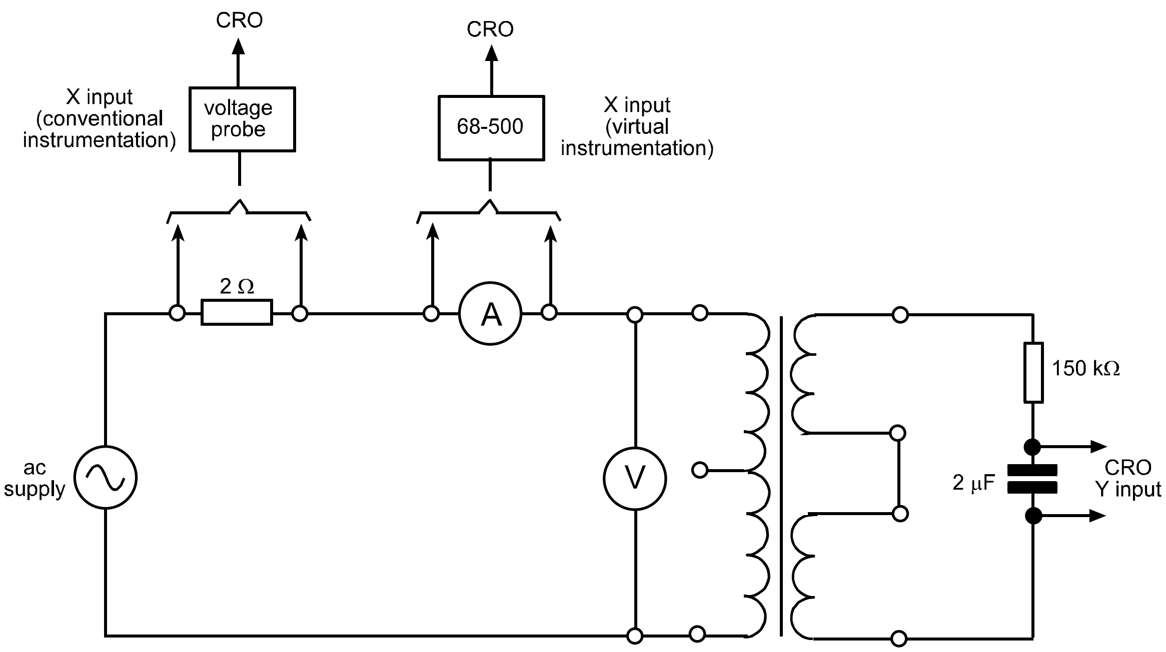


Figure 3-6-4

Question 6.2 *Give one source of error in measuring the no-load losses by the oscilloscope method.*

6.3 Content

The two principal causes of power loss in a transformer, namely core loss and hysteresis loss, are introduced to the student.

6.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter	68-117
Auxiliary Equipment	• Differential Voltage Probe	68-151
	• Oscilloscope	

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.

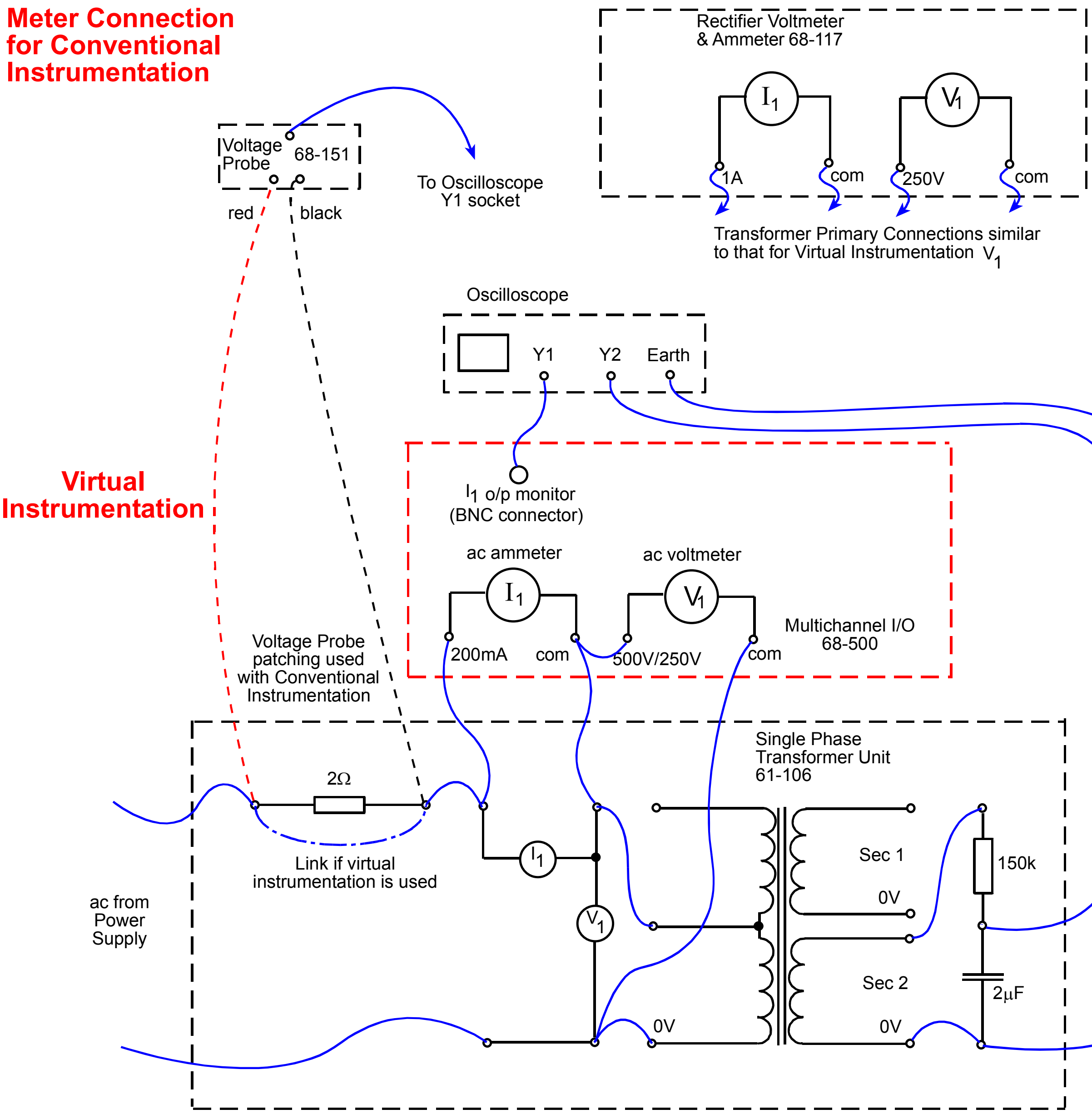
For Virtual Instrumentation, switch on the PC and start the Virtual Instrumentation Software 68-912-USB (see manual 60-070-VIP).

If you have Virtual Instrumentation and access to an Excel® 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 - Core-Loss Loop

	Product Version	
	230 V	**120 V**
Make all connections shown in Figure 3-6-5. 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 to '1 A'. This allows currents up to 200 mA to be monitored when the 200 mA socket is connected and software selected. On the Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0%. If conventional instrumentation is being used, switch on the Differential Probe and set the 'Attenuation Ratio' to 1:20. The Y1 input to the oscilloscope is measured, via the differential probe, across a 2 ohm resistor connected in series with the primary winding; the voltage drop across the resistor is directly proportional to the primary current. Switch on the oscilloscope and set it to the X-Y setting, set both X and Y volts/division to 20 mV/div. Set Y2 input to 'invert', this will be the 'Y' axis on the XY display. On the Universal Power Supply 60-105, set the *'3 phase circuit breaker'* to the on position.		
Set the primary voltage V1 to .... by use of the *'variable output voltage'* control (as read by virtual or conventional instrumentation).	*80 V*	*40 V*
Observe the trace on the oscilloscope. Position the loop about the centre of the screen and make a sketch of it using a copy of Figure 3-6-6 for the appropriate product version (230 V or 120 V).		
Repeat the experiment with the voltage set to	*160 V & 230 V*	*80 V & 125 V*

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



Note:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

Figure 3-6-5: Practical 6.1 Circuit Diagram

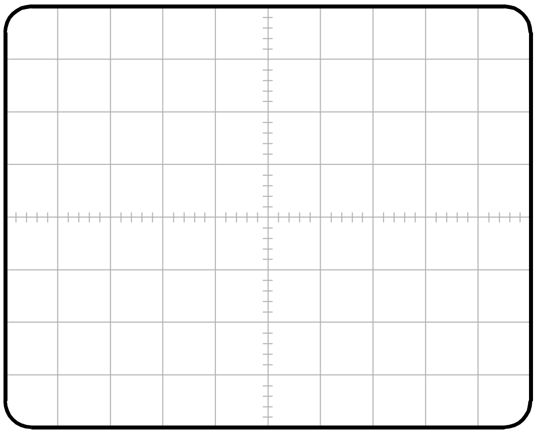
6.7 Practical Aspects

Core loss in a power transformer is usually constant, since most of these operate with a fixed voltage applied to the primary. It is important to reduce the core loss to as low a value as practicable, in order to improve efficiency and reduce the temperature rise associated with any power loss. This is achieved by using a laminated core to reduce eddy current loss and choosing a transformer steel which has low hysteresis loss.

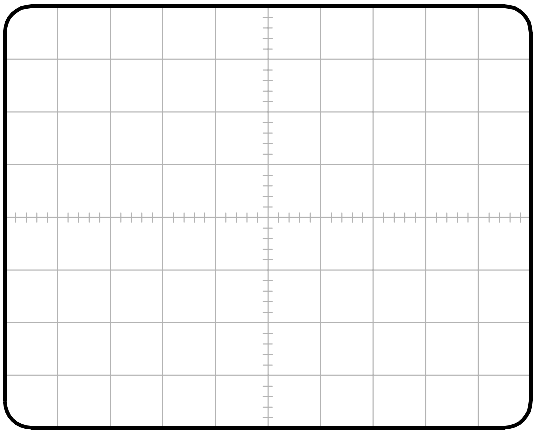
It is also an aim of the designer to reduce the current taken by the transformer when it is supplying no external load; i.e. the current required to set up the working flux in the core. This is partly brought about by minimising the airgaps between laminations.

The core loss as displayed on the oscilloscope, is not suited to the accurate measurement of losses, but does provide a useful means of comparing different core structures and gives some insight into the factors which determine the no-load losses; for example, the effect of introducing an air gap into the magnetic circuit.

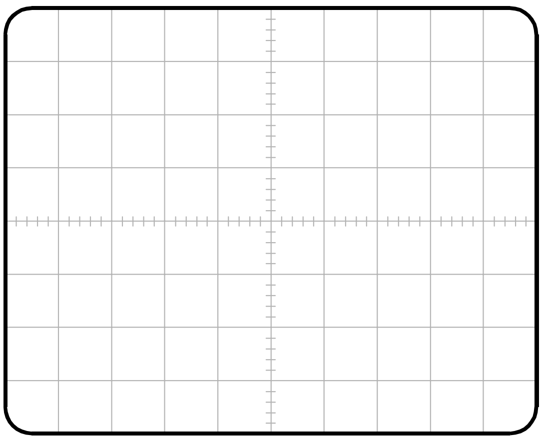
6.8 Exercise 6.1 Graphical Results (230V Product Version)



80V applied voltage



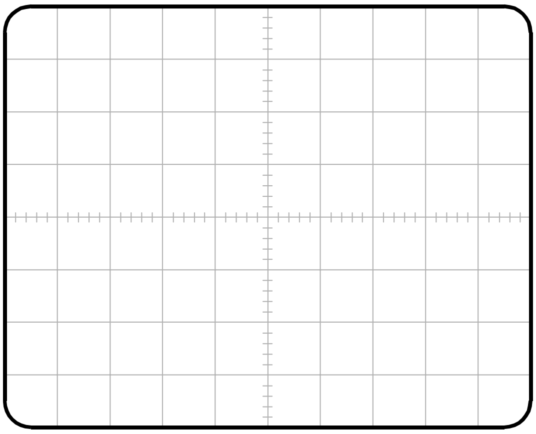
160V applied voltage



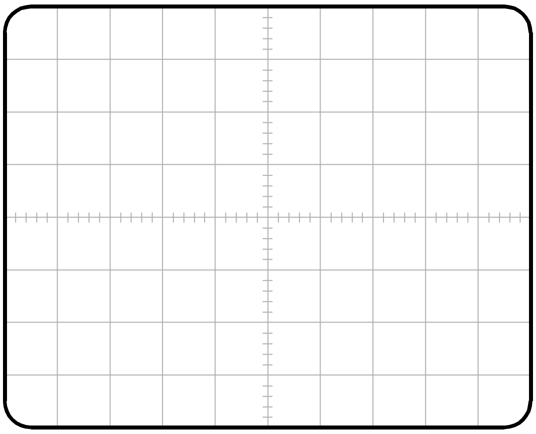
230V applied voltage

Figure 3-6-6

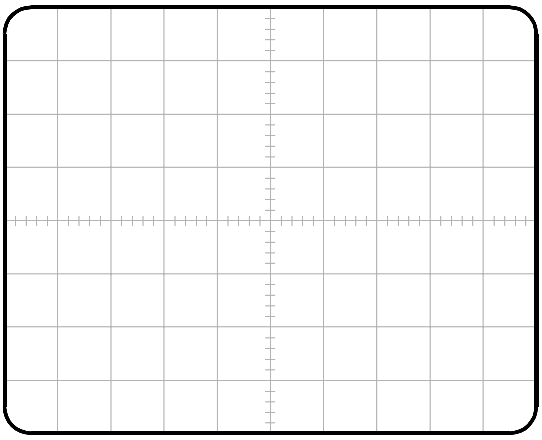
6.9 Exercise 6.1 Graphical Results (120 V Product Version)



40V applied voltage



80V applied voltage



125V applied voltage

Figure 3-6-6

7 Open Circuit Test

7.1 Assignment Information

7.1.1 Objectives

When you have completed this assignment you will:

- be able to construct an equivalent circuit of a transformer on no-load.

7.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed or read Assignment 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.)

7.1.3 Practicals

1. Open Circuit Test

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

Many electrical machines, particularly transformers, ac motors and generators can be more easily analysed and their performance better understood with the aid of an equivalent circuit in which the effects of core loss, copper loss, flux leakage, etc., are represented by electrical resistances and inductances. An equivalent circuit will produce the same phasor diagram as the machine itself and the values used to construct either diagram are derived from tests on the actual machine.

In Assignment 5, a phasor diagram was drawn for a transformer on no-load showing the relationship between primary voltage, primary current and flux in the core where it was assumed that the power loss in the core was negligible. In this assignment, measured values of core loss, primary voltage and current will be used to construct an equivalent circuit and a more detailed phasor diagram.

7.2.2 The Equivalent Circuit

A real transformer with no-load on its secondaries may be represented as an ideal transformer with no core loss and which requires zero magnetizing current plus two parallel elements R_c and X_m as in Figure 3-7-1.

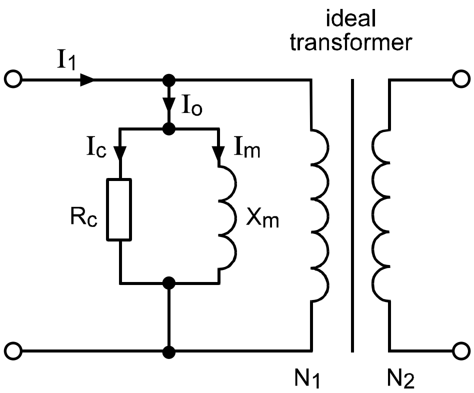


Figure 3-7-1

The resistance R_c is the core loss element. The current through this will be in phase with the applied voltage and will dissipate power equivalent to that of the core at a specified voltage and frequency.

The reactance X_m is the magnetizing element. Its current will lag the applied voltage by 90°; i.e. it is in quadrature with the applied voltage, and no power is dissipated. The current taken by X_m produces the magnetomotive force which sets up the flux in the core.

By measuring the current and power taken from the supply, as shown in Figure 3-7-2, values for the elements of the equivalent circuit can be derived and the phasor diagram constructed.

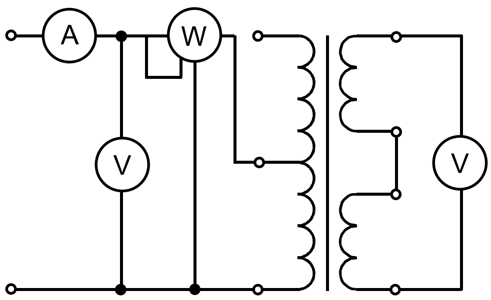


Figure 3-7-2

Using the test results obtained in this assignment a phasor diagram similar to that in Figure 3-7-3 can be constructed.

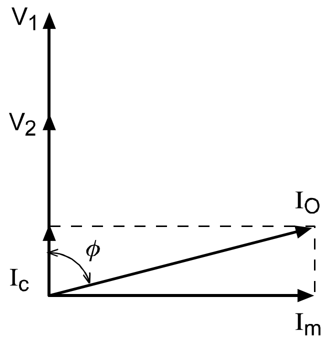


Figure 3-7-3

We will first calculate the phase angle between the current I_1 and the primary voltage V_1, then derive values for the core loss and magnetizing currents.

Let P_1 = Primary power input (Wattmeter W1)

V_1 = Voltage applied to primary (Voltmeter V1)

V_2 = Voltage across secondary (Voltmeter V2)

I_O = Total primary current on no-load (Ammeter I1)

I_c = In phase component of current I_O (core loss component)

ϕ = Quadrature component of current I_O (magnetizing component)

I_m = Phase angle between V_1 and I_O.

We can now calculate the currents through the core loss resistance R_c and the magnetizing reactance X_m also the phase relationships between these currents and the primary voltage.

A word of explanation is needed as to why we refer to the total primary current on no-load as I_O instead of I_1. I_O represents the phasor sum of the core loss current I_C and the magnetizing current I_m as shown in Figure 3-7-3. When the transformer is supplying no external load, this is the total current taken by the primary, therefore for this condition $I_O = I_1$. When the transformer is supplying a load, there is a large additional current flowing in the primary and in this case I_1 is not equal to I_O but to the phasor sum of I_O and primary load current component.

The volt-amperes taken by the primary on no-load is:

$$VA_1 = V_1 I_O$$

And the power input is:

$$P_1 = V_1 \times I_O \cos\phi$$

Hence:

$$\cos\phi = \frac{P_1}{V_1 I_O}$$

and:

$I_c = I_O \cos\phi$ (core loss component in phase with the applied voltage)

$I_m = I_O \sin\phi$ (magnetizing component in quadrature with applied voltage)

Now that the currents I_c and I_m have been evaluated we can find the values of the equivalent core-loss resistance R_c and magnetizing current X_m. using the following equations:

$$R_c = \frac{V_1}{I_c}$$

$$X_m = \frac{V_1}{I_m}$$

7.3 Content

This assignment will enable the student to derive an electrical circuit that will act as a model for the transformer on no-load. This electrical model can then be extended to represent the complete transformer.

7.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	68-117
	• Electrodynamic Wattmeter	68-204

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 powe r 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).*

7.6 Practical 7.1 – Open Circuit Test

Make all connections shown in Figure 3-7-4.

If virtual instrumentation is being used, set the 250 V/500 V range switch 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' socket is connected. Additionally, 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 or up to 200 mA to be monitored when the 200 mA socket is connected and software selected.

On the Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0%.

Set the *'3 phase circuit breaker'* to the on position and then rotate the *'variable output voltage'* control to give a voltage on V1 of ………………… (as read by virtual or conventional instrumentation).

Product Version	
230 V	**120 V**
230 V	*125 V*

Measure the primary current I1 and the secondary voltage V2, and record the results in copy of Practical 7.1, Results Table for the appropriate version (230 V or 120 V).

On virtual or conventional instrumentation, record the primary input power to the transformer in your copy of the results table.

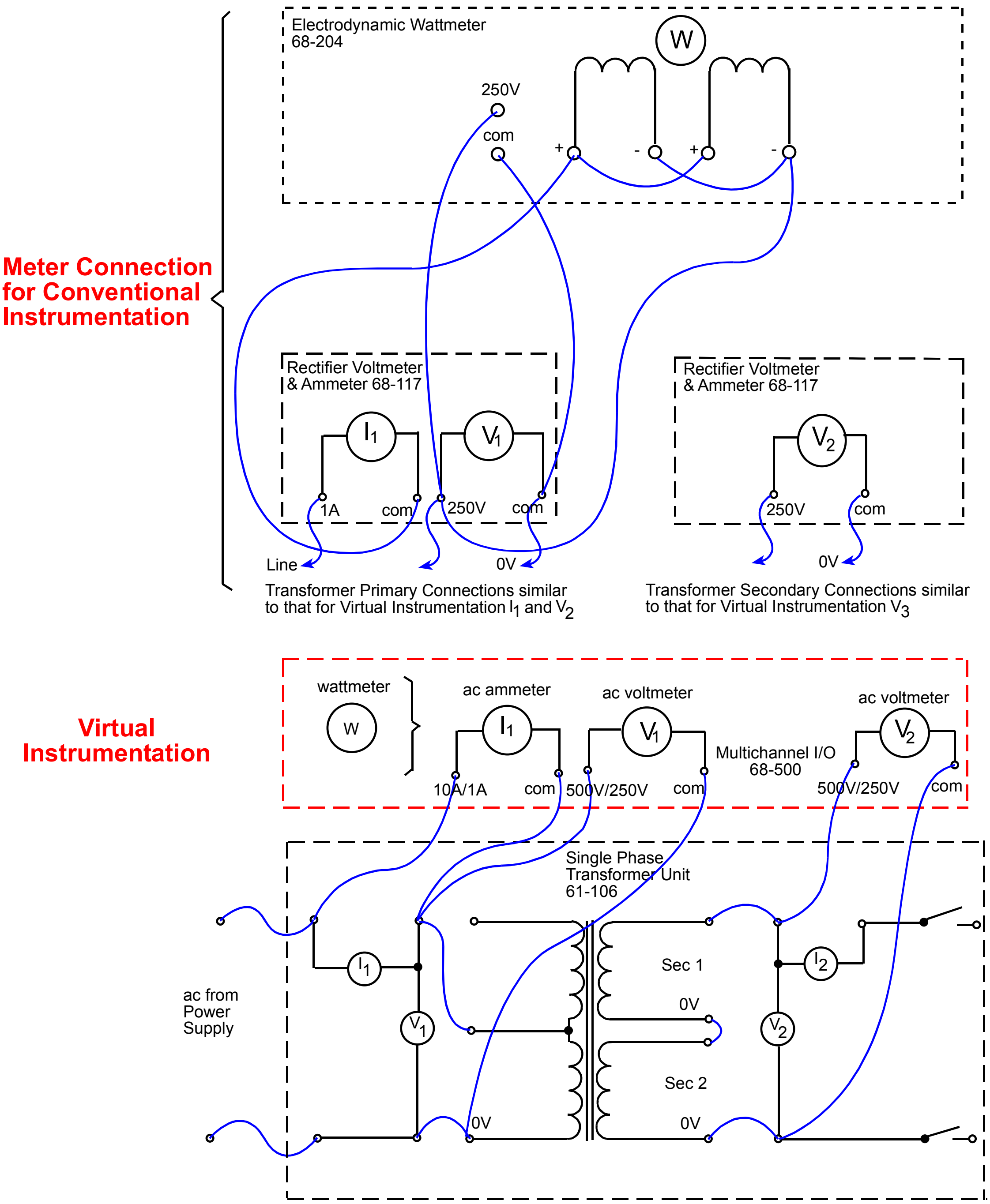
Turn the *'variable output voltage'* control to 0% on the Universal Power Supply 60-105 and then switch off the *'3 phase circuit breaker'.*

7.6.1 Exercise 7.1

Calculate cos ϕ, the angle ϕ, I_c and I_m from the test results recorded in Practical 7.1 and construct the phasor diagram.

7.6.2 Exercise 7.2

Now that the currents I_c and I_m have been evaluated, we can find the values of the equivalent core loss resistance R_c and magnetizing reactance X_m. Draw the equivalent circuit for the transformer on no-load and insert these values into it. The methods of calculating R_c and X_m is detailed in the introduction section of this assignment.



Note:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

Figure 3-7-4: Practical 7.1 Circuit Diagram

7.6.3 Referred Values

When a measurement has been made on one winding of a transformer, it is often convenient to think in terms of the equivalent effect as it would apply to another winding. For instance, if the transformer you have been using were to be used in reverse, with the secondary winding now used as the primary, the current required to support the same flux in the core would be multiplied by the factor N_1/N_2 . Also the voltage supported by that flux would be multiplied by N_2/N_1 .

7.6.4 Exercise 7.3

Deduce the turns ratio from your results in Practical 7.1 Results Table.

7.6.5 Exercise 7.4

A transformer has a turns ratio of 0.5. An open circuit test is performed on the primary and R_c is found to be 600 Ω and X_m is found to be 160 Ω. Calculate the values of R_c and X_m which would have been found if you had performed the open circuit test on the secondary winding instead of the primary.

7.7 Practical Aspects

The equivalent circuit which you have constructed in this assignment provides a model of the transformer on no-load which is compatible with the phasor diagram. At this stage, it does not provide a complete model, since the effect of load current in the winding impedance has not been considered. In the next assignment, we will add the circuit elements necessary to complete the equivalent circuit of the transformer.

7.8 Practical 7.1 - Results Tables and Graphs (230 V Product Version)

Primary Volts V_1	Primary Current I_0	Input Power P_1	Secondary Volts V_2

7.9 Practical 7.1 - Results Tables and Graphs (120 V Product Version)

Primary Volts V_1	Primary Current I_0	Input Power P_1	Secondary Volts V_2

8 Short Circuit Test

8.1 Assignment Information

8.1.1 Objectives

When you have completed this assignment you will know:

- how to predict the efficiency of a transformer over a range of loads,
- how to complete the equivalent circuit.

8.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed assignments 5, 6 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.)

8.1.3 Practicals

1. Short Circuit Test
2. Core Loss During Short Circuit Test

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

The last assignment examined the behaviour of the transformer on no-load. Now suppose that a load current I_2 flows in the secondary winding. It will tend to reduce the flux in the core and hence the EMFs, including the back EMF in the primary. The result is an increase in primary current which can be calculated from the changes in MMF (ampere-turns).

On no-load the primary MMF was $I_O N_1$.

Additional MMF required is $I_2 N_2$ to cancel the secondary's demagnetising MMF.

Thus the primary must supply a total MMF of:

$$I_O N_1 + I_2 N_2$$

The current in the N_1 turns of the primary thus becomes:

$$I_1 = I_O + I_2 \frac{N_2}{N_1}$$

From this we can see that the load on the secondary has in effect been transferred to the primary and the additional primary current is taken from the power supply.

Winding resistance

Each winding of a transformer has resistance. When a current flows this gives rise to a voltage drop and to a power loss, usually referred to as the 'copper loss'.

$$\text{Copper loss} = I_1{}^2 R_1 + I_2{}^2 R_2$$

Leakage Reactance

The flux produced by current flow in the primary turns does not all link with the secondary turns, as shown in Figure 3-8-1(a).

Similarly, the counter-flux produced by load current in the secondary turns does not all link with primary turns.

The effect of leakage flux in a real transformer is similar to having an ideal transformer in which all the flux links both windings, plus separate inductors connected in series with the primary and secondary as in Figure 3-8-1(b). In the equivalent circuit, reactances X_1 and X_2 will represent the leakage components in series with the primary and secondary windings.

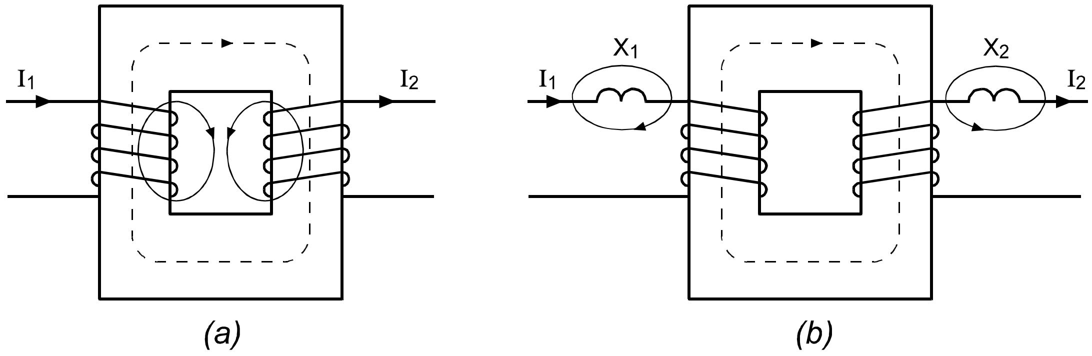


Figure 3-8-1

8.2.2 Completing the Equivalent Circuit

By adding the winding resistances and leakage reactances to the equivalent circuit of the transformer on no-load, we can extend it to form a complete model of the transformer. The degree of complexity to which the equivalent circuit is taken will depend on the particular application for which it is to be used. The complete equivalent circuit is shown in Figure 3-8-2.

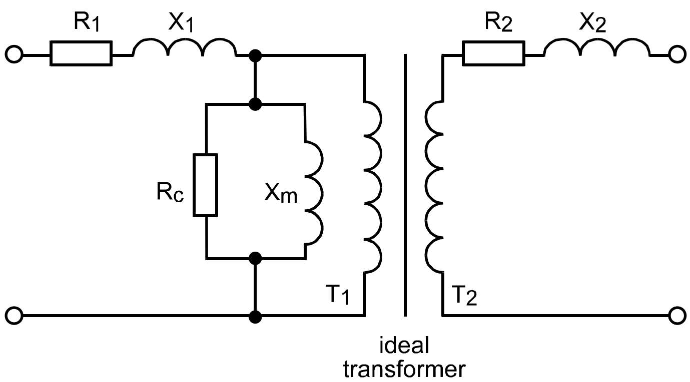


Figure 3-8-2

8.2.3 Short Circuit Test

The magnitude of the total effective winding resistance and leakage reactance can be found by placing a short circuit across the secondary, and finding out how much voltage at the primary terminals is needed to drive rated current through the transformer. This voltage will be quite small, so that the core losses (the effect of R_c and X_m) will be negligible. The required circuit is shown in Figure 3-8-3.

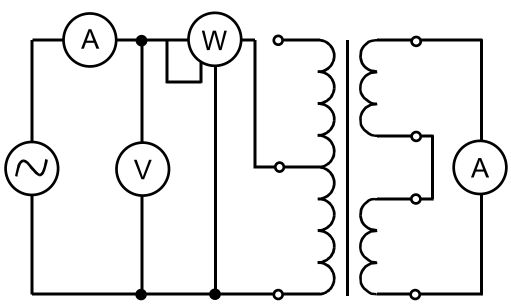


Figure 3-8-3

There is, however, a preliminary test which we shall undertake in order to overcome some limitations in our laboratory situation. In industry the testing of a transformer would be carried out with high accuracy instruments, regularly recalibrated. Also it happens that in large transformers (for which open and short circuit tests are most valuable) the results are not usually nearly so dependent on measurement errors as in our small one. The reasons will become apparent later. But to ensure that you get good results it will be advisable to check that the voltmeter, ammeter and Electrodynamic Wattmeter are consistent with one another if conventional instrumentation is used.

8.2.4 Calculation of Winding Resistance and Leakage Resistance

The input power W1 which is measured in the short circuit test is unlikely to be the same as V_1I_1 calculated from measurements. Let us suppose for the moment that the impedance at the primary terminals is a series combination of resistance R_1' and reactance X_1'.

Then since there is no power dissipated in the reactance:

$$W_1 = I_1^{\,2} R_1'$$

so that:

$$R_1' = \frac{W_1}{I_1^{\,2}}$$

Also the total impedance is:

$$\frac{V_1}{I_1} = \sqrt{R_1'^2 + X_1'^2}$$

So that X_1' can be calculated as:

$$X_1' = \sqrt{\left(\frac{V_1}{I_1}\right)^2 - R_1'^2}$$

Note that only a single resistance and a single reactance value are obtained from these calculations. We must find out how they are related to the individual primary and secondary resistances and reactances.

8.2.5 Referred Values

In just the same way as the core losses in Assignment 7 were referred to the secondary, having been established for the primary, so with the winding resistances and reactances the secondary contribution can be referred to the primary (or vice versa). The same factor is applied, the square of the turns ratio.

Thus, if the core magnetising and loss components are neglected, the equivalent circuit of the transformer shown in Figure 3-8-4 is valid. Figure 3-8-4 is the circuit relevant to your practical results, since if in this circuit the ideal transformer is short circuited at the secondary terminals, the primary of it becomes effectively a short circuit also since no voltage can exist across it.

The winding resistance and reactance referred to the primary are:

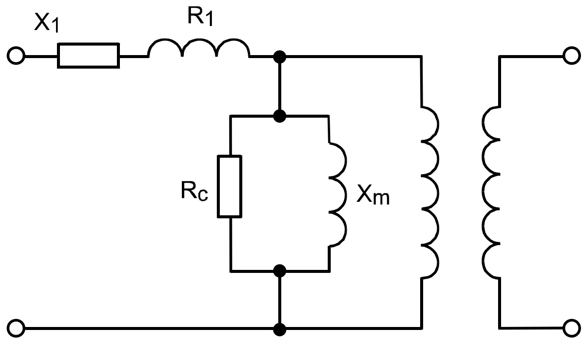
$$R_1' = R_1 + \left[\frac{N_1}{N_2}\right]^2 R_2$$

and:

$$X_1' = X_1 + \left[\frac{N_1}{N_2}\right]^2 X_2$$

The complete equivalent circuit of course requires the components representing the core magnetisation and losses, R_c and X_m, to be added.

An exact analysis would show that slightly different values would be appropriate in each different equivalent circuit, but in a typical transformer the values of R_c and X_m are so much higher than the series impedances referred to the primary that the same value very nearly is appropriate when added to any of the circuits in Figure 3-8-4.



impedances in Ω

Figure 3-8-4

8.3 Content

In this assignment, you will measure the power taken by the transformer when secondary short circuited and passing the full load current.

8.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	68-117
	• Electrodynamic Wattmeter	68-204

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® 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 - Short Circuit Test

	Product Version	
	230 V	120 V
Make the connections shown in Figure 3-8-5. 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 1A/10A range switches for I1 and I2 channels to '10 A'. This allows currents up to 10 A to be monitored when the 10 A/1 A socket is connected. On the Universal Power Supply 60-105 , ensure the *'variable output voltage'* control is set to 0%.		
Set the *'3 phase circuit breaker'* to the on position and then rotate the *'variable output voltage'* control to give a reading of…………………………. (as read by I2 virtual or conventional instrumentation).	*0.43 A*	*0.8 A*

Measure the primary voltage V1 and current I1 using the virtual or conventional instrumentation. Record the results in a copy of the appropriate Practical 8.1, Results Table for the appropriate product version (230 V or 120 V).

Include in your Practical 8.1, Results Table the power value read on the virtual or conventional Electrodynamic Wattmeter.

Leaving the *'variable output voltage'* control in its set position on the Universal Power Supply 60-105, switch off the *'3 phase circuit breaker'.*

That completes the short circuit test as it is normally performed, but in order to discover a little more about it we shall do a further related test.

Remember not to move the *'variable output voltage'* control on the power supply unit.

8.6.1 Exercise 8.1

Calculate the values of R_1' and X_1' from Practical 8.1, Results Table.

Draw the equivalent circuit of the transformer in the form having all impedances on the primary side of the ideal transformer. Mark in the values calculated in this practical and include values for R_c and X_m from Assignment 7, use your own results if you have them.

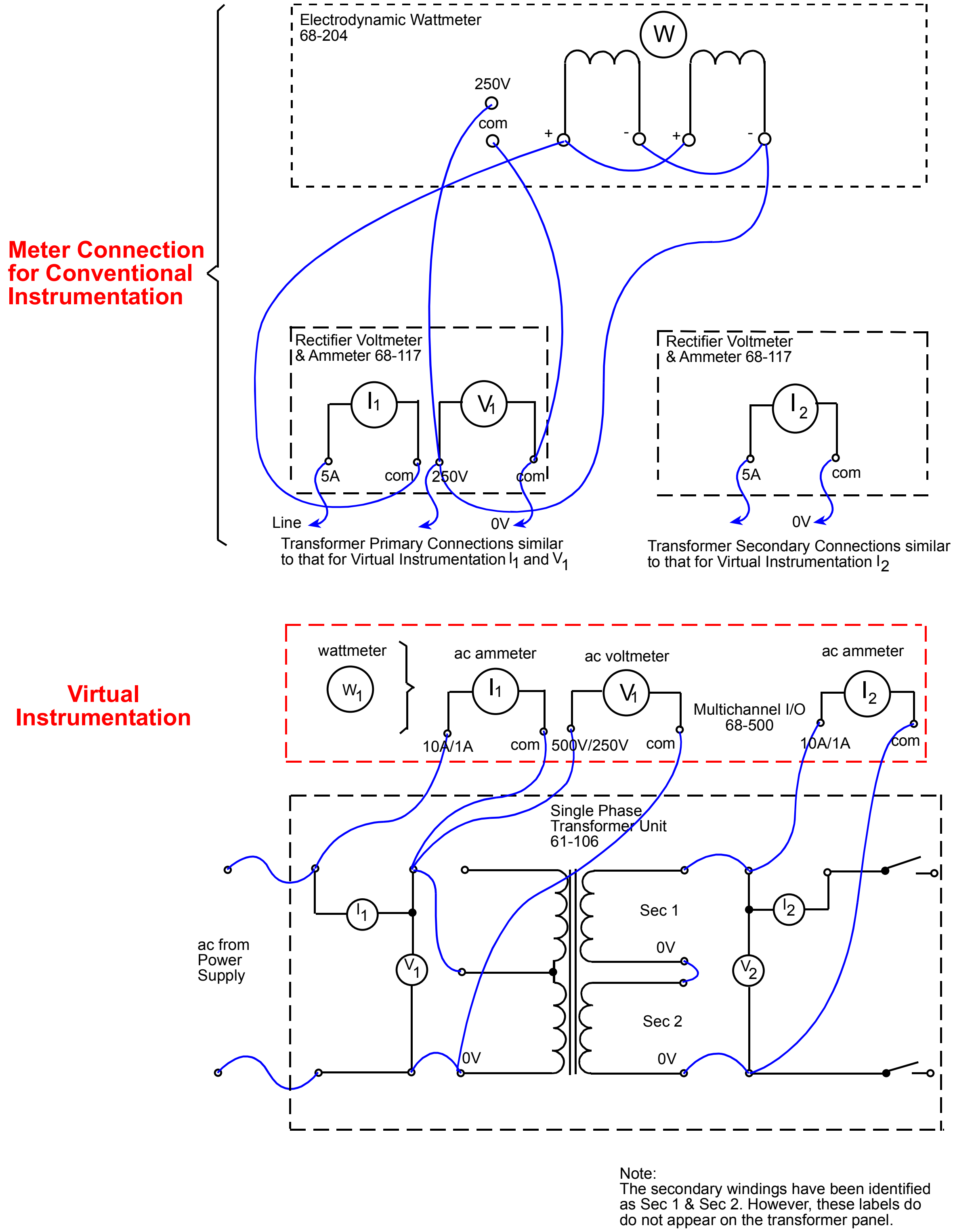


Figure 3-8-5: Practical 8.1 Circuit Diagram

8.7 Practical 8.2 - Core Loss During Short Circuit Test

Ensuring that the power supply is switched off, remove the connections to the secondary ammeter (I2).

On the Universal Power Supply 60-105, set the *'3 phase circuit breaker'* to the on position and read the power indicated on the virtual or conventional Electrodynamic Wattmeter. Record this value on a copy of Practical 8.2, Results Table for the appropriate product version (230 V or 120 V)

The value of the core loss during the short circuit test would have been much less than the quantity measured in this practical. This is because the core flux will have been roughly halved by the reduction in voltage due to the current in the primary resistance and leakage inductance. Since eddy current loss is proportional to the square of the flux density and hysteresis loss, a fair estimate of the core loss in the short circuit test is about one quarter of the loss you measured with the short circuit removed.

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

8.8 Practical Aspects

It may seem that it would be far simpler to measure the winding resistance with an ohm meter, and the leakage reactance may seem rather uncertain from your measurements. But consider the situation with a very large transformer.

Large transformers have thick conductors in order to pass large currents without excessive heating. The resistance is often too low to measure with an ordinary ohmmeter and in any case may differ between ac and dc values, so R_1' is better determined by the ammeter and Electrodynamic Wattmeter method using ac.

You may have found the reactance uncertain because its calculation involved a small difference between two large quantities. But in a large transformer, the reactance is usually much larger than the resistance and, in this case, the errors of the measurement matter far less.

Notes

8.9 Practical 8.1 - Results Tables (230 V Product Version)

Primary Voltage (V_1)	Primary Current (I_1)	Input Power (P_1)	Secondary Current (I_2)
			0.43 A

8.10 Practical 8.2 - Results Tables (230 V Product Version)

Core loss with short circuit removed	

8.11 Practical 8.1 - Results Tables (120 V Product Version)

Primary Voltage (V_1)	Primary Current (I_1)	Input Power (P_1)	Secondary Current (I_2)
			0.8 A

8.12 Practical 8.2 - Results Tables (120 V Product Version)

Core loss with short circuit removed	

9 The Transformer On Load

9.1 Assignment Information

9.1.1 Objectives

When you have completed this assignment you will:

- know the effect of temperature on efficiency and voltage regulation when operating under load.

9.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have read or completed Assignments 7 and 8.
- 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. Temperature Rise of the Transformer On 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.

9.2 Theory

9.2.1 Heat Transfer from the Transformer

When a transformer is connected to its supply, heat will be generated by iron losses within the core (these are constant for a fixed primary voltage) and by copper losses due to current flowing in the primary and secondary windings (these are proportional to the square of the load current). This internal power loss will cause the transformer temperature to rise until the rate at which heat is generated internally is equalled by the rate at which heat is removed by convection, conduction and radiation.

Heat produced by iron losses is transferred by conduction to the core surface, while that due to copper loss by conduction through the copper conductors and surrounding insulation is transferred to the winding surface. Most of the heat is then removed by natural convection to the surrounding air in the case of small transformers and by natural or forced convection to the cooling oil in the larger power transformers.

As the heat flow is outward from the region where heat is generated, the hottest parts will be the least accessible and the designer must take account of the difference between the temperature rise at the point of measurement and the temperature rise at the 'hot spots' of the transformer.

The rate at which heat is removed is proportional to the temperature difference between the transformer and the cooling medium. On first switching on to a steady load, the transformer will be at the same temperature as its surroundings and initially most of the heat produced by the iron and copper losses will be stored in the body of the transformer, causing its temperature to increase. As its temperature continues to rise the temperature difference between the transformer and the cooling medium also increases (assuming that the cooling air or fluid is at a steady temperature) causing a proportionate increase in the rate at which heat is removed. As the transformer approaches its steady temperature, more heat is transferred to the cooling medium and less into raising the body temperature. Eventually, the temperature rise will be sufficient to cause all the internal heat to be transferred to the coolant and the body of the transformer will then remain at a steady temperature.

It can be seen that improving the rate at which heat is removed from a transformer leads to a reduction in its operating temperature. For most power transformers which are mounted in an enclosure it is important to provide adequate ventilation holes to allow cooling air to pass freely over the core and windings (some small transformers can be cooled by conduction of heat to a metal case which itself is adequately ventilated). We can summarise this by saying that in a transformer (or other machine), the final steady temperature will depend on the rate at which heat is generated. This is proportional to the internal power losses which are related to the loading and efficiency of the transformer, and on the rate at which heat is transferred to the surroundings. This is dependent on the temperature difference between the transformer and its coolant, on the surface area exposed to the coolant and on the rate at which fresh coolant can be brought into contact with the transformer.

Product Version	
230 V	120 V
230 V	125 V

9.2.2 Introduction to Practical

The principal aim of this assignment is to measure the temperature rise of a transformer from first switching on the load until a steady temperature has been reached. We shall also calculate efficiency and regulation at the end of the heat run.

In the practical which follows, the primary voltage will be set to its nominal value of…………………………………………………………………………………… at the start of the test. As the test proceeds, the primary voltage will be maintained at its nominal value and readings will be taken of core temperature, primary current, primary power together with secondary voltage, current and power until the transformer has reached its steady temperature. From these readings, the efficiency and temperature rise above ambient can be calculated.

At the conclusion of this practical, the load is switched off and a reading taken of the secondary voltage on open circuit with the primary voltage set to its nominal value. This enables the voltage regulation to be calculated.

The circuit diagram for the load test is given in Figure 3-9-1.

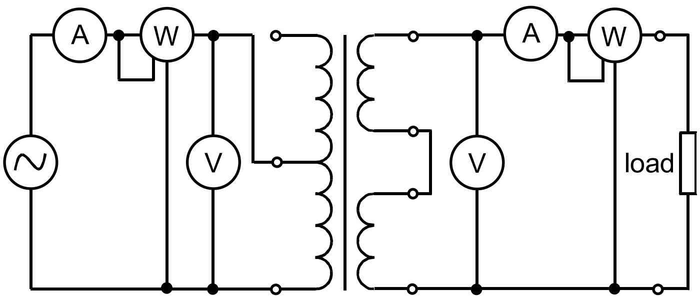


Figure 3-9-1

9.3 Content

In this assignment, the temperature rise of the transformer is measured on load and its efficiency and voltage regulation calculated when hot.

9.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- K-Type temperature monitor cable
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	Or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	68-117
	• Electrodynamic Wattmeter (two off)	68-204
Auxiliary Equipment	• Multimeter with K-Type thermocouple input.	
	• Clock (to measure the duration of the test)	

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® 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 - Temperature Rise of Transformer on Load

	Product Version	
	230 V	**120 V**
Make all connections shown in Figure 3-9-2. If virtual instrumentation is being used, set the 250 V/500 V range switches for V1 and V3 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' sockets are connected. Additionally, set the 1 A/10 A range switches for I1 and I3 channels to '1 A'. This allows currents up to 1 A to be monitored when the 10 A/1 A socket is connected. On the Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0%. Ensure the load switch on the Single Phase Transformer Unit is set to the 'off' position.		
Ensure that all switches on bank 1 of the Resistance Load 67-142 are set in the 'on' position to give a load of …………………………………………….. Banks 2 and 3 are not connected.	*548 Ω*	*326.6 Ω*
Connect a multimeter with a K-Type TC Temperature input to the Single Phase Transformer Unit 'temperature output' socket using the connector cable provided.		
On the Universal Power Supply 60-105, set the *'3 phase circuit breaker'* to the on position and rotate the *'variable output voltage'* control to give a primary voltage of ………………………………………………………… (as read by virtual or conventional instrumentation).	*230 V*	*125 V*

Take initial readings of both the ambient and transformer core temperatures. Record these in the first row of a copy of Practical 9.1, Results Table.

Also record in Practical 9.1, Results Table the secondary voltage as read on virtual or conventional instrumentation meter V3.

	Product Version	
	230 V	120 V
Switch on the load switch on the Single Phase Transformer Unit.		
Adjust and maintain the primary voltage from 60-105 throughout the test to.	*230 V*	*125 V*

For the row time 0 in the Results Table, record values of primary voltage and current and secondary voltage and current in Practical 9.1, Results Table for the appropriate product version.

Using either virtual or a conventional wattmeter, read the primary power. Record this value in Practical 9.1, Results Table for the appropriate product version.

Using either virtual or a conventional wattmeter, read the secondary power. Record this value in Practical 9.1, Results Table for the appropriate product version.

Repeat these readings after 5 minutes and record the results in Practical 9.1, Results Table.

Repeat the readings for the times listed in the appropriate Practical 9.1, Results Table.

Switch off the load switch on the Single Phase Transformer Unit.

Record in Practical 9.1, Results Table the secondary voltage when the load is removed.

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

9.6.1 Exercise 9.1

Calculate and record the core temperature rise T_{rise} above ambient from readings taken during the load test:

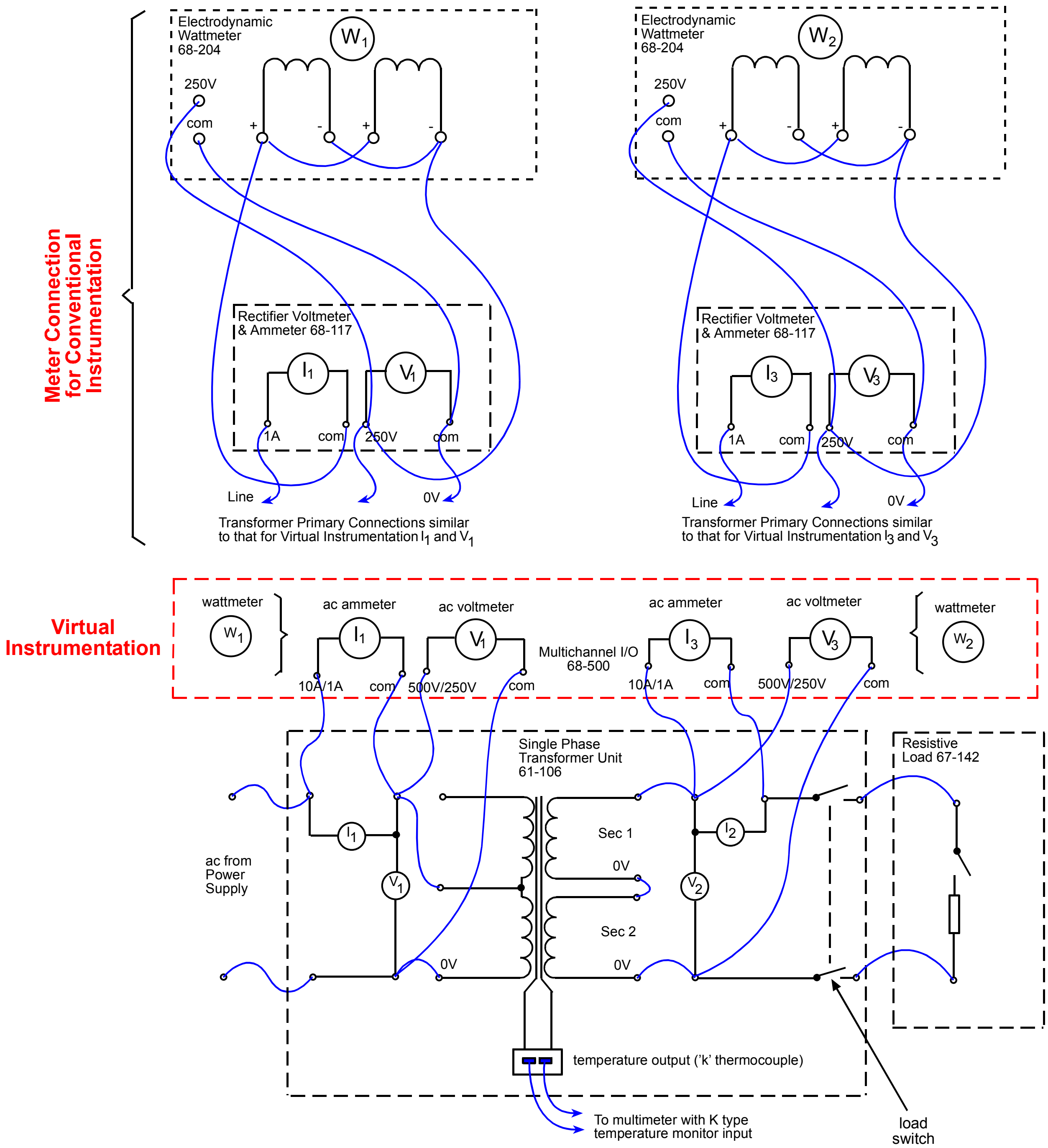
$$T_{rise} = T_{core} - T_{ambient} \ (^{\circ} C)$$

Plot core temperature rise and ambient temperature using the axes suggested in Practical 9.1, Results Table.

9.6.2 Exercise 9.2

Calculate and record the efficiency from readings taken at the beginning and end of the load test:

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



Notes:
The secondary windings have been identified as Sec 1 & Sec 2. However, these labels do do not appear on the transformer panel.

Figure 3-9-2: Practical 9.1 Circuit Diagram

9.7 Practical Aspects

The user of a power transformer will be mainly concerned with its efficiency, voltage and temperature rise. It can then be worked out how much power will be drawn from the supply, what voltage will be obtained from the secondary, and what the operating temperature will be for a given supply voltage, applied load and ambient temperature.

It is worth mentioning at this point some of the tests which are carried out by the manufacturer to meet a standard specification (such as British Standards Institute BS2214 - Performance of Power Transformers not Exceeding 2 kVA). These will include a full load heat run, which requires the transformer to be operated at full load and at rated primary voltage until the rate of change of surface temperature does not exceed 1°C per hour. The temperature rise of the windings is calculated from measurements of the winding resistance made at ambient temperature and at final temperature.

$$\text{Temperature rise } (^\circ\text{C}) = \left(\frac{R_2 - R_1}{R_1}\right)(T_1 + 234.5)$$

where:

- T_1 is the ambient temperature
- R_1 is the resistance at ambient temperature
- R_2 is the resistance at final temperature

The mean temperature of the windings for a given ambient temperature can be derived from this calculation and should be within a specified value (in BS2214 this is 110°C).

The secondary voltage, again at the rated primary voltage, is measured at the start and finish of the full load heat run and should be within $\pm 5\%$ of its nominal value for windings giving an output voltage of more than 100 volts.

When specifying voltage regulation, it is usual to express this as the change in secondary voltage between no-load and full-load as a percentage of the no load voltage:

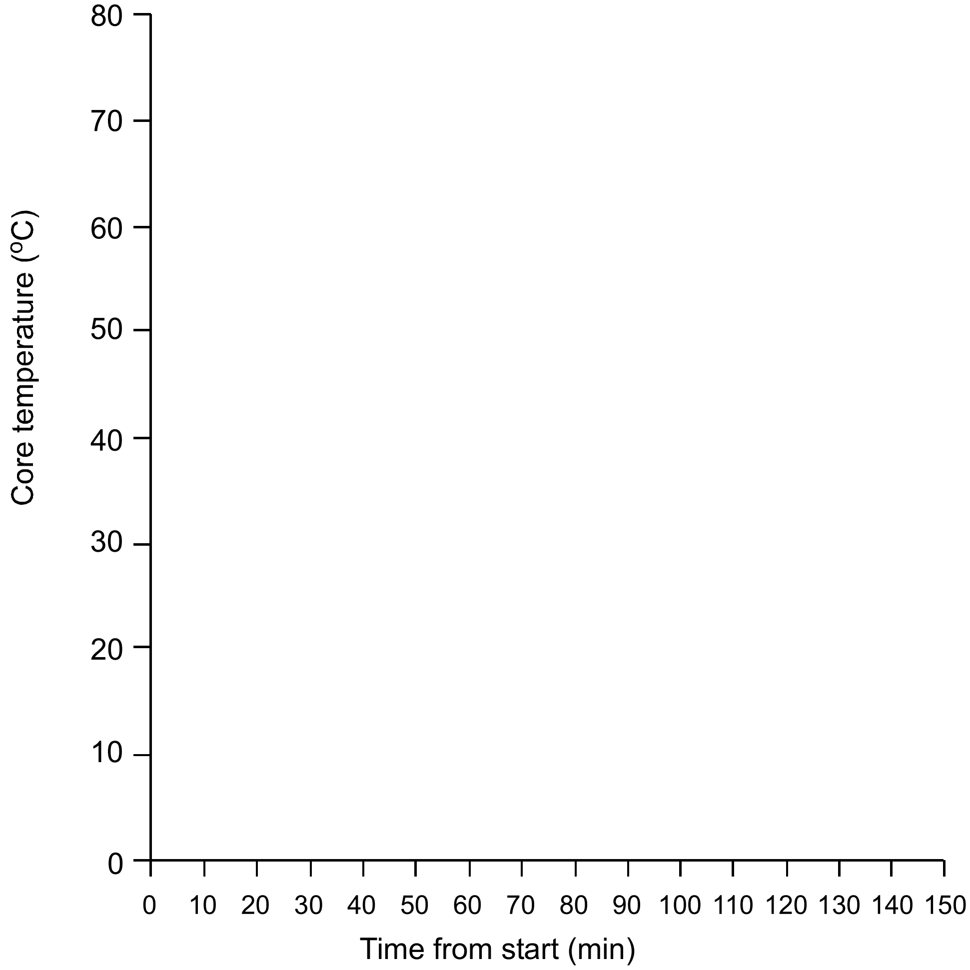
$$\text{Voltage Regulation} = \frac{\text{No Load Voltage - Full Load Voltage}}{\text{No Load Voltage}} \times 100\%$$

An alternative definition which may be encountered in some transformer specifications expresses voltage regulation as the change in secondary voltage between no load and full load as a percentage of the full load voltage.

In the heat run test carried out in this assignment, we have simplified the experimental procedure by using a fixed value of load resistance throughout the test and by measuring the core temperature only, omitting measurement of the hot and cold winding resistance.

9.8 Practical 9.1 - Results Tables and Graphs (230 V Product Version)

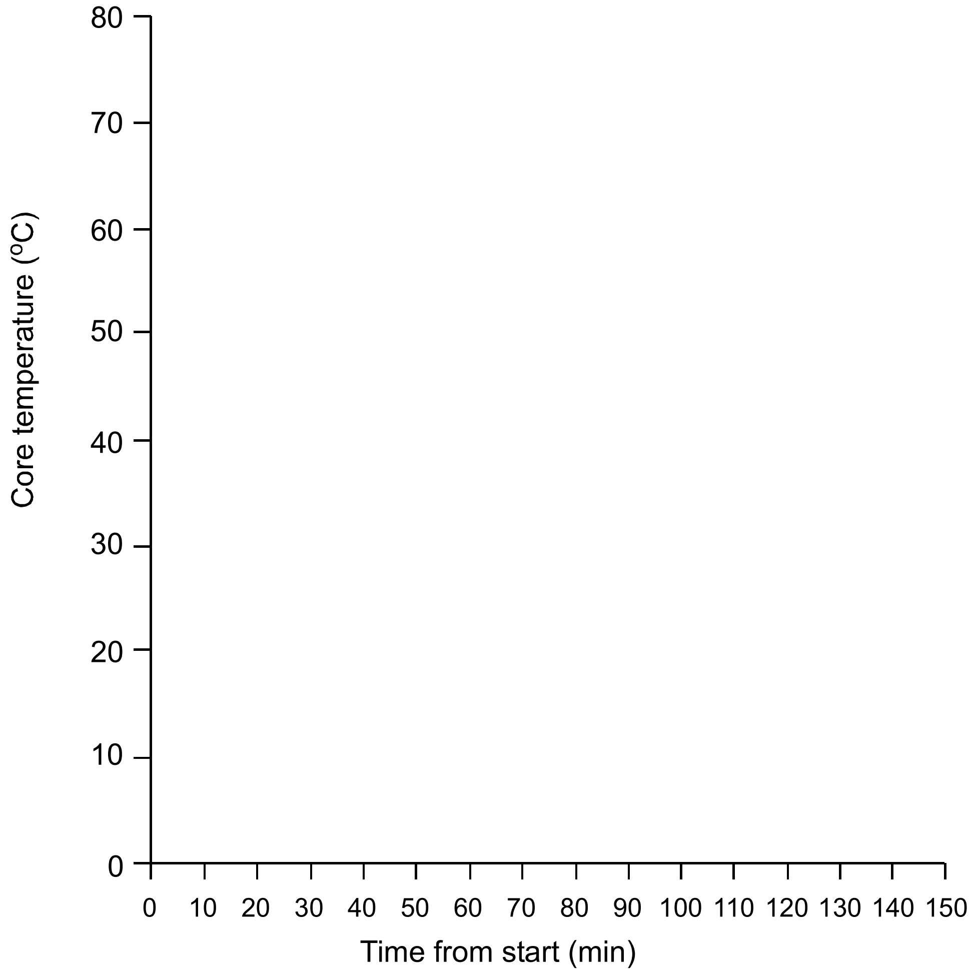
Time min	T_{core} (°C)	T_{amb} (°C)	T_{rise} (°C)	V_1 (V)	I_1 (A)	P_1 (W)	V_3 (V)	I_3 (A)	P_2 (W)
Initial Readings									
0									
5									
10									
15									
25									
35									
45									
60									
75									
90									
105									
120									
135									
150									



Exercise 9.1 Axes

9.9 Practical 9.1 - Results Tables and Graphs (120 V Product Version)

Time min	T_{core} (°C)	T_{amb} (°C)	T_{rise} (°C)	V_1 (V)	I_1 (A)	P_1 (W)	V_3 (V)	I_3 (A)	P_2 (W)
Initial Readings									
0									
5									
10									
15									
25									
35									
45									
60									
75									
90									
105									
120									
135									
150									



Exercise 9.1 Axes

10 Voltage Regulation

10.1 Assignment Information

10.1.1 Objectives

When you have completed this assignment you will:

- be able to calculate the voltage regulation and efficiency of a transformer at different loads from measurements made in open and short circuit tests.

10.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignments 8 and 9.
- 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. Open Circuit Test
2. Short Circuit Test

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

In small power transformers it is not too difficult to measure the regulation (voltage drop with load) and the efficiency directly. With large transformers there are difficulties. It is not always easy to provide either the power or the load; and efficiency measurements make excessive demands for measurement accuracy. A large transformer might be typically 98% efficient. If wattmeter measurements of input and output power were each subject to as little as ±1% possible error, the losses might be assessed as anything from zero to twice the true value.

In practice therefore, the equivalent circuit is extensively used as a means of predicting the regulation and the efficiency of large transformers. As Assignments 7 and 8 have pointed out, the equivalent circuit is ascertained by means of the open and short circuit tests. By extending the short circuit test, useful results of direct relevance to the efficiency calculations can be obtained. Also by referring the series elements of the equivalent circuit to the secondary, as indicated in Figure 3-10-1, the calculations on regulation are simplified.

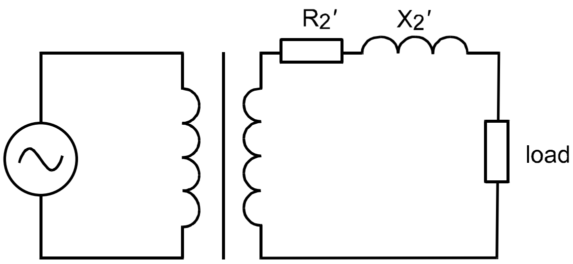


Figure 3-10-1

In this assignment we shall first measure the secondary voltage and the power absorbed from the supply, with the secondary on open circuit and rated voltage on the primary, Figure 3-10-2(a). We shall then measure the power and current in the primary circuit with the secondary passing various currents on short circuit, Figure 3-10-2(b).

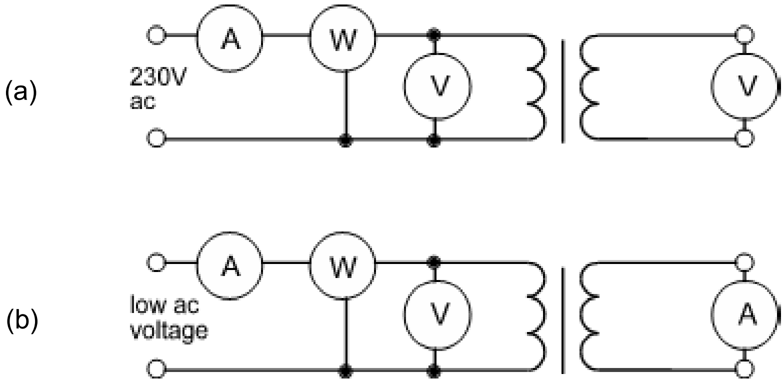


Figure 3-10-2

10.3 Content

In this assignment, the voltage regulation and efficiency of a transformer are calculated at different loads from measurements made in open and short circuit tests.

10.4 Equipment Required

- Universal Power Supply 60-105.
- Single Phase Transformer Unit 61-106
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	68-117
	• Electrodynamic Wattmeter	68-204

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 - Open Circuit Test

Make all connections shown in Figure 3-10-3.

If virtual instrumentation is being used, set the 250 V/500 V range switch for the V1 and V2 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 channels to '1 A'. This allows currents up to 1 A to be monitored when the 10 A/1 A socket is connected.

On the Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0%.

Set the *'3 phase circuit breaker'* to the on position and then rotate the *'variable output voltage'* control to give an output of…………………………….. (as read by virtual or conventional instrumentation meter V1).

Product Version	
230 V	**120 V**
230 V	*125 V*

Record the primary current and the secondary voltage readings on a copy of the appropriate Practical 10.1, Results Table (230 V or 120 V product version).

Using the virtual or conventional wattmeter, record the value of the primary power in the appropriate Practical 10.1, Results Table.

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

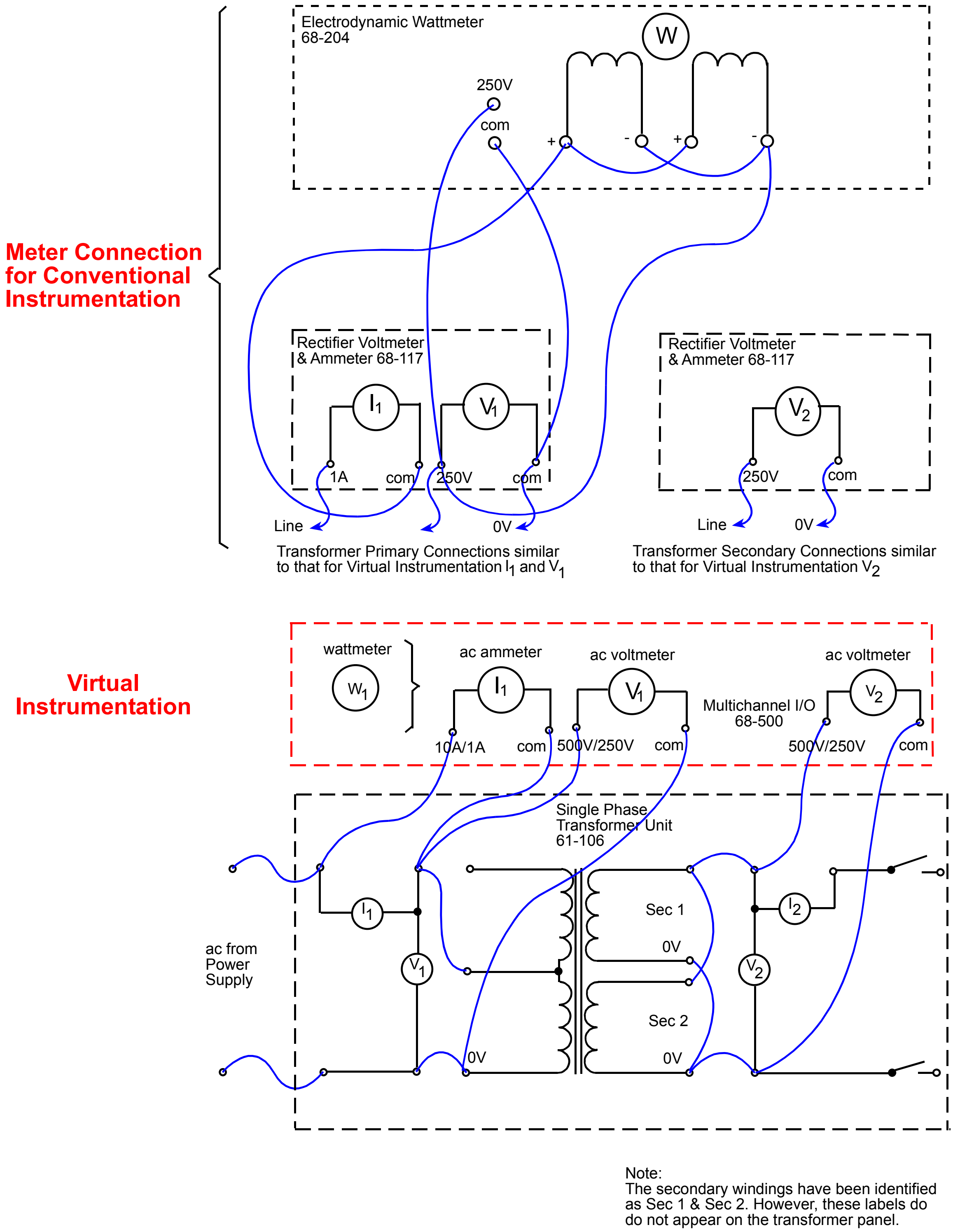


Figure 3-10-3: Practical 10.1 Circuit Diagram

10.7 Practical 10.2 - Short Circuit Test

	Product Version	
	230 V	**120 V**
Make the connections shown in Figure 3-10-4. Note that the only change from the set up of Figure 3-10-3 is that V2 is replaced with the ac ammeter I2. 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 channels to '1 A'. This allows currents up to 1 A to be monitored when the 10 A/1 A socket is connected.		
On the Universal Power Supply 60-105, set the *'3 phase circuit breaker'* to the on position and then rotate the *'variable output vol*tage' control until the current through the secondary winding is ………………………….. (as read by virtual or conventional instrumentation).	*0.22 A*	*0.4 A*
Record the primary voltage and current readings on a copy of the appropriate Practical 10.2, Results Table for 230 V or 120 V product versions. Using the virtual or conventional wattmeter, record the value of the primary power in the appropriate Practical 10.2, Results Table. <u>Do not exceed the maximum current values given and do not leave the transformer operating with the maximum value for more than 2 minutes.</u> **CAUTION:** Before the 1 A level is reached, set the 1 A/10 A range switches for I1 and I2 channels to '10 A' on the Multichannel I/O Unit 68-500. This allows currents up to 10 A to be monitored when the 10 A/1 A socket is connected. If conventional instrumentation is being used, ensure the 5 A socket on the ac ammeter of 68-117 is used.		
Repeat the measurements for secondary currents of……………………….. Record the results in the appropriate Practical 10.2, Results Table.	*0–1.33 A in 0.22 A steps*	*0–2.4 A in 0.4 A steps*

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

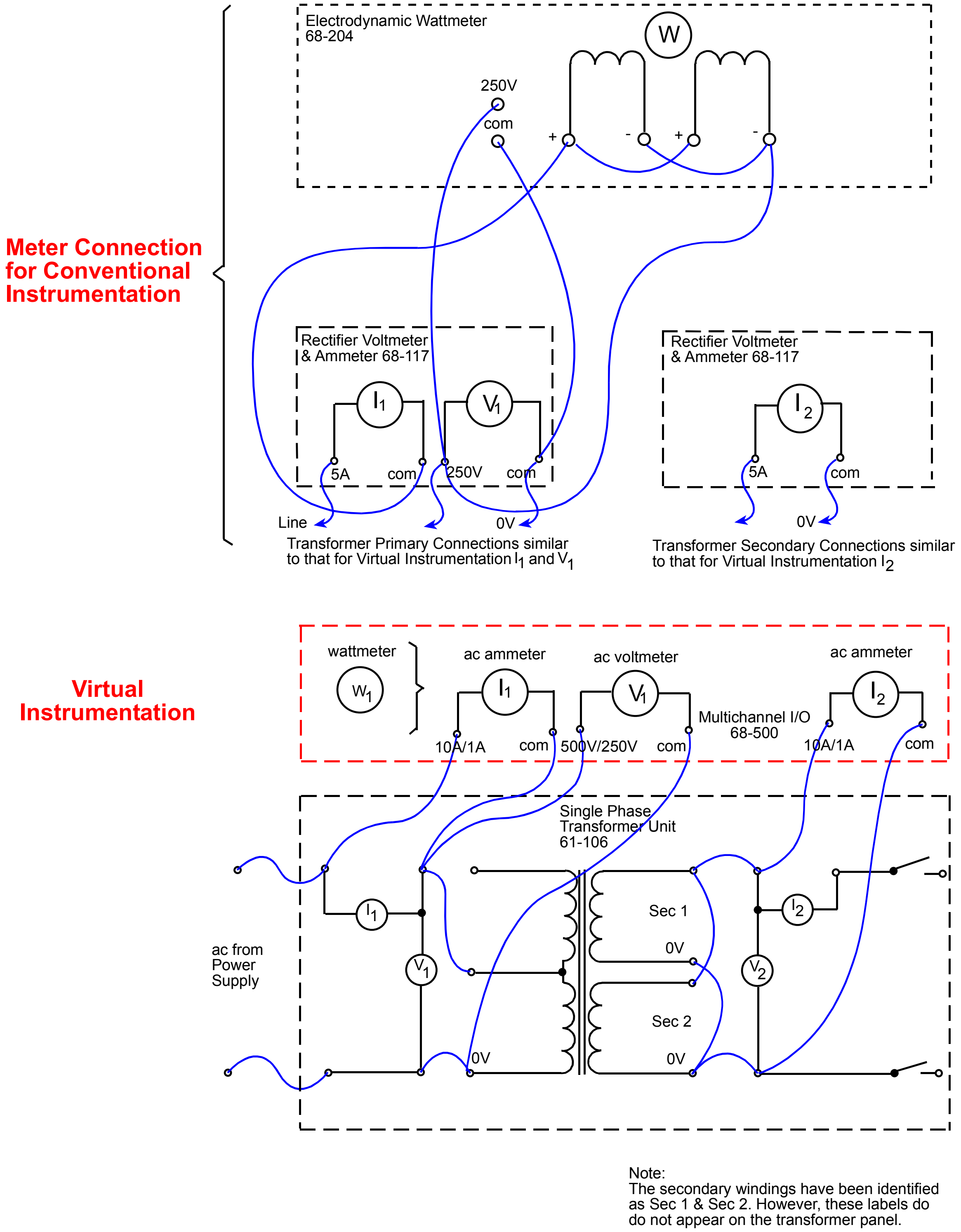


Figure 3-10-4: Practical 10.2 Circuit Diagram

10.8 Evaluation of Results

10.8.1 Exercise 10.1 – Transformer Efficiency

$$\text{Efficiency} = \eta = \frac{\text{Output Power}}{\text{Input Power}}$$

From this equation, we can see that efficiency could be measured directly by taking wattmeter readings of input and output power with the transformer on full load. However, this method can lead to inaccuracies, as the wattmeter error on full load will be significant, particularly for transformers whose efficiency is over 90%.

Since:

$$\text{Output Power} = \text{Input Power} - \text{Losses}$$

Therefore:

$$\eta = \frac{\text{Input Power} - \text{Losses}}{\text{Input Power}} = 1 - \frac{\text{Losses}}{\text{Input Power}}$$

Hence:

$$\eta = 1 - \frac{\text{Losses}}{\text{Output Power} + \text{Losses}}$$

Therefore:

$$\eta\% = \left[1 - \frac{(P_{OC} + P_{SC})}{\text{Output Power} + (P_{OC} + P_{SC})}\right]$$

where P_{oc} and P_{sc} are the losses found in the open and short circuit tests respectively.

	Product Version	
	230 V	**120 V**
The full load of the transformer with secondary windings connected in parallel is ………………………………………………………………………… Complete Exercise 10.1, Results Table using the wattmeter readings of Practical 10.1, Results Table and Practical 10.2, Results Table for P_{oc} and P_{sc}. Calculate the efficiency.	*0.86 A at 115 V*	*1.6 A at 62.5 V*

10.8.2 Exercise 10.2

Plot a graph of efficiency against load using the axes suggested in Exercise 10.2 Graph Results Axes.

10.8.3 Exercise 10.3 – Evaluating R_2' and X_2' in the Equivalent Circuit

In our evaluation of R_2' and X_2', we need to know the turns ratio of the secondary to the primary windings. In practice, it is not always possible to obtain the number of turns on the primary and secondary whereas we can easily measure the voltage ratio directly from the open circuit test. The two ratios should correspond well to one another.

$$\frac{T_2}{T_1} \approx \frac{V_{20}}{V_{10}}$$

where V_{10} and V_{20} are the primary and secondary terminal voltages on open circuit.

The open circuit test also gives the no-load secondary voltage with rated voltage applied to the primary. This is required in our calculation of percentage regulation.

From the measurements taken in the short circuit test, we can first evaluate the impedance Z_1' and resistance R_1' as seen at the primary side.

$$Z_1' = \frac{V_{1SC}}{I_{1SC}} \qquad R_1' = \frac{W_{1SC}}{(I_{1SC})^2}$$

and then refer these to the secondary by multiplying by the square of the turns ratio (or voltage ratio). Knowing Z_2' and R_2' we can then derive X_2'.

$$Z_2' = \frac{V_{1SC}}{I_{1SC}}\left[\frac{T_2}{T_1}\right]^2$$

$$R_2' = \frac{W_{1SC}}{(I_{1SC})^2}\left(\frac{T_2}{T_1}\right)^2$$

$$X_2' = \sqrt{(Z_2')^2 - (R_2')^2}$$

where:

Z_2' is the impedance referred to secondary

R_2' is the winding resistance referred to secondary

X_2' is the leakage reactance referred to secondary

$\frac{T_2}{T_1}$ is the turns ratio (for this the voltage ratio on open circuit, $\frac{V_{20}}{V_{10}}$ is used.)

V_{1SC}, I_{1SC} and W_{1SC} are values obtained in the short circuit test.

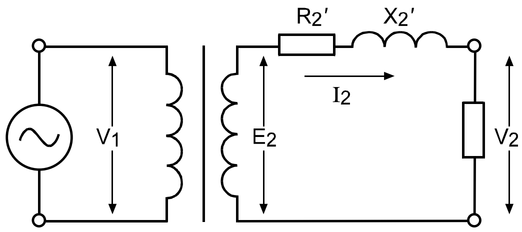
Using the results in Practical 10.2 for full load secondary current, complete Exercise 10.3 Results Table.

10.8.4 Voltage Regulation

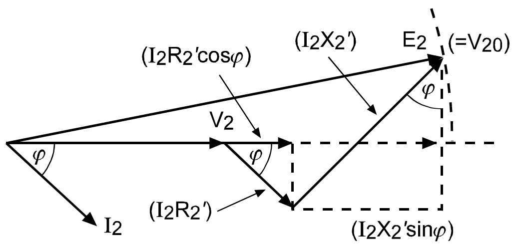
We have now reached a point where we can calculate the voltage drop across the impedance Z_2' for a given value of load current in the secondary winding. We can use this to find the regulation as a percentage of the no-load secondary voltage.

The load applied to the transformer secondary may be purely resistive or have an inductive or capacitive component, e.g. an induction motor or a long unloaded transmission line. Our calculation of voltage regulation must therefore take account of the nature of the load.

In Figure 3-10-6(a), the transformer on load is shown as an ideal transformer with zero winding impedance plus components representing leakage reactance and winding resistance referred to the secondary side.



(a)



(b)

Figure 3-10-6

The voltage V_2 applied to the load at the secondary terminals will be the voltage E_2 produced across the secondary of the ideal transformer but reduced by the voltage drop across the impedance formed by R_2' and X_2'.

From the equivalent circuit, we can derive a phasor diagram such as that of Figure 3-10-6(b) showing these voltage components and their phase relationship.

In this diagram, the load is inductive and the secondary current I_2 will lag the secondary terminal voltage V_2 by angle ϕ. We can see that if the load is disconnected there will be no voltage drop across R_2' or X_2' and the no-load or open circuit voltage V_{20} across the secondary terminals will be the voltage E_2.

On load the internal voltage E_2 is equal to the phasor sum of the terminal voltage V_2, the voltage drop across the winding resistance which is in phase with the load current, and that due to the leakage reactance which is in quadrature with it.

As the inherent regulation is the difference between the terminal voltage at no-load V_{20} and the terminal voltage on load V_2 we can use the phasor diagram to obtain an equation for the percentage regulation in terms of load current I_2, phase angle ϕ, and the impedance formed by R_2' and X_2'. However, this will produce a fairly complex expression and for most purposes we can derive a simplified equation. From the phasor diagram of Figure 3-10-6 (b), we can see that the expression;

$$V_2 + I_2R_2'\cos\phi + I_2X_2'\sin\phi$$

is nearly equal in magnitude to V_{20}.

Hence:

$$V_{20} - V_2 \approx I_2R_2'\cos\phi + I_2X_2'\sin\phi$$

$$\%\ \text{Regulation} = \frac{V_{20} - V_2}{V_{20}} \times 100 \approx \frac{I_2R_2\ \cos\phi + I_2X_2\sin\phi}{V_{20}} \times 100$$

As an example of the use of this equation, let us first calculate the percentage regulation when the transformer is supplying a purely resistive load (phase angle ϕ is 0°). Values for V_{20}, R_2' and X_2' are assumed.
Let:

$V_{20} = 125\ \text{V}$ no-load terminal voltage

$I_2 = 0.88\ \text{A}$ secondary load current

$R_2' = 12.3\ \Omega$ referred secondary winding resistance

$X_2' = 11.3\ \Omega$ referred leakage reactance

$\phi = 0°$ phase angle

$$\%\ \text{Regulation} \approx \frac{I_2R_2'\cos\phi + I_2X_2'\sin\phi}{V_{20}} \times 100$$

Resistive Load

$\cos\phi = 1 \qquad \sin\phi = 0$

$$\%\ \text{Regulation} \approx \frac{0.88 \times 12.3 \times 1 + 0}{125} \times 100 = 8.6\%$$

For inductive or capacitive loads, the secondary current will lag or lead the terminal voltage by phase angle ϕ. Thus a power factor of 0.5 lagging represents an inductive load whose phase angle is 60°.

Again using the values given above let us calculate the voltage regulation for a power factor of 0.6 lagging and 0.5 leading.

Inductive Load

$$\cos\phi = 0.6 \qquad \sin\phi = 0.8$$

$$\%\ \text{Regulation} = \frac{0.88\times 12.3 \text{ x } 0.6 + 0.88\times 11.3\times 0.8}{125}\times 100 = 11.5\%$$

Capacitive Load

$$\cos\phi = 0.5 \qquad \sin\phi = 0.87$$

In this case the term involving $\sin\phi$ will be negative as shown by the phasor diagram in Figure 3-10-7.

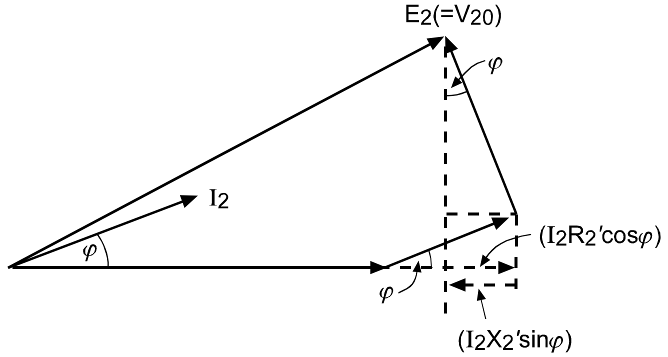


Figure 3-10-7: Phasor Diagram for a Capacitive Load

$$\%\ \text{Regulation} = \frac{0.88\times 12.3\times 0.5 - 0.88\times 11.3\times 0.87}{125}\times 100 = 2.5\%$$

10.8.5 Exercise 10.4

Use the results obtained in Practical 10.1 to calculate the voltage regulation of the transformer for a load current of 2 A at 0.6 power factor lagging.

10.8.6 Questions

Question 10.1 — *Do you think it is possible for a transformer to have a full load terminal voltage which is greater than its no-load terminal voltage?*

What load condition may produce this result?

10.9 Practical Aspects

In many transformer applications, it is important to limit the variation in secondary voltage which will occur as the load is changed. In power system work, the electricity supply authority will normally specify the maximum and minimum voltage which will be provided at the consumer terminals.

In power system transformer variation in secondary voltage may be limited by automatic tap-changing equipment which senses the output voltage and effectively alters the turns ratio to suit the load. However, the attainment of low inherent regulation can only be brought about by reducing the winding resistance and leakage reactance of the transformer. This in turn requires an increase in the cross-sectional area of copper in the winding and of iron in the core. Both these steps would lead to an increase in the size and cost, so a compromise is reached and a value of regulation is specified which is acceptable to the user (such as British Standards Institute BS2214 - Performance of Power Transformers not Exceeding 2 kVA) calls for a regulation not greater than 10% unless otherwise specified by the purchaser.

In assessing regulation, direct measurement from load tests is to be preferred over calculated values derived from open and short circuit tests. In small transformers, this is often possible but for large transformers it may not be practical to provide the load required; indirect methods must then be used.

The method described in this assignment is in common use though a lengthier and more precise expression for percentage regulation is sometimes employed, particularly where this figure is less than 5%. The measuring instruments will also be calibrated against recognised standards at regular intervals.

Generally, the efficiency of a transformer is greatest at its full load rating. It can be shown that efficiency is a maximum when the copper loss is equal to the fixed core loss.

In power transformers which operate over a range of load conditions, it is usual to design the transformer so that the copper loss is equal to the core loss at around 50% of full load, giving an efficiency/load curve similar to that in Exercise 10.2 graph.

For this reason, when specifying a transformer it is best to provide information on the load range over which it will operate.

Notes

10.10 Practical 10.1 - Results Table (230 V Product Version)

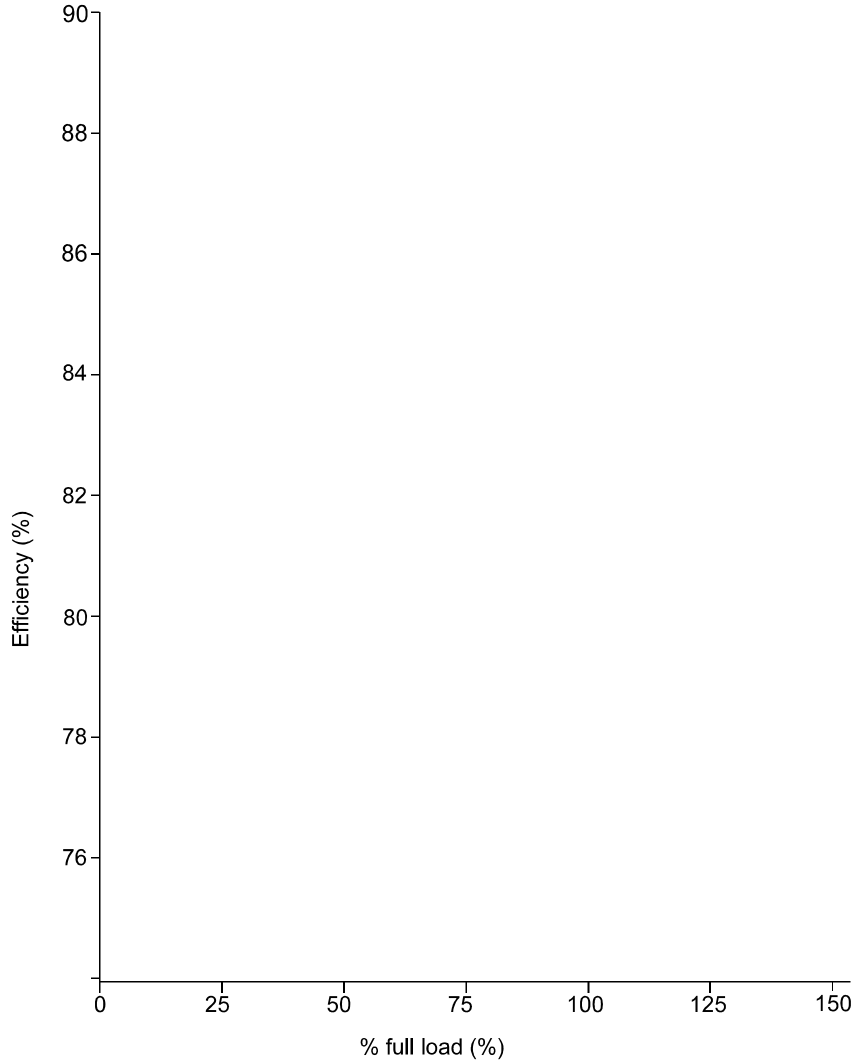
Open Circuit Test			
Primary Volts V_1	Primary Current I_0	Input Power P_1	Secondary Volts V_2

10.11 Practical 10.2 - Results Table (230 V Product Version)

Short Circuit Test				
Primary Voltage (V)	Primary Current (A)	Input Power (W)	Secondary Current (A)	Load (%)
			0.22	25
			0.44	50
			0.66	75
			0.88	100
			1.1	125
			1.33	150

10.12 Exercise 10.1 - Results Table and Graph (230 V Product Version)

% Full Load	Output Power (W)	Core Loss P_{oc}	Copper Loss P_{sc}	$P_{OC} + P_{SC}$	$\text{Output} + (P_{OC} + P_{SC})$	$\dfrac{P_{OC} + P_{SC}}{\text{Output} + (P_{OC} + P_{SC})}$	Efficiency (%)
25							
50							
75							
100							
125							
150							



10.13 Exercise 10.3 - Results Table (230 V Product Version)

$\frac{V_{20}}{V_{10}} = n$	$Z_2' = \frac{V_{1SC}}{I_{1SC}} \times n^2$	$R_2' = \frac{W_{1SC}}{(I_{1SC})^2} \times n^2$	$X_2' = \sqrt{(Z_2')^2 - (R_2')^2}$

10.14 Practical 10.1 - Results Table (120 V Product Version)

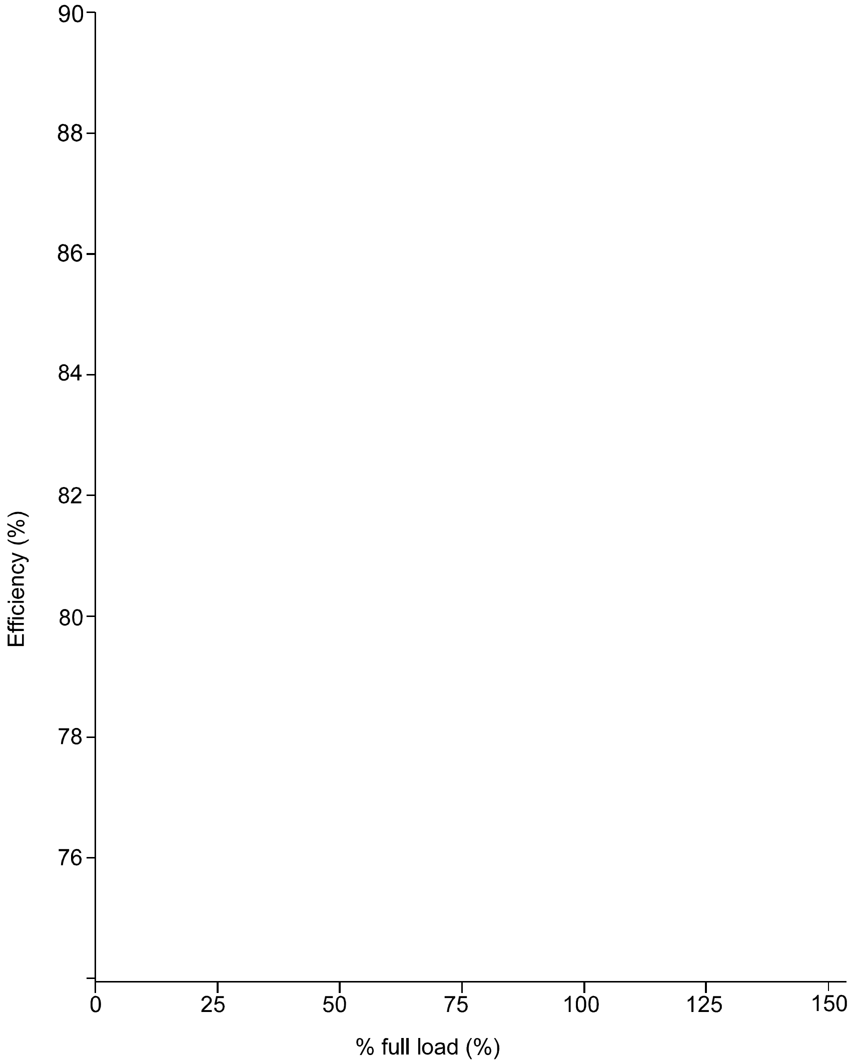
Open Circuit Test			
Primary Volts V_1	Primary Current I_0	Input Power P_1	Secondary Volts V_2

10.15 Practical 10.2 - Results Table (120 V Product Version)

Short Circuit Test				
Primary Voltage (V)	Primary Current (A)	Input Power (W)	Secondary Current (A)	Load (%)
			0.22	25
			0.44	50
			0.66	75
			0.88	100
			1.1	125
			1.33	150

10.16 Exercise 10.1 - Results Table and Graph (120 V Product Version)

% Full Load	Output Power (W)	Core Loss P_{oc}	Copper Loss P_{sc}	$P_{OC} + P_{SC}$	$\text{Output} + (P_{OC} + P_{SC})$	$\frac{P_{OC} + P_{SC}}{\text{Output} + (P_{OC} + P_{SC})}$	Efficiency (%)
25							
50							
75							
100							
125							
150							



10.17 Exercise 10.3 - Results Table (120 V Product Version)

$\frac{V_{20}}{V_{10}} = n$	$Z_2' = \frac{V_{1SC}}{I_{1SC}} \times n^2$	$R_2' = \frac{W_{1SC}}{(I_{1SC})^2} \times n^2$	$X_2' = \sqrt{(Z_2')^2 - (R_2')^2}$

4 Three Phase Transformer Assignments

4.1 Introduction

This chapter contains assignments for the Three Phase Transformer Trainer which together with the Single Phase Transformer form the 60-070-TFM 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 power conversion and distribution to be investigated.

The assignments are:

11 Star and Delta Transformer

12 Star and Delta Loads

13 Interconnected Star (Zigzag) Transformation

14 Power in Star Secondary Windings

15 Power in Delta Secondary Windings

16 Six Phase Transformers

17 Four Wire Systems

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

4.2 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 the Reference Manual 60-070-TFM.

4.3 Wiring Diagrams

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

After this assignment, the student should be 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.

4.4 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 for the recording of measurements etc are given at the end of the assignment for both versions (230 V and 120 V) of the trainer.

11 Star and Delta Transformation

11.1 Assignment Information

11.1.1 Objectives

When you have completed this assignment you will:

- be familiar with the trainer,
- understand the principles of isolation and voltage reduction,
- be able to derive the voltage and phase relationships of commonly used three phase transformers.

11.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have a clear understanding of voltage and current in simple ac circuits,
- you should have some knowledge of basic transformer operation,
- 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.

11.1.3 Practicals

1. Delta to Star Transformation
2. Star to Star Transformation
3. Star to Delta Transformation
4. Delta to Delta Transformation

NOTE:

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

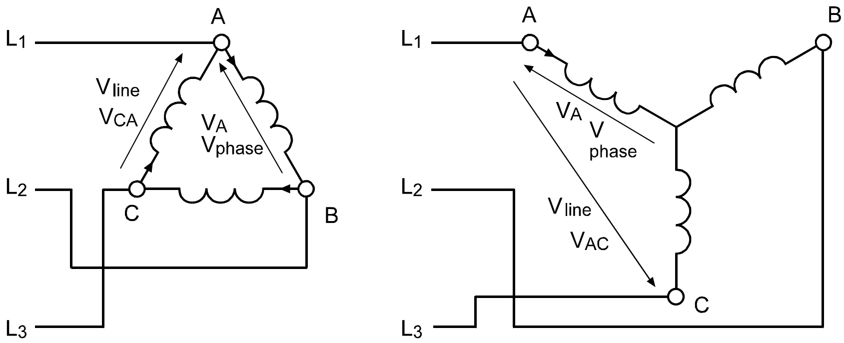
Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

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 Transformer Connections

Every three phase device (eg, transformers, generators or motors) has elements or windings that can be segregated into three divisions. It is usual to describe each division as a phase. The two usual ways of connecting the three divisions are known as *star* and *delta*. Figure 4-11-1 shows the two connections.



(a) Delta (b) Star

Figure 4-11-1

The term V_{line} refers to the line voltage, that is the voltage between any two lines of a three phase system.

The term V_{phase} refers to the phase voltage, that is the voltage between a line and a common reference potential (generally neutral). However, this should be regarded with care as it can also be used to mean the voltage across the winding or windings associated with one phase.

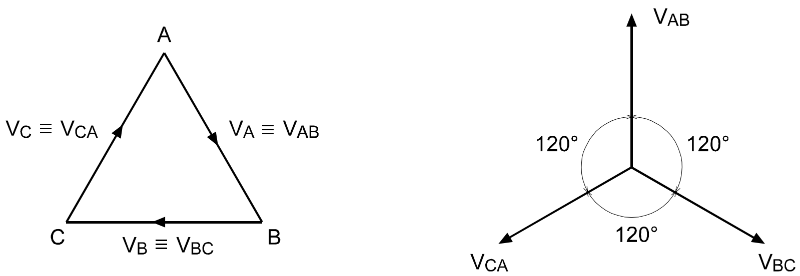
Consider the voltages in the two types of connection.

11.2.1.1 Delta Connected Windings

It can clearly be seen from Figure 4-11-1(a) that for the delta connected system the phase voltage is the same as the line voltage.

Hence:

$$V_{phase} = V_{line}$$



(a) *(b)*

Figure 4-11-2: Delta Connection Phasor Diagram

This is demonstrated in Figure 4-11-2. Figure 4-11-2(a) shows how the voltages in the windings sum to zero. Figure 4-11-2(b) shows the three voltages as separate phasors, symmetrically spaced at 120° to each other. Note there is no neutral point.

11.2.1.2 <u>Star Connected Windings</u>

Consider the voltages in the system. From Figure 4-11-1(b), it is apparent that each line voltage is the phasor difference of two of the phase voltages. That is the line voltage V_{AB} is obtained by subtracting V_B from V_A.

Figure 4-11-3 shows the phasor diagram for the voltages in the star connected system.

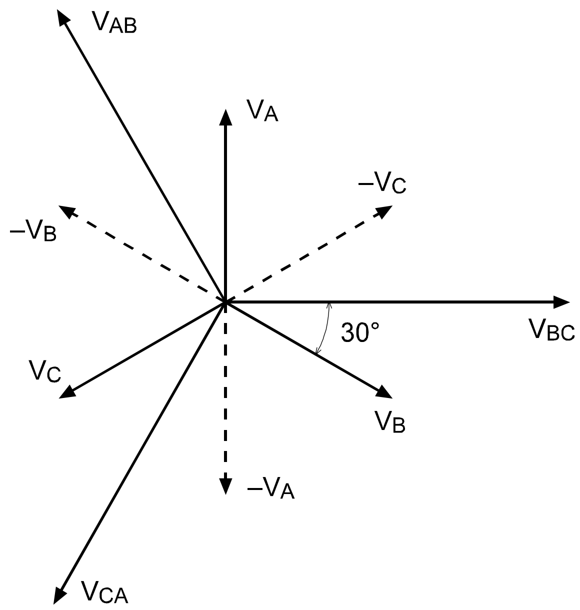


Figure 4-11-3: Star Connection Phasor Diagram

From this the relationship between the phase and the line voltages can be calculated.

$$V_{line} = 2 \times V_{phase} \cos 30 = \sqrt{3} V_{phase}$$

11.3 Content

The practicals in this assignment familiarise the student with the trainer and provide an introduction to isolation and voltage reduction.

11.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	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® 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 - Delta/Star Connected Transformer

Product Version	
230 V	120 V

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-11-6 (a) and (b) or (c). A simplified circuit is shown in Figure 4-11-4.

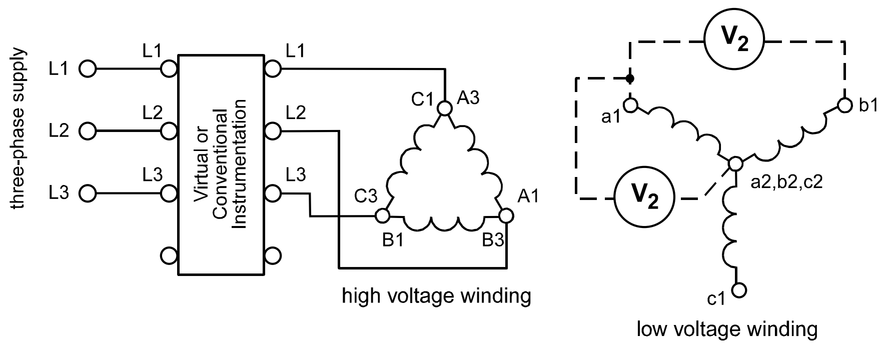


Figure 4-11-4

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

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.

	230 V	120 V
Turn the dial on the power supply so that a voltage of............................. is indicated on the primary virtual or conventional instrumentation V1.	*400 V*	*208 V*

Record the primary line voltage V1, on a copy of the appropriate Practical 11.1, Results Table (230 V or 120 V product version). Note for a delta connected primary, the phase and line voltages are the same.

Record the secondary phase voltage and secondary line voltage as read on virtual or conventional instrumentation V2, on a copy of the appropriate Practical 11.1, Results Table (230 V or 120 V product version).

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

11.6.1 Exercise 11.1

Calculate the ratio.

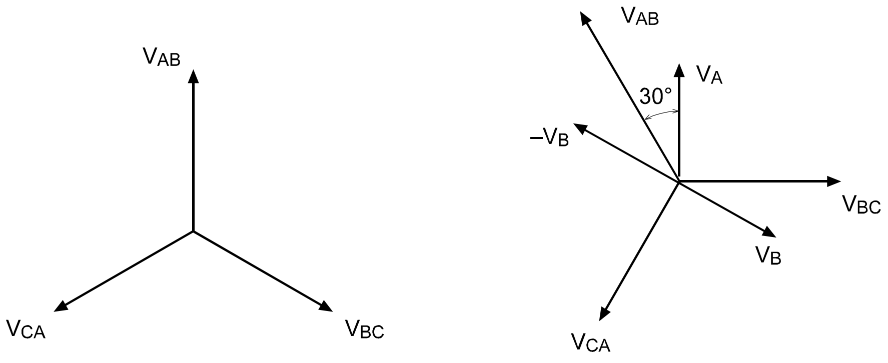
$$\frac{\text{Line Voltage}}{\text{Phase Voltage}}$$

11.6.2 Exercise 11.2

Using the theory given in the theory section draw the phasor diagram for the star connected secondary from the results obtained in the practical.

11.6.3 Practical Aspects

The delta/star connected transformer is often used as a distribution transformer so that a lead may be brought out from the neutral point for four wire distribution.



Delta connected primary
(a)

Star connected secondary
(b)

Figure 4-11-5

Figure 4-11-5 shows the line voltages for the delta connected primary and the star connected secondary as explained in the theory section. Figure 4-11-5(b) shows that the secondary voltages for this connection lead the primary by 30°.

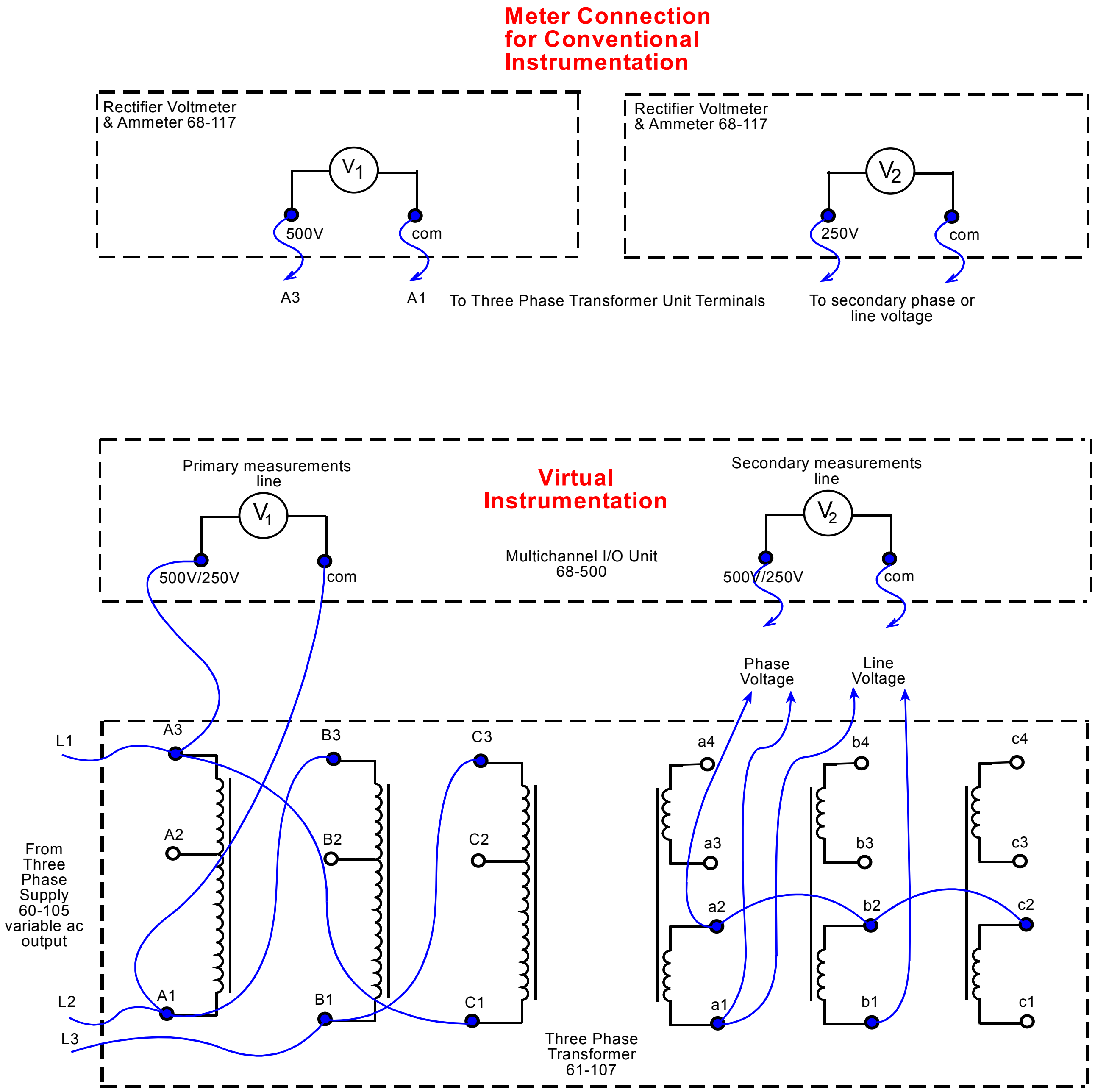
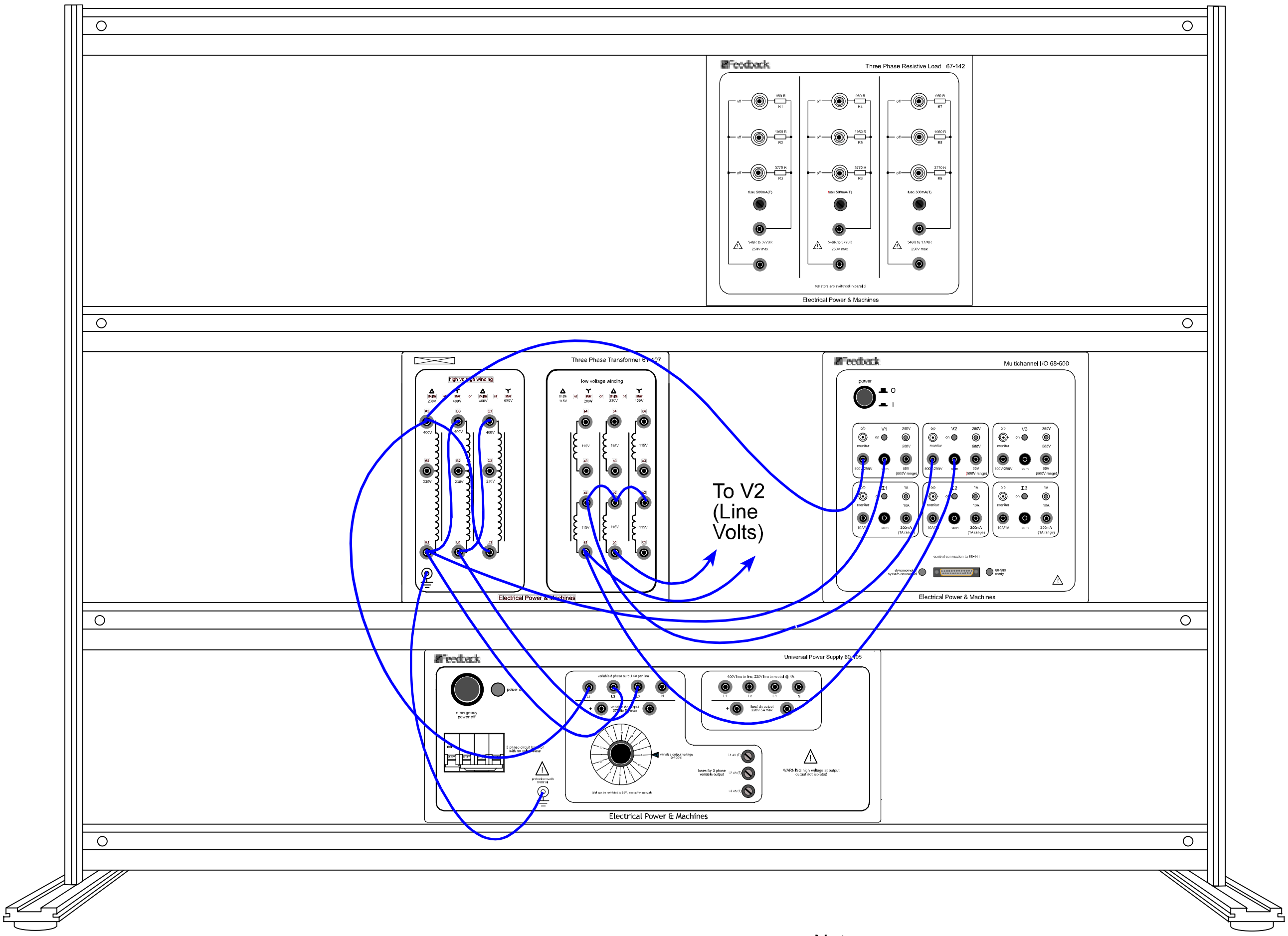


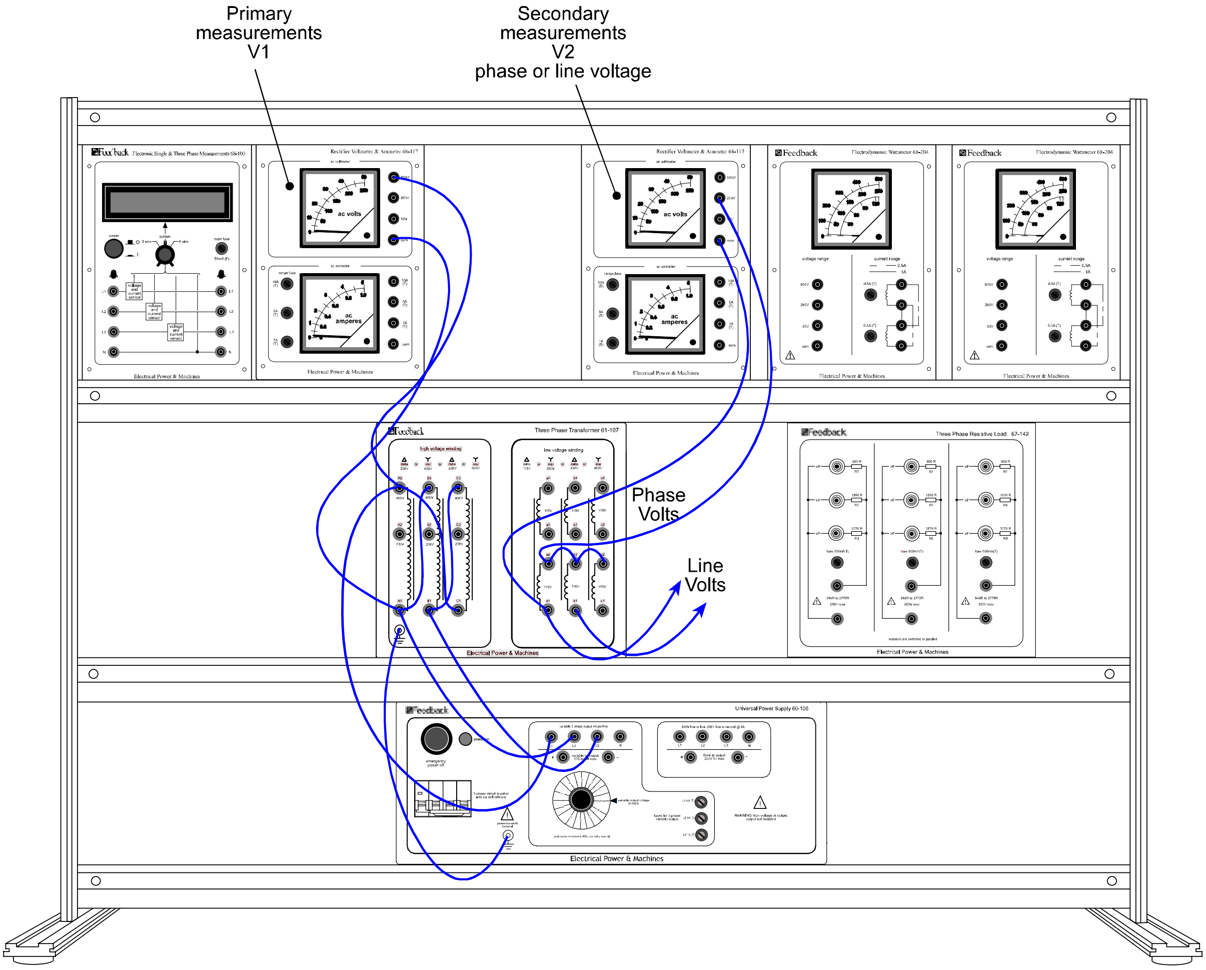
Figure 4-11-6(a): Practical 11.1 Circuit Diagram



Note:
Phase Voltage connections to V2 are shown to 68-500.

For Line voltage connections, disconnect phase voltage connections and connect the meter V2 to the 'Line volts' connecting as shown.

Figure 4-11-6(b): Wiring Diagram (Virtual Instrumentation)



Note:
Phase Voltage connections
to the voltmeter are shown.

For line voltage connections,
disconnect phase voltage connections
and connect the meter V2 to the 'line
.volts' connections shown.

Figure 4-11-6(c): Wiring Diagram (Conventional Instrumentation)

11.7 Practical 11.2 - Star/Star Connected Transformer

Product Version	
230 V	**120 V**

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-11-8 (a) and (b) or (c). A simplified circuit is shown in Figure 4-11-7.

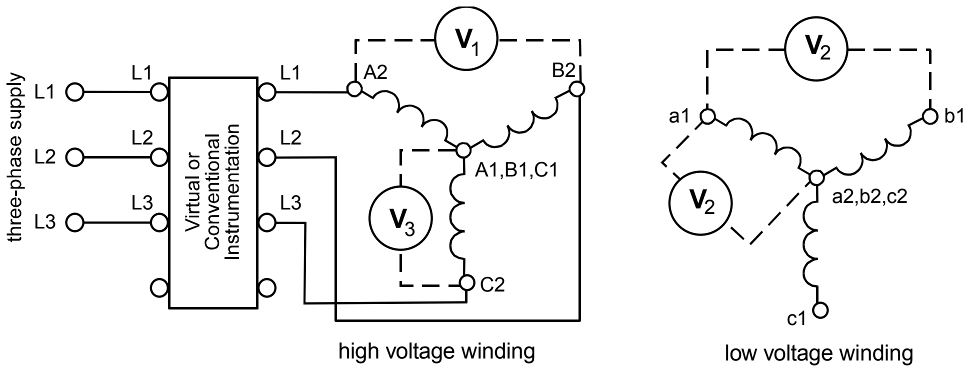


Figure 4-11-7

If virtual instrumentation is being used, set the 250 V/500 V range switches for the 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. Set channel V1 to 500 V range.

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.

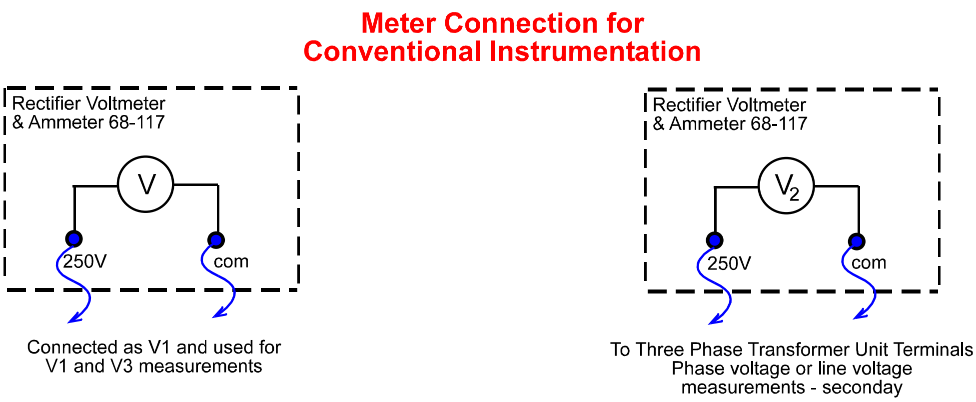
Turn the dial on the power supply so that a voltage of.......................... is indicated on the primary virtual or conventional instrumentation V1 meter.

230 V	120 V
400 V	*208 V*

Record the primary line and phase voltage V1/V3, on a copy of the appropriate Practical 11.2, Results Table (230 V or 120 V product version).

Record the secondary phase voltage and secondary line voltage as read on virtual or conventional instrumentation V2, on a copy of the appropriate Practical 11.2, Results Table (230 V or 120 V product version).

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



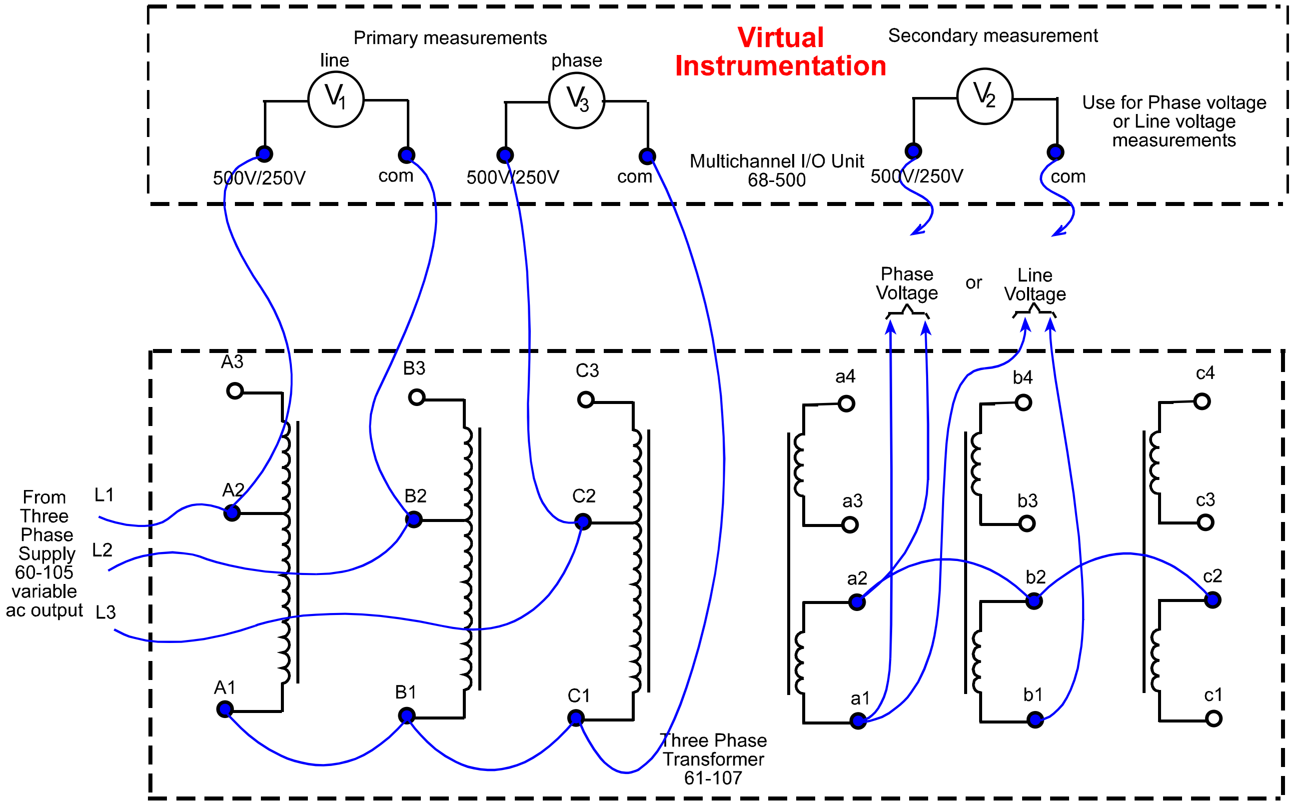
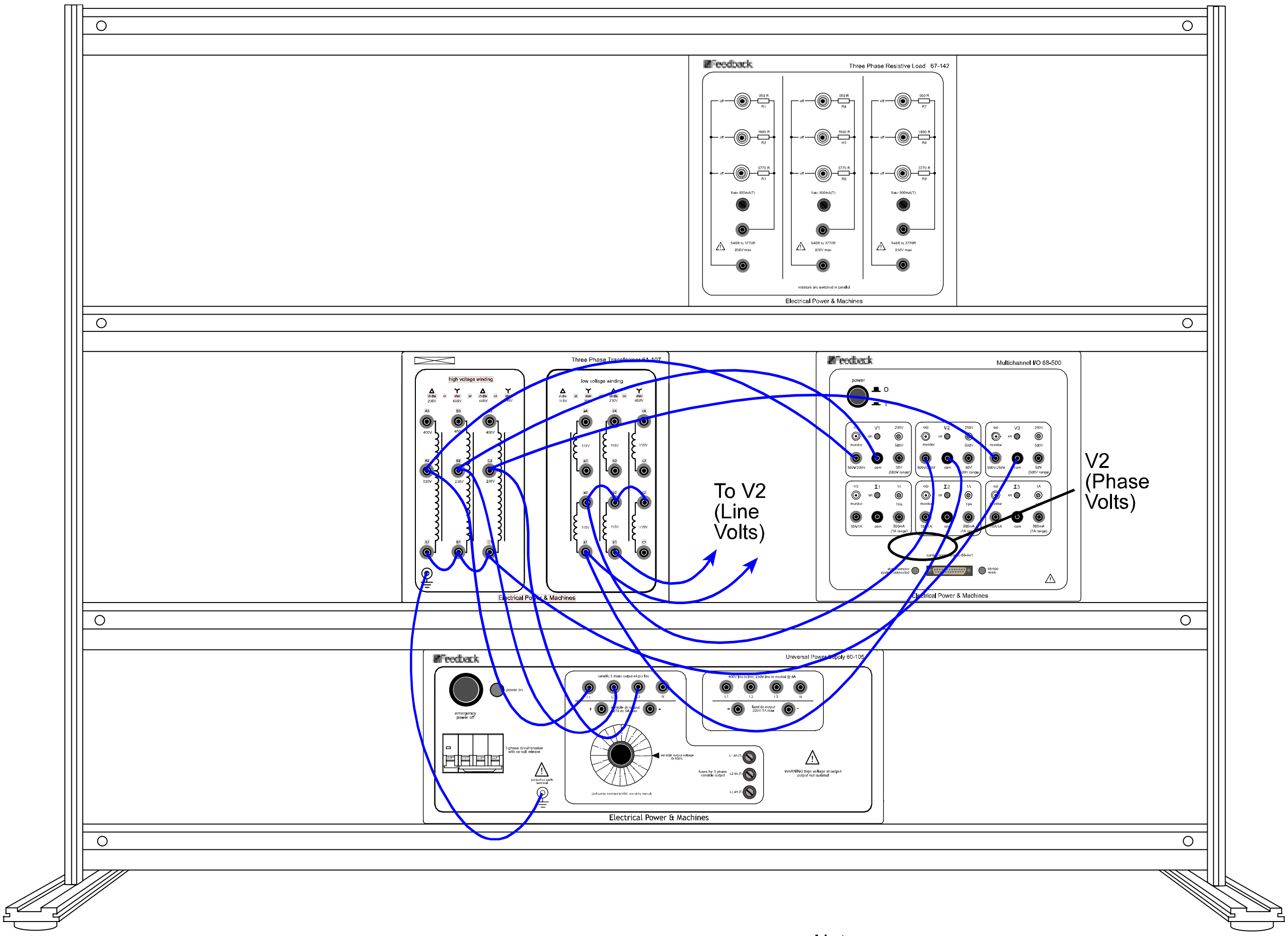


Figure 4-11-8(a): Practical 11.2 Circuit Diagram



Note:
Phase Voltage connections to V2 are shown to 68-500.

For Line voltage connections, disconnect phase voltage connections and connect the meter V2 to the 'line volts' connections shown.

Figure 4-11-8(b): Practical 11.2 Wiring Diagram (Virtual Instrumentation)

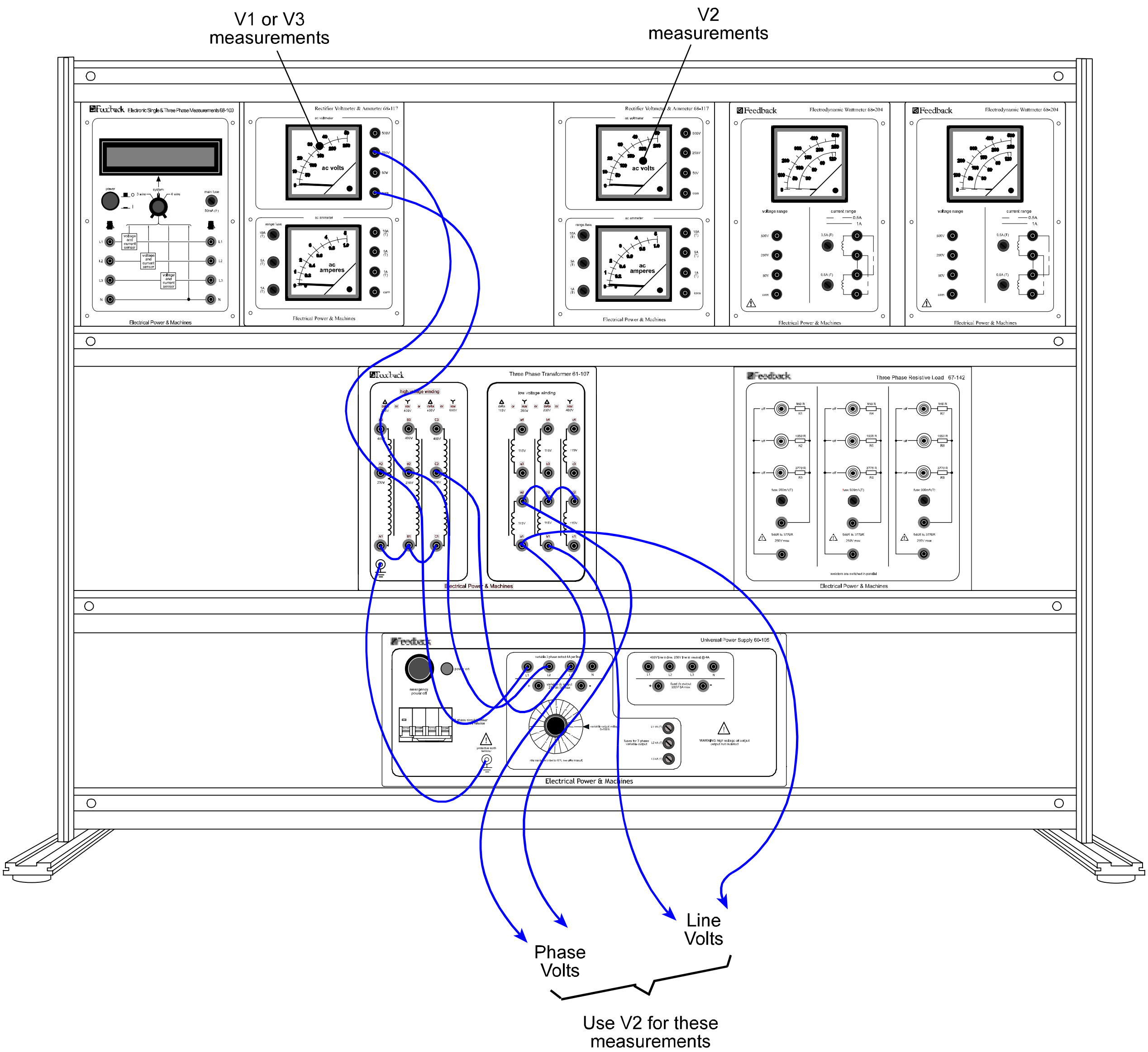


Figure 4-11-8(c): Practical 11.2 Wiring Diagram (Conventional Instrumentation)

11.7.1 Exercise 11.3

Using the equation relating phase and line voltages given in the theory section for a star connected system.

$$V_{line} = \sqrt{3}V_{phase}$$

Calculate the primary star connected phase voltage.

How does the primary phase voltage for the star connected system compare to the primary phase voltage for the delta connected system?

11.7.2 Practical Aspects

It can be seen that both connections for Practicals 11.1 and 11.2 both provide the same secondary voltages per phase. However, if we consider the primary voltages it becomes apparent that the delta connected primary needs a higher phase voltage than the star connected primary in order to produce the same voltage per phase at the secondary.

It is for this reason that the star/star connection is preferred by many supply authorities, since it is more economical for high voltage applications as it minimises the turns per phase and the winding insulation.

Another advantage of the star/star connected transformer is that with star points available on both sides it is possible to provide a neutral connection.

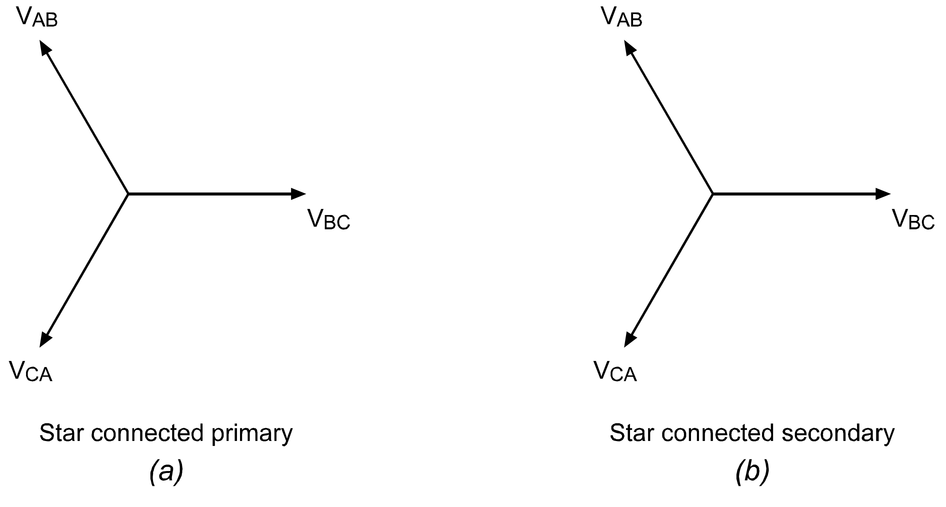


Figure 4-11-9

Figure 4-11-9 shows the line voltages for the star connected primary and the star connected secondary as explained in the Theory section. Figure 4-11-9(b) shows that the secondary voltages for this connection are in phase with the primary.

11.8 Practical 11.3 - Star/Delta Connected Transformer

Product Version	
230 V	**120 V**

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-11-11(a) and (b) or (c). A simplified circuit is shown in Figure 4-11-10.

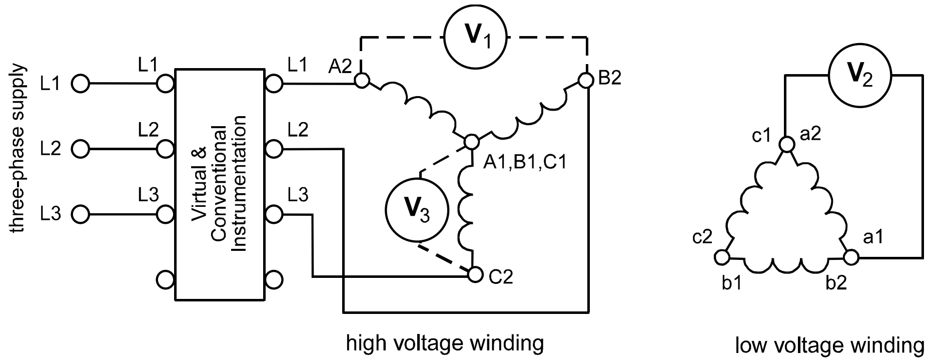


Figure 4-11-10

If virtual instrumentation is being used, set the 250 V/500 V range switches for the 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. Set channel 1 to 500 V range.

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.

	230 V	120 V
Turn the dial on the power supply so that a voltage of.......................... is indicated on the primary virtual or conventional instrumentation V1.	*400 V*	*208 V*

Record the primary line voltage, on a copy of the appropriate Practical 11.3, Results Table (230 V or 120 V product version).

Record the secondary phase line voltage as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 11.3, Results Table (230 V or 120 V product version).

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

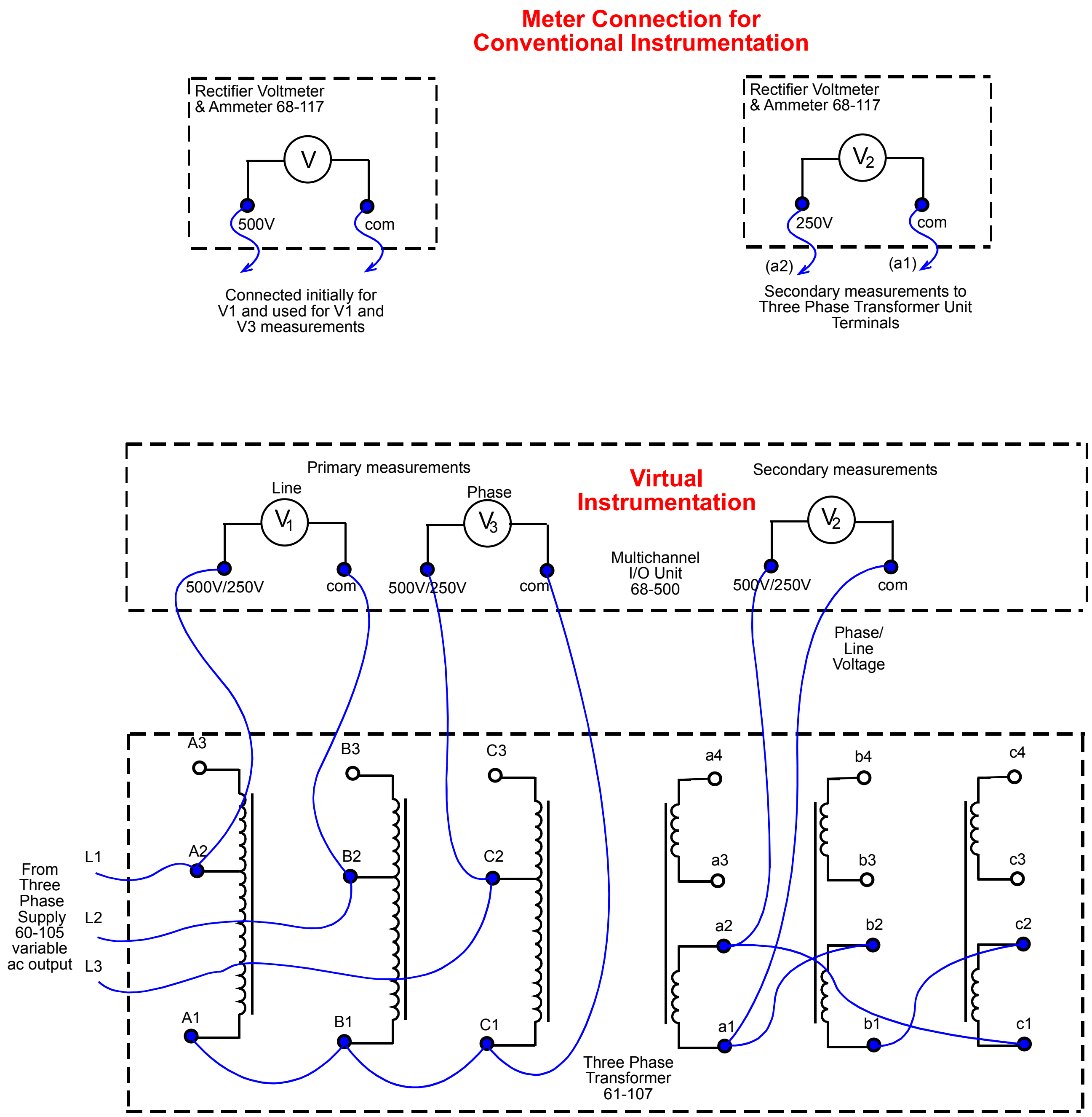


Figure 4-11-11(a): Practical 11.3 Circuit Diagram

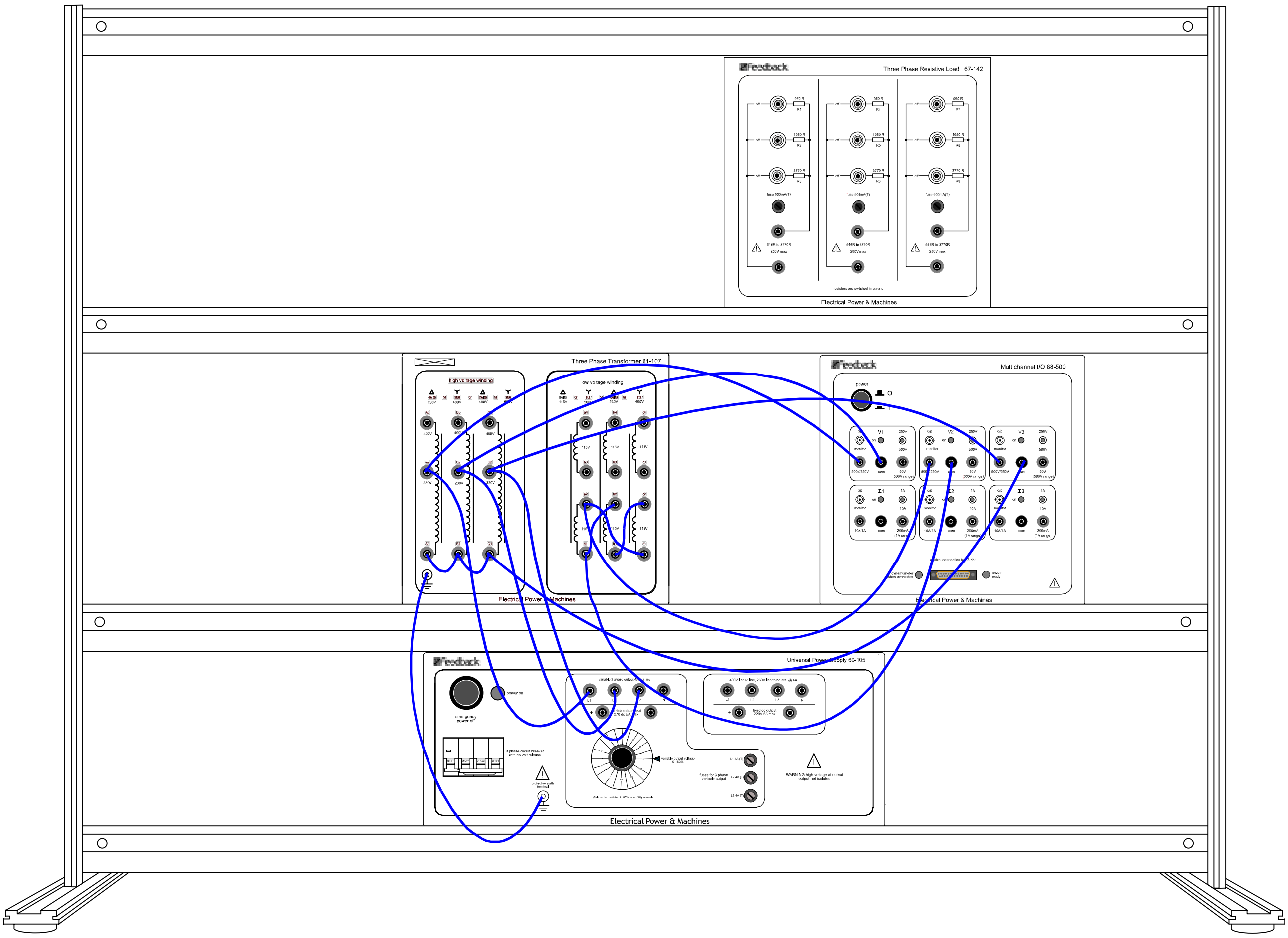


Figure 4-11-11(b): Practical 11.3 Wiring Diagram (Virtual Instrumentation)

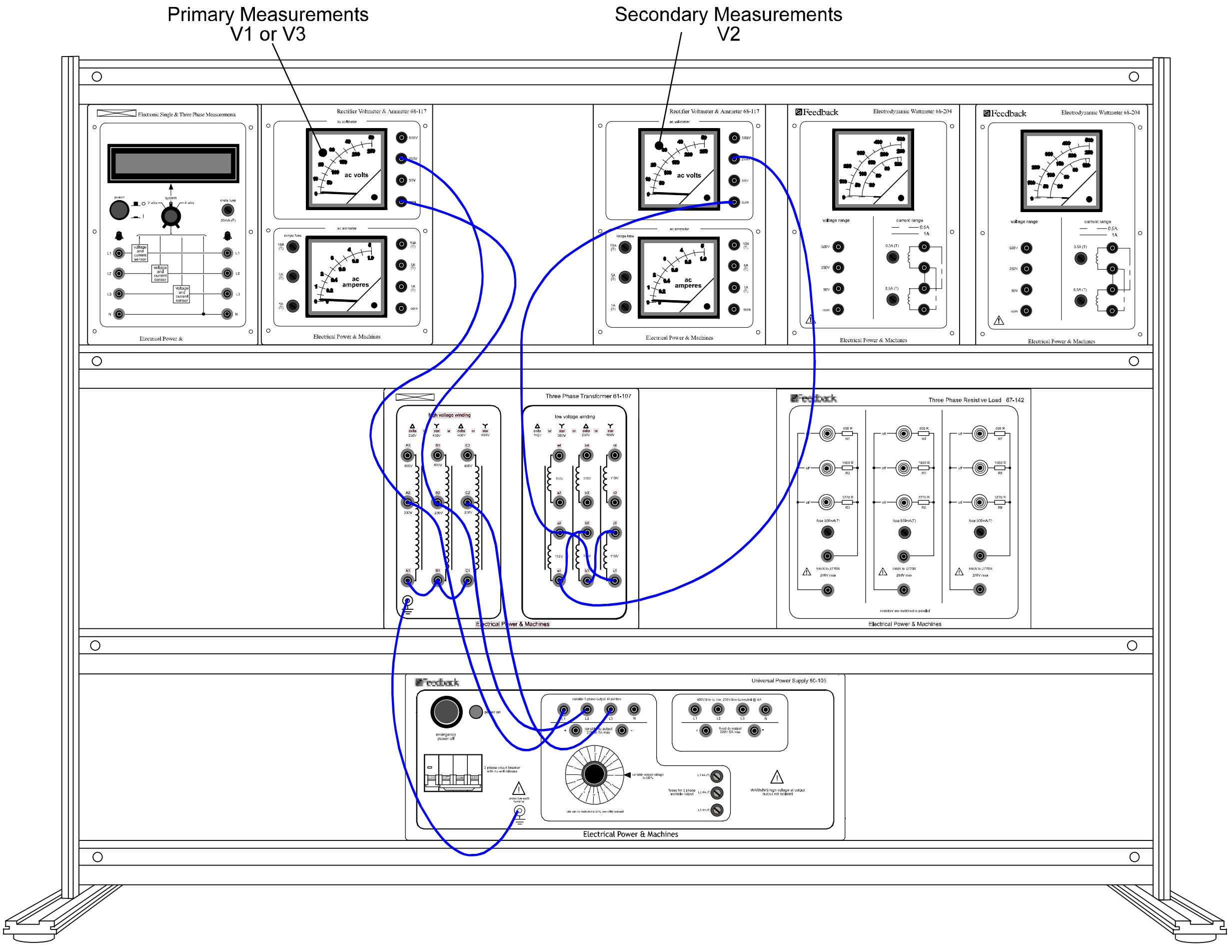


Figure 4-11-11(c): Practical 11.3 Wiring Diagram (Conventional Instrumentation)

11.8.1 Practical Aspects

The star/delta connection is often used for step down supply networks to three phase balanced loads. The delta connected windings can carry third harmonic currents that provide a sinusoidal flux that help to stabilise the starpoint voltage**.**

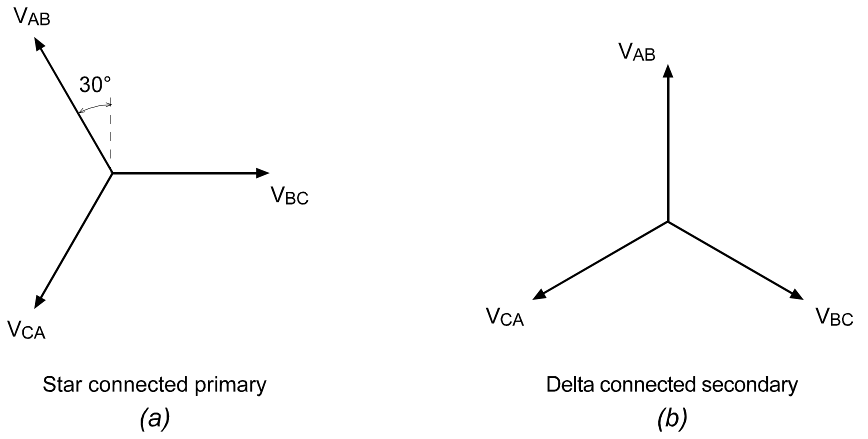


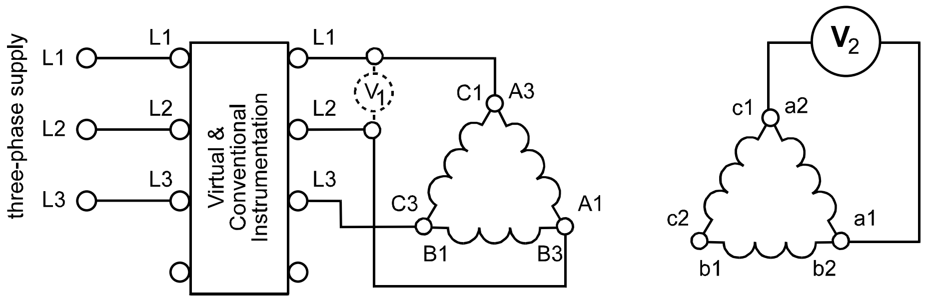
Figure 4-11-12

Figure 4-11-12 shows the line voltages for the star connected primary and the delta connected secondary as explained in the Theory section. Figure 4-11-12(b) shows that the secondary voltages for this connection lag the primary by 30°.

11.9 Practical 11.4 - Delta/Delta Connected Transformer

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-11-14(a) and (b) or (c). A simplified circuit is shown in Figure 4-11-13.



high voltage winding   low voltage winding

Figure 4-11-13

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

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.

Turn the dial on the power supply so that a voltage of………………………. is indicated on the primary virtual or conventional instrumentation V1.

Product Version	
230 V	**120 V**
400 V	*208 V*

Record the primary line voltage, on a copy of the appropriate Practical 11.4, Results Table (230 V or 120 V product version). Note that for delta connection phase and line voltages are the same.

Record the secondary line voltage as read on virtual or conventional instrumentation V2, on a copy of the appropriate Practical 11.4, Results Table (230 V or 120 V product version).

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

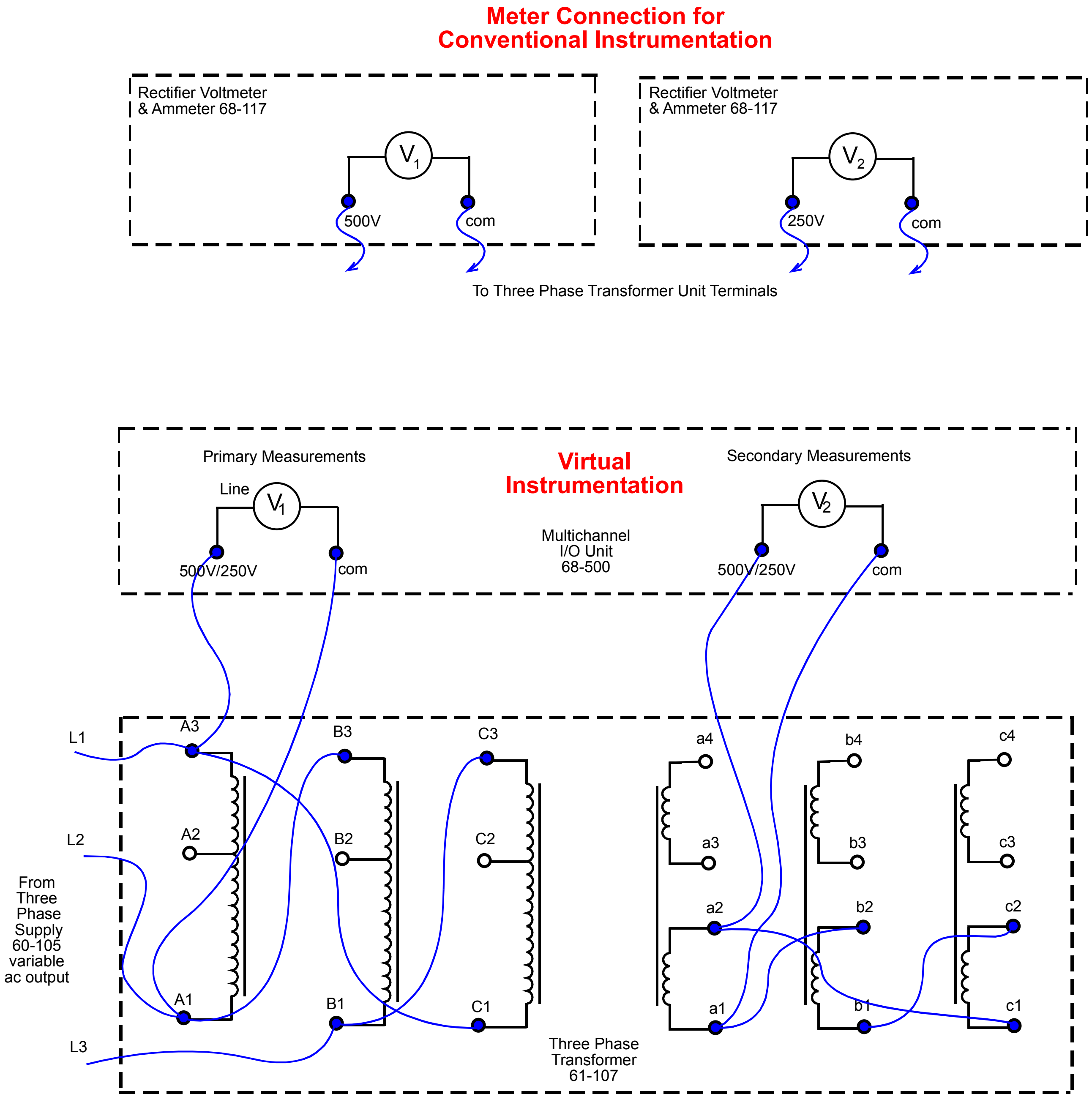


Figure 4-11-14(a): Practical 11.3 Circuit Diagram

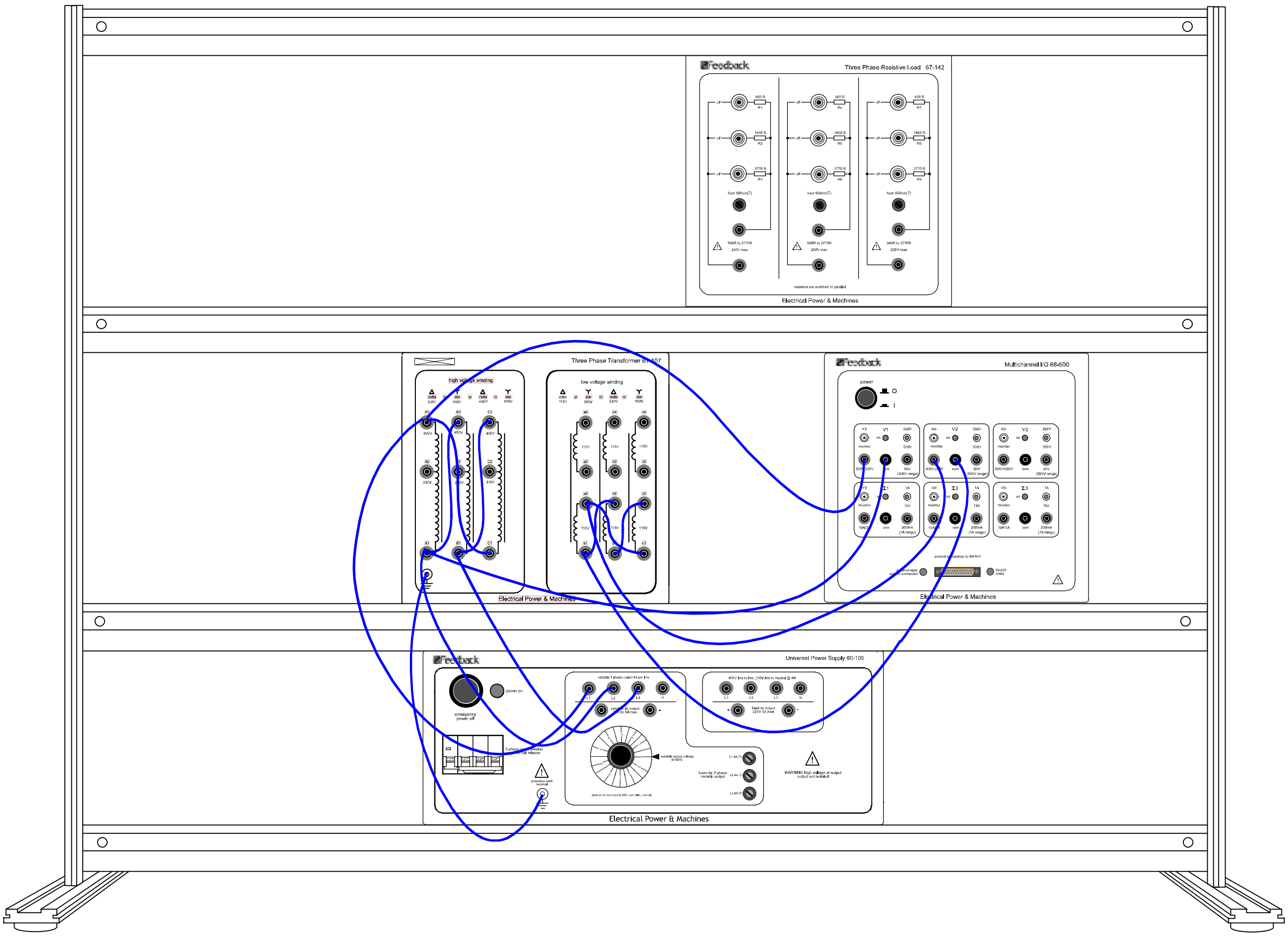


Figure 4-11-14(b): Practical 11.4 Wiring Diagram (Virtual Instrumentation)

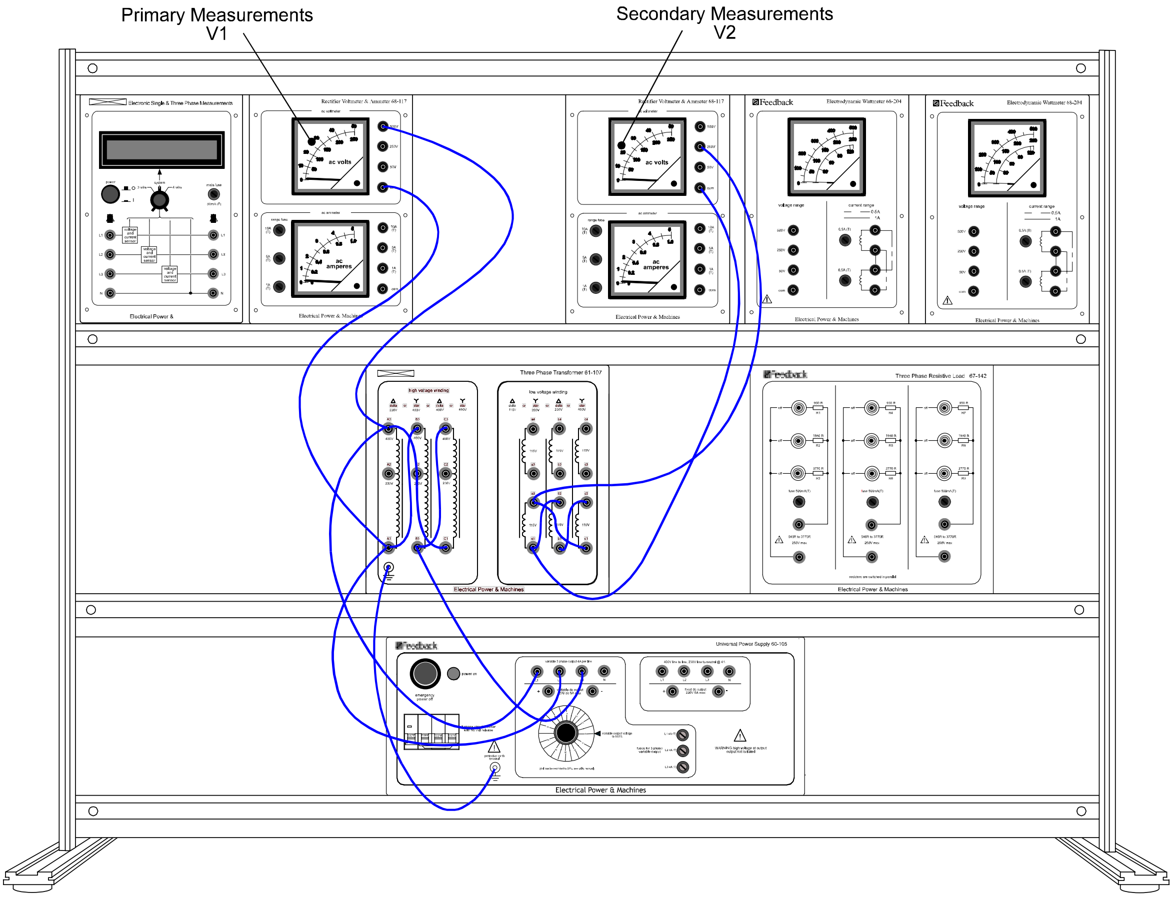


Figure 4-11-14(c): Practical 11.4 Wiring Diagram (Conventional Instrumentation)

Exercise 11.4

Calculate the voltage across each primary phase winding.

The turns ratio can be found from:

$$\frac{\text{Primary Phase Voltage}}{\text{Secondary Phase Voltage}} = \text{Turns Ratio}$$

11.9.1 Practical Aspects

The delta/delta connected transformer is more suited to large low voltage applications. However it is more expensive than its equivalent with star windings due to the greater number of turns and hence insulation materials required.

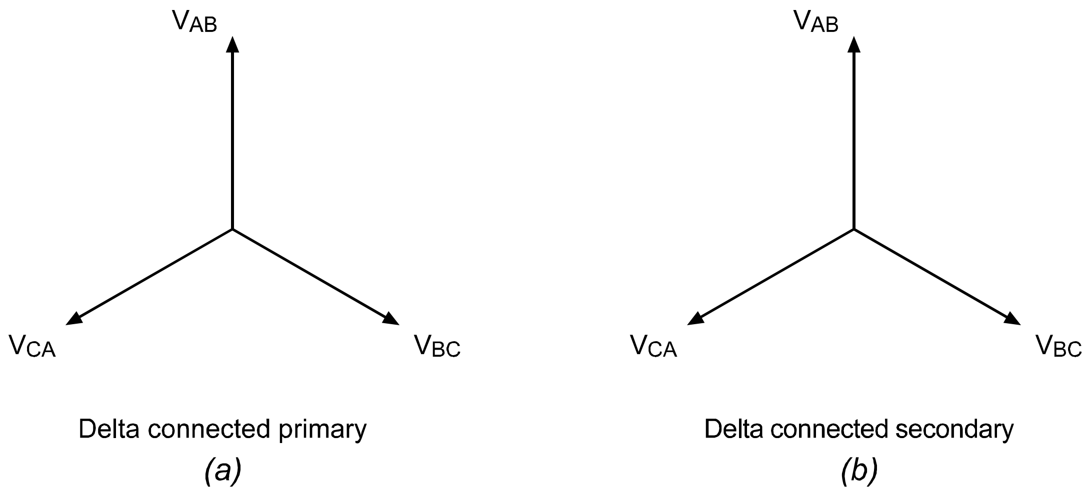


Figure 4-11-15

Figure 4-11-15 shows the line voltages for the delta connected primary and the delta connected secondary as explained in the Theory section. The figure shows that the primary and secondary voltages for this connection are in phase.

11.10 Practical 11.1 - Results Tables (230 V Product Version)

Delta Connected Primary	Star Connected Secondary			
Primary Line Voltage (V)	Phase Voltages (V)		Line Voltages (V)	
	V_{a1a2}		V_{a1b1}	

11.11 Practical 11.2 - Results Tables (230 V Product Version)

Star Connected Primary		Star Connected Secondary			
Line Voltage (V)	Phase Voltage (V)	Phase Voltages (V)		Line Voltages (V)	
		V_{a1a2}		V_{a1b1}	

11.12 Practical 11.3 - Results Tables (230 V Product Version)

Star Connected Primary		Delta Connected Secondary	
Line Voltage (V)	Phase Voltage (V)	Phase/Line Voltages (V)	
		V_{a1a2}	

11.13 Practical 11.4 - Results Tables (230 V Product Version)

Delta Connected Primary	Delta Connected Secondary	
Primary Line Voltage (V)	Phase/Line Voltages (V)	
	V_{a1a2}	

11.14 Practical 11.1 - Results Tables (120 V Product Version)

Delta Connected Primary	Star Connected Secondary			
Primary Line Voltage (V)	Phase Voltages (V)		Line Voltages (V)	
	V_{a1a2}		V_{a1b1}	

11.15 Practical 11.2 - Results Tables (120 V Product Version)

Star Connected Primary		Star Connected Secondary			
Line Voltage (V)	Phase Voltage (V)	Phase Voltages (V)		Line Voltages (V)	
		V_{a1a2}		V_{a1b1}	

11.16 Practical 11.3 - Results Tables (120 V Product Version)

Star Connected Primary		Delta Connected Secondary	
Line Voltage (V)	Phase Voltage (V)	Phase/Line Voltages (V)	
		V_{a1a2}	

11.17 Practical 11.4 - Results Tables (120 V Product Version)

Delta Connected Primary	Delta Connected Secondary	
Primary Line Voltage (V)	Phase/Line Voltages (V)	
	V_{a1a2}	

12 Star and Delta Loads

12.1 Assignment Information

12.1.1 Objectives

When you have completed this assignment you will:

- understand the behaviour of current in three phase systems,
- be able to derive the current and phase relationships of commonly used three phase transformers.

12.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignment 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. Delta Supply Star Load
2. Star Supply Star Load
3. Star Supply Delta Load
4. Delta Supply Delta Load

NOTE:

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

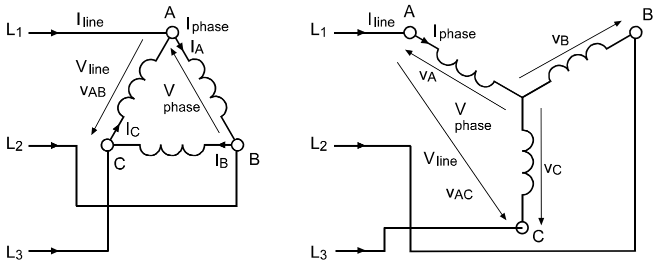
Where parameters specific to an appropriate trainer versions are given within a practical, they appear in a table adjacent to the associated step of the practical procedure.

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

12.2 Theory

12.2.1 Transformer Connections

Assignment 11 introduced three phase star and delta connections. Figure 4-12-1 demonstrates the current flow in the windings for both connections.



Delta connected
(a)

Star connected
(b)

Figure 4-12-1

The term I_{line} refers to the line current, that is the current through each connection line to the three phase system.

The term I_{phase} refers to the phase current, that is the current through each individual phase winding.

Consider the currents in the two types of connection.

12.2.1.1 Star Connected Windings

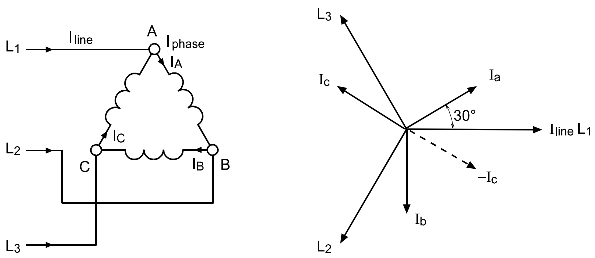
It can be clearly seen from Figure 4-12-1(b) that for the star connected system the phase current is the same as the line current.

Hence:

$$I_{phase} = I_{line}$$

12.2.1.2 Delta Connected Windings

Figure 4-12-2 shows the phasor diagram for the currents in the delta connected system.



Delta connected

(a) *(b)*

Figure 4-12-2

From this, the relationship between phase and line currents can be calculated.

$$I_{line} = 2 \times I_{phase} \cos 30 = \sqrt{3} I_{phase}$$

12.3 Content

The practicals in this assignment provide an introduction to balanced three phase systems.

12.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation 60-070-VIP	• Multichannel I/O Unit • Software Pack CD	68-500 68-912-USB
	or	
Conventional Instrumentation 60-070-CI2	• Rectifier Voltmeter & Ammeter (two off)	68-117

- Auxiliary Equipment

  Digital multimeter (Not provided)

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® 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 - Delta Supply Star Load

Product Version	
230 V	**120 V**
548 Ω per phase	*140 Ω per phase*

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-12-4. A simplified circuit is shown in Figure 4-12-3.

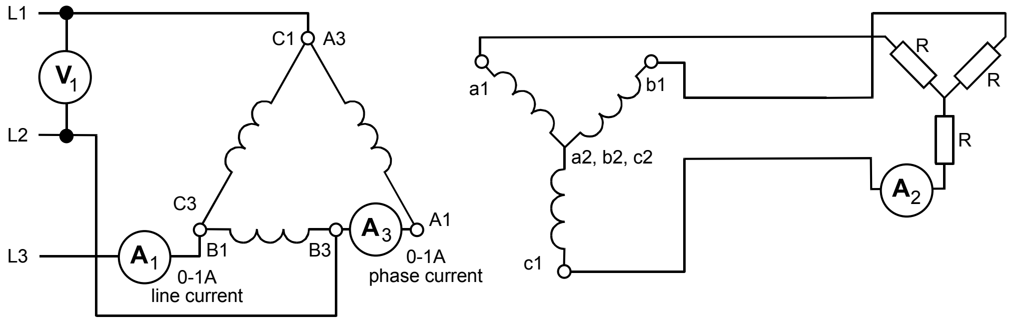


Figure 4-12-3

If virtual instrumentation is being used, set the 1 A/10 A range switches for the I1, I2 and I3 channels to 1 A on the Multichannel I/O Unit 68-500. This also allows low currents of up to 200 mA to be monitored when the 200 mA sockets are connected, with the range being software selected.

Set the Voltmeter V1 range switch to the 500 V range.

Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance load of……………………….

	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.		
Turn the dial on the power supply to set the primary voltage V1 to………………………………………………………………………………………	*400 V*	*216 V*

Record the primary line current, the primary phase current and the average line/phase secondary current as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 12.1, Results Table (230 V or 120 V product version).

Complete the appropriate Practical 12.1, Results Table for the load values listed in the table.

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

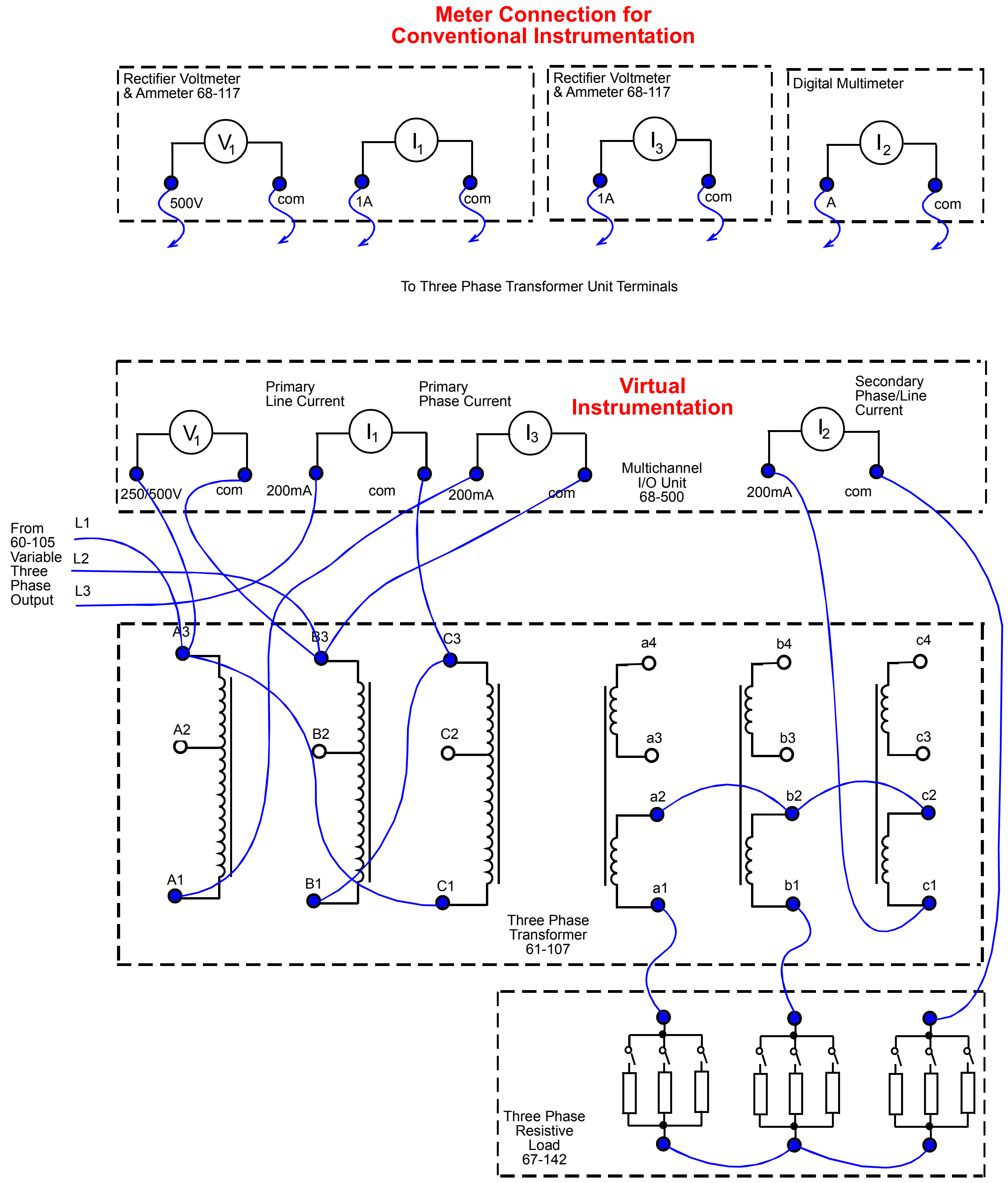


Figure 4-12-4: Practical 12.1 Circuit Diagram

12.7 Practical 12.2 - Star Supply Star Load

Product Version	
230 V	120 V

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-12-6. A simplified circuit is shown in Figure 4-12-5.

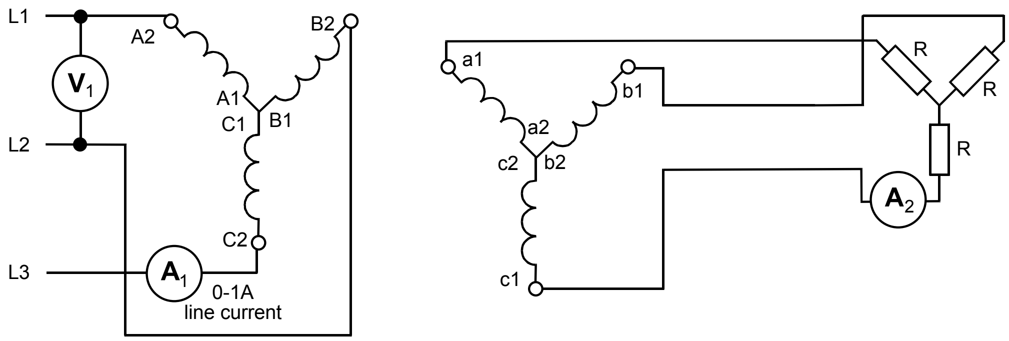


Figure 4-12-5

If virtual instrumentation is being used, set the 1 A/10 A range switches for the I1 and I2 channels to 1 A on the Multichannel I/O Unit 68-500. This also allows low currents of up to 200 mA to be monitored when the 200 mA sockets are connected, with the range being software selected.

	230 V	120 V
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance load of..........................	*548 Ω per phase*	*140 Ω per phase*

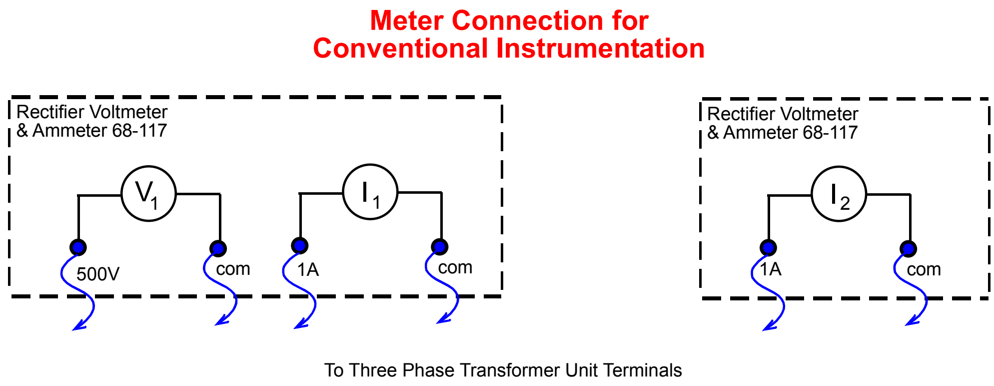
On the Universal Power Supply 60-105, ensure the *'variable output voltage'* control is set to 0% then set the *'3 phase circuit breaker'* to the on position.

	230 V	120 V
Turn the dial on the power supply to set the primary voltage V1 to..................	*400 V*	*216 V*

Record the primary phase/line current and the average line/phase secondary current as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 12.2, Results Table (230 V or 120 V product version).

Complete the appropriate Practical 12.2, Results Table for the load values listed in the table.

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



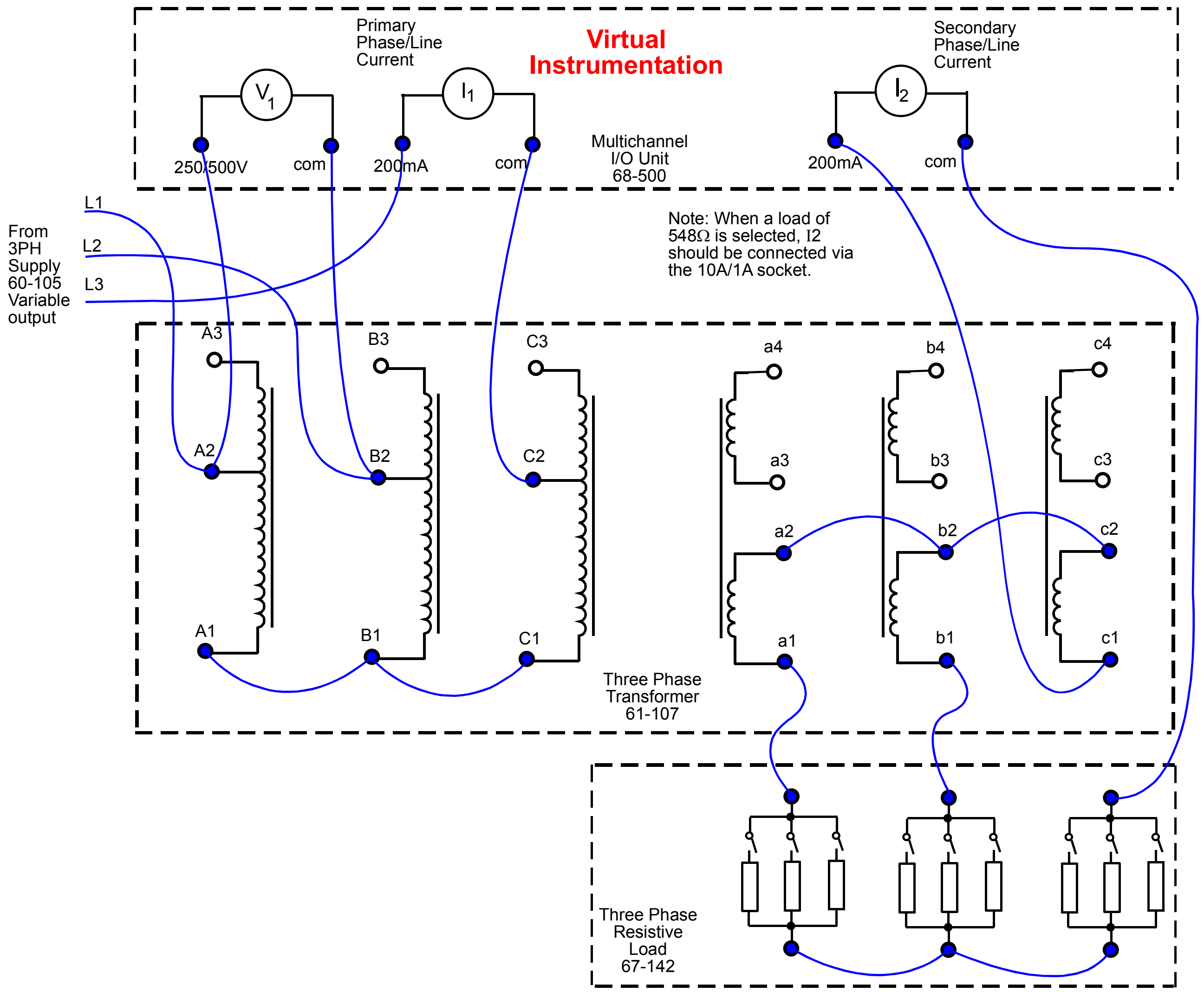


Figure 4-12-6: Practical 12.2 Circuit Diagram

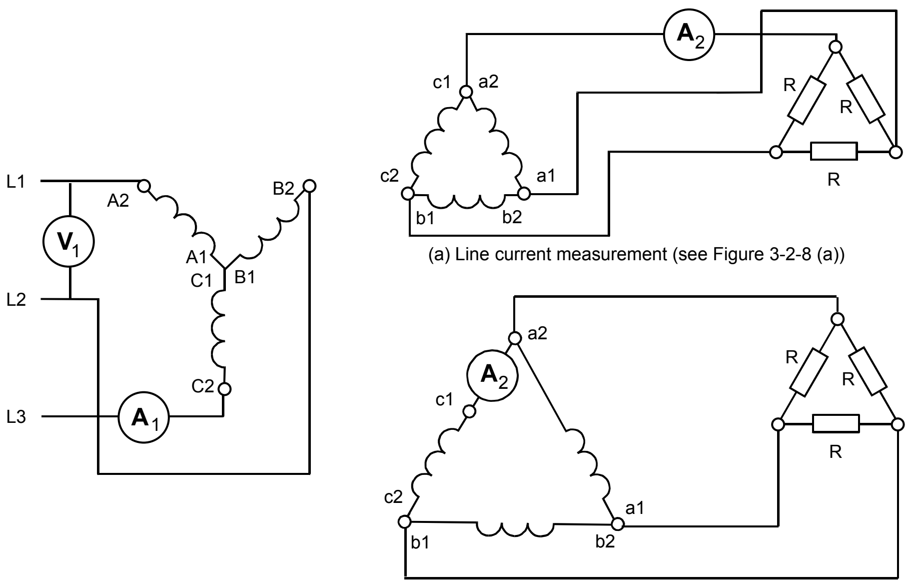
12.8 Practical 12.3 - Star Supply Delta Load

Product Version	
230 V	120 V

12.8.1 Secondary Line Current Measurement

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-12-8(a). A simplified circuit is shown in Figure 4-12-7(a).



(b) Phase current measurement (see Figure 3-2-8 (b))

Figure 4-12-7

If virtual instrumentation is being used, set the 1 A/10 A range switches for the I1 and I2 channels to 1 A on the Multichannel I/O Unit 68-500. This also allows low currents of up to 200 mA to be monitored when the 200 mA sockets are connected, with the range being software selected.

Instruction	230 V	120 V
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance load of..........................	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set a primary voltage V1 of....................	*400 V*	*216 V*

	Product Version	
	230 V	**120 V**
Record the primary phase /line current I1 and the secondary line current I2 as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 12.3, Results Table (230 V or 120 V product version).		
Complete the appropriate Practical 12.3, Results Table for the load values listed in the table.		
Turn the *'variable output voltage'* control to 0% on the Universal Power Supply 60-105 and then switch off the *'3 phase circuit breaker'.*		
12.8.2 Secondary Phase Current Measurement		
Reconfigure trainer connections as shown in Figure 4-12-8(b). A simplified circuit diagram is shown in Figure 4-12-7(b). The secondary wiring only needs to be changed for this set up.		
If virtual instrumentation is being used, set the 1 A/10 A range switches for the I1 and I2 channels to 1 A on the Multichannel I/O Unit 68-500. This also allows low currents of up to 200 mA to be monitored when the 200 mA sockets are connected, the range being software selected.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance load of..........................	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set a primary voltage V1 of....................	*400 V*	*216 V*

Record the secondary phase current I2 as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 2.3, Results Table (230 V or 120 V product version).

Complete the appropriate Practical 12.3, Results Table for the load values listed in the table.

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

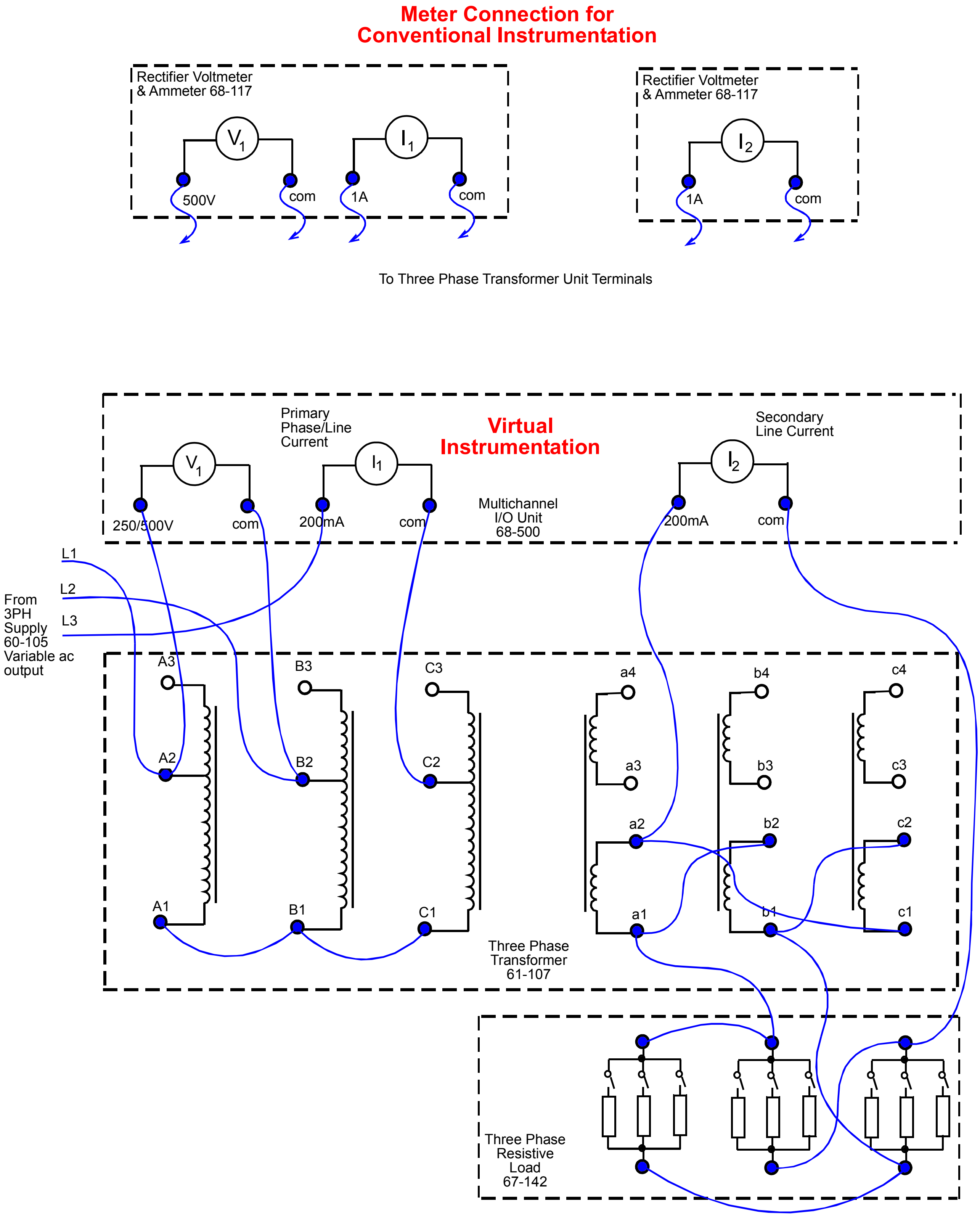


Figure 4-12-8(a): Practical 12.3 Circuit Diagram

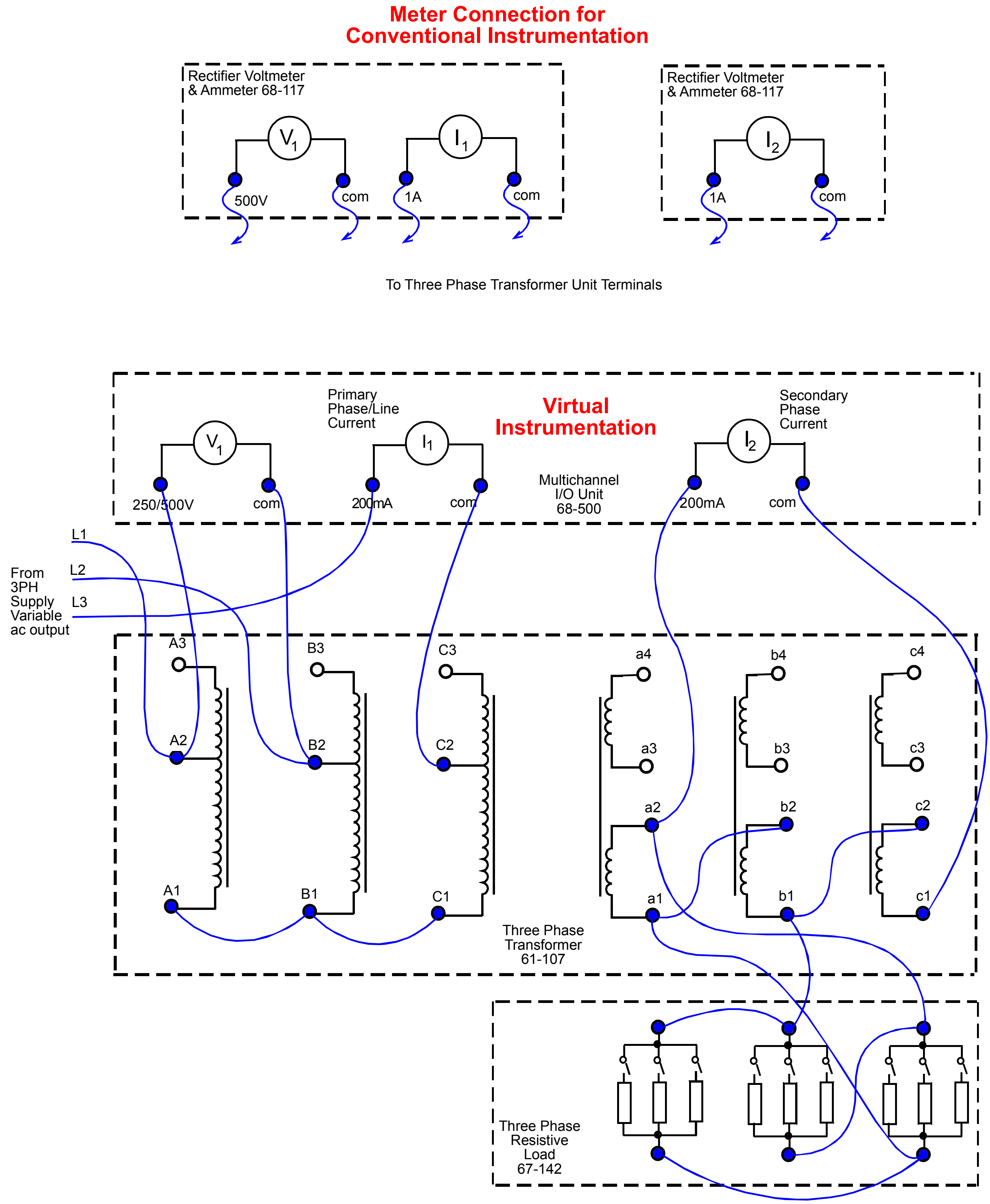


Figure 4-12-8(b): Practical 12.3 Circuit Diagram

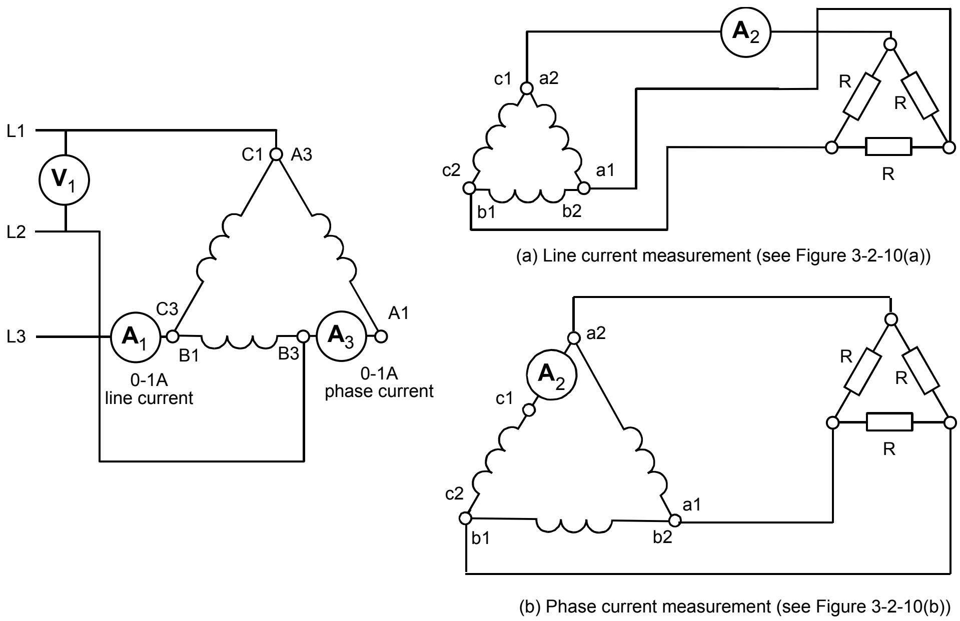
12.9 Practical 12.4 - Delta Supply Delta Load

Product Version	
230 V	**120 V**

12.9.1 Secondary Line Current Measurement

Ensure that the Universal Power Supply 60-105 is switched off.

Make the connections shown in Figure 4-12-10(a). A simplified circuit is shown in Figure 4-12-9(a).



(a) Line current measurement (see Figure 3-2-10(a))

(b) Phase current measurement (see Figure 3-2-10(b))

Figure 4-12-9

If virtual instrumentation is being used, set the 1 A/10 A range switches for the I1, I2 and I3 channels to 1 A on the Multichannel I/O Unit 68-500. This also allows low currents of up to 200 mA to be monitored when the 200 mA sockets are connected, the range being software selected.

Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance load of..........................

230 V	120 V
548 Ω per phase	*140 Ω per phase*

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.

	Product Version	
	230 V	**120 V**
Turn the dial on the power supply to set a primary voltage of……………………	*400 V*	*216 V*
Record the primary line current, the primary phase current and the secondary line current as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 12.4, Results Table (230 V or 120 V product version).		
Complete the appropriate Practical 12.4, Results Table for the load values listed in the table.		
Turn the *'variable output voltage'* control to 0% on the Universal Power Supply 60-105 and then switch off the *'3 phase circuit breaker'.*		
12.9.2 Secondary Phase Current Measurement		
Reconfigure trainer connections as shown in Figure 4-12-10(b). A simplified circuit diagram is shown in Figure 4-12-9(b). The secondary wiring only needs to be changed for this set up.		
If virtual instrumentation is being used, set the 1 A/10 A range switches for the I1, I2 and I3 channels to 1 A on the Multichannel I/O Unit 68-500. This also allows low currents of up to 200 mA to be monitored when the 200 mA sockets are connected, the range being software selected.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance load of……………………..	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set a primary voltage of……………………	*400 V*	*216 V*

Record the secondary phase current as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 12.4, Results Table (230 V or 120 V product version).

Complete the appropriate Practical 12.4, Results Table for the load values listed in the table.

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

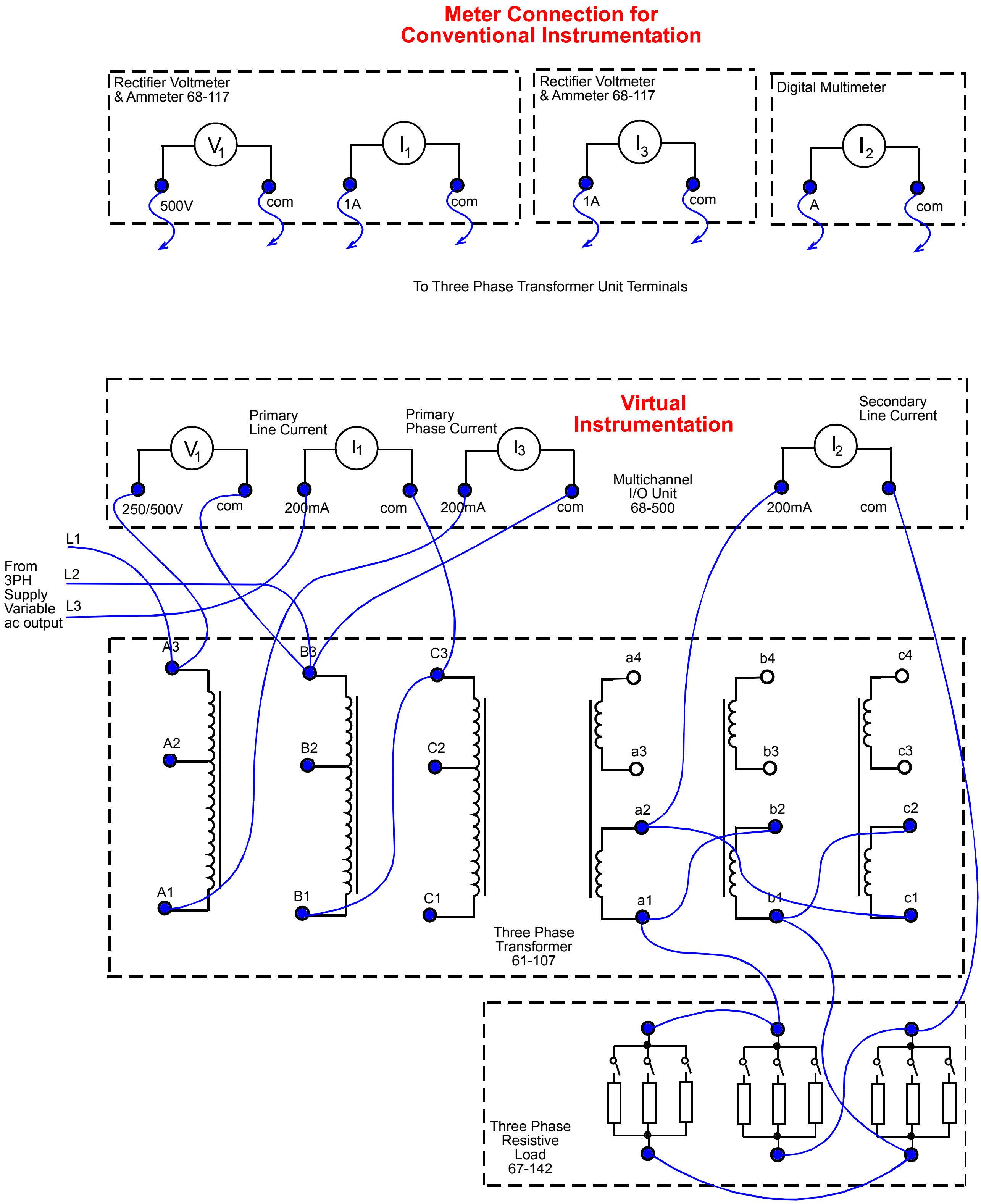


Figure 4-12-10(a): Practical 12.4 Circuit Diagram

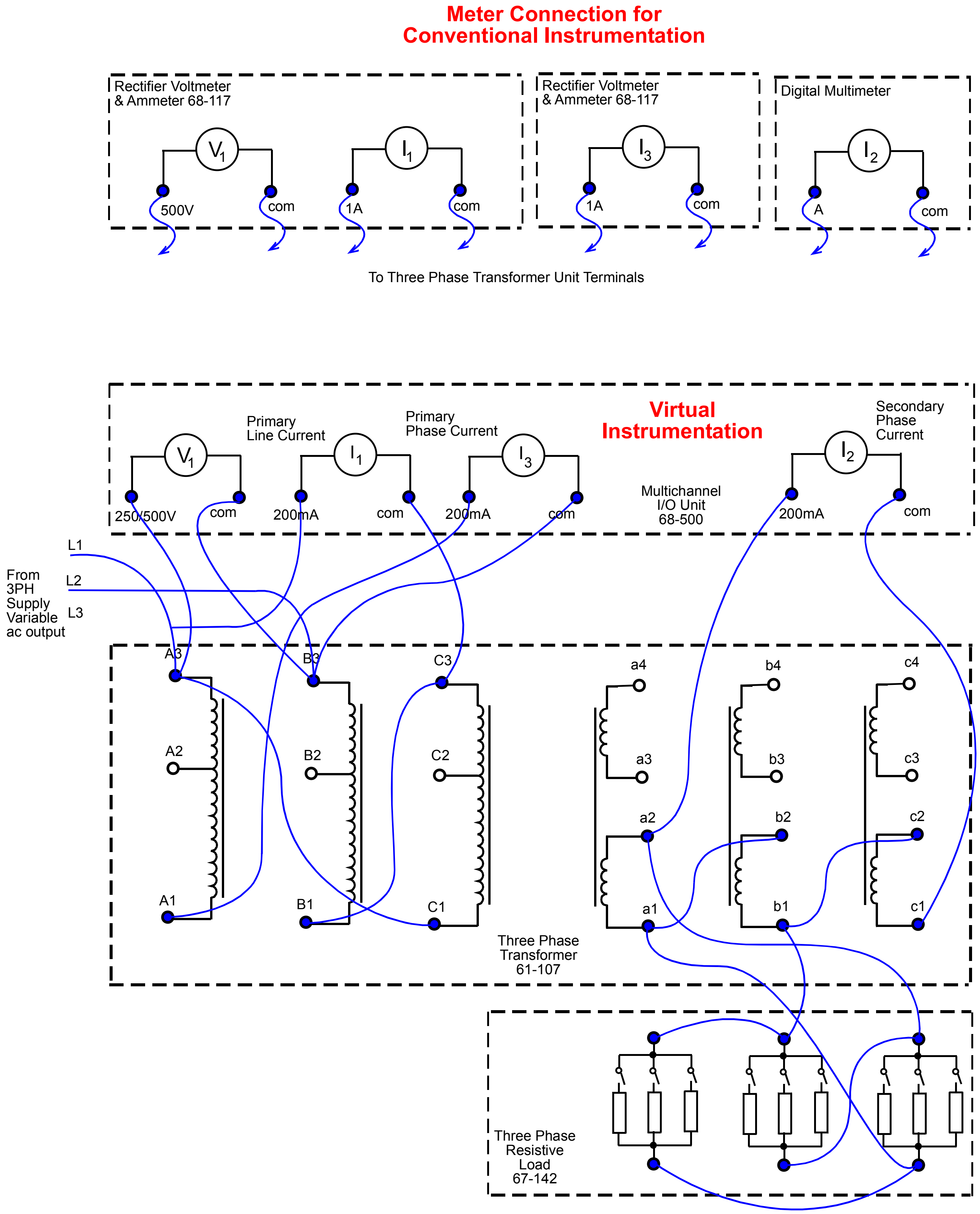


Figure 4-12-10(b): Practical 12.4 Circuit Diagram

12.10 Practical 12.1 - Results Tables - Delta Supply Star Load (230 V Product Version)

Resistance Load (Ω)	Primary Phase Current (A)	Primary Line Current (A)	Secondary Phase/Line Current (A)
548 (all resistance switches on)			
640 (3770 switches off)			
760 (1950 switches off)			
1280 (950 switches off)			
1950 (950 and 3770 switches off)			

12.11 Practical 12.2 - Results Tables - Star Supply Star Load (230 V Product Version)

Resistance Load (Ω)	Primary Phase/Line Current (A)	Secondary Phase/Line Current (A)
548 (all resistance switches on)		
640 (3770 switches off)		
760 (1950 switches off)		
1280 (950 switches off)		
1950 (3770 and 950 switches off)		

12.12 Practical 12.3 - Results Tables - Star Supply Delta Load (230 V Product Version)

Resistance Load (Ω)	Primary Phase/Line Current (A)	Secondary Line Current (A)	Secondary Phase Current (A)
548 (all resistance switches on)			
640 (3770 switches off)			
760 (1950 switches off)			
1280 (950 switches off)			
1950 (3770 and 950 switches off)			

12.13 Practical 12.4 - Results Tables - Delta Supply Delta Load (230 V Product Version)

Resistance Load (Ω)	Primary Line Current (A)	Primary Phase Current (A)	Secondary Line Current (A)	Secondary Phase Current (A)
548 (all resistance switches on)				
640 (3770 switches off)				
760 (1950 switches off)				
1280 (950 switches off)				
1950 (3770 and 950 switches off)				

12.14 Practical 12.1 - Results Tables - Delta Supply Star Load (120 V Product Version)

Resistance Load (Ω)	Primary Phase Current (A)	Primary Line Current (A)	Secondary Phase/Line Current (A)

12.15 Practical 12.2 - Results Tables - Star Supply Star Load (120 V Product Version)

Resistance Load (Ω)	Primary Phase/Line Current (A)	Secondary Phase/Line Current (A)

12.16 Practical 12.3 - Results Tables - Star Supply Delta Load (120 V Product Version)

Resistance Load (Ω)	Primary Phase/Line Current (A)	Secondary Line Current (A)	Secondary Phase Current (A)

12.17 Practical 12.4 - Results Tables - Delta Supply Delta Load (120 V Product Version)

Resistance Load (Ω)	Primary Line Current (A)	Primary Phase Current (A)	Secondary Line Current (A)	Secondary Phase Current (A)

13 Interconnected Star (Zigzag) Transformation

13.1 Assignment Information

13.1.1 Objectives

When you have completed this assignment you will:

- understand the behaviour of voltage and current in interconnected star secondary windings,
- be able to derive voltage, current and phase relationships of the interconnected star secondary windings.

13.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignment 11 and 12.
- 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. Star to Interconnected Star
2. Delta to Interconnected Star

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 Zigzag Star Transformer Connection

Figure 4-13-1 shows the zigzag star connection, a secondary from one leg of the core is connected in series with a reverse connected secondary from the next leg. The resulting phase voltages are mutually spaced by 120°, as in a normal star transformer. However the voltages are slightly reduced, and there is a phase shift of 30° between the primary and secondary voltages of the transformer.

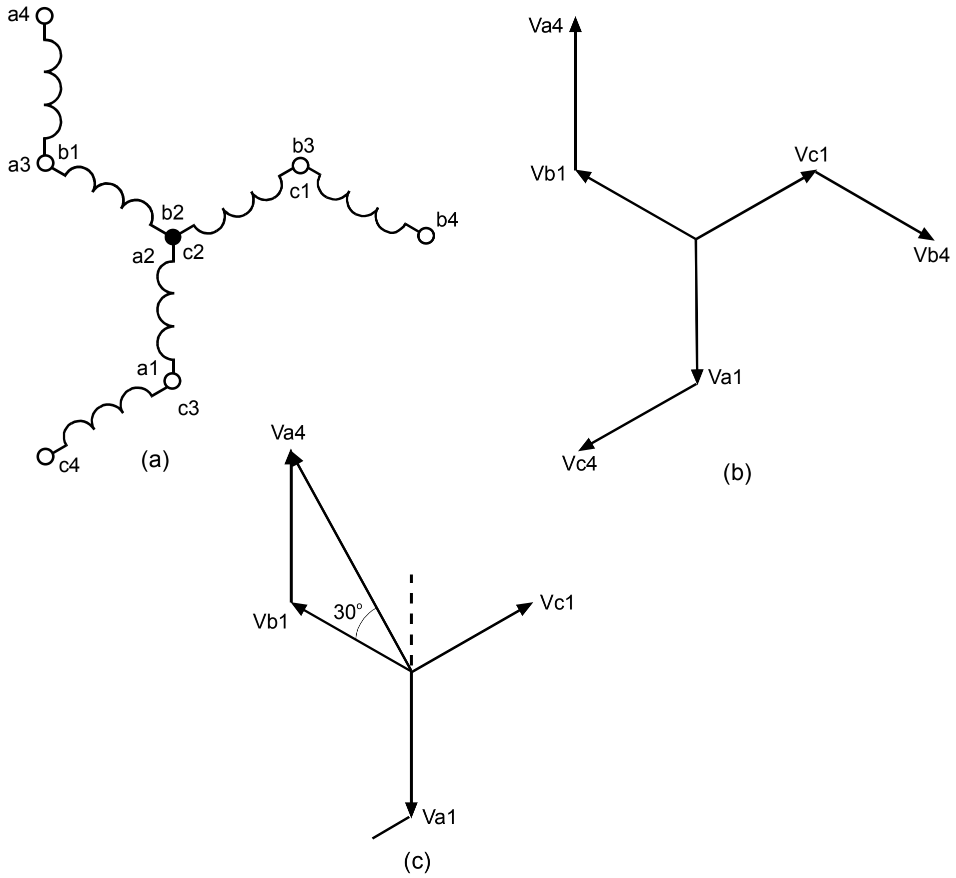


Figure 4-13-1

A phasor diagram of voltages for the zigzag star connections is shown in Figure 4-13-1(b)&(c). Since the total phase voltage is dropped across two phase windings in each leg, the total phase voltage is given by the equation.

$$V_{phase} = V_{a4}\cos 30 + V_{b1}\cos 30$$

$$= \sqrt{3}V_{a1}$$

$$V_{line} = \sqrt{3}V_{phase}$$

13.3 Content

The practicals in this assignment introduce another connection known as zigzag or interconnected star.

13.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter (two off)	68-117

- Auxillary Equipment:

  Digital Multimeter

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® 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 - Star to Zigzag Star Transformation

Product Version	
230 V	**120 V**

Make the connections shown in Figure 4-13-3. A simplified circuit diagram is shown in Figure 4-13-2.

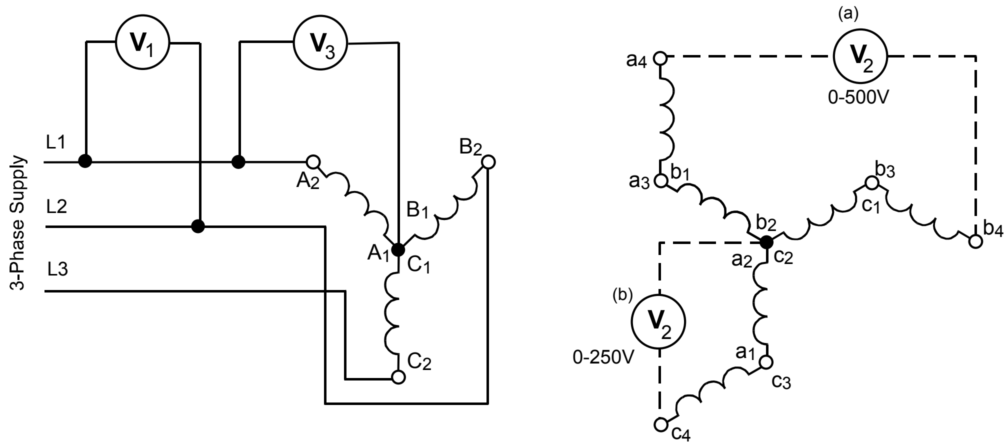


Figure 4-13-2

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.

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.

	230 V	120 V
Turn the dial on the power supply to set the primary voltage to................	*400 V*	*216 V*

Record the primary line voltage V1, the primary phase voltage V3 and the secondary line voltage V2(a) and the secondary phase voltage V2(b) as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 13.1, Results Table (230 V or 120 V product version). Note that V2 is used for both secondary line and phase voltage measurements.

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

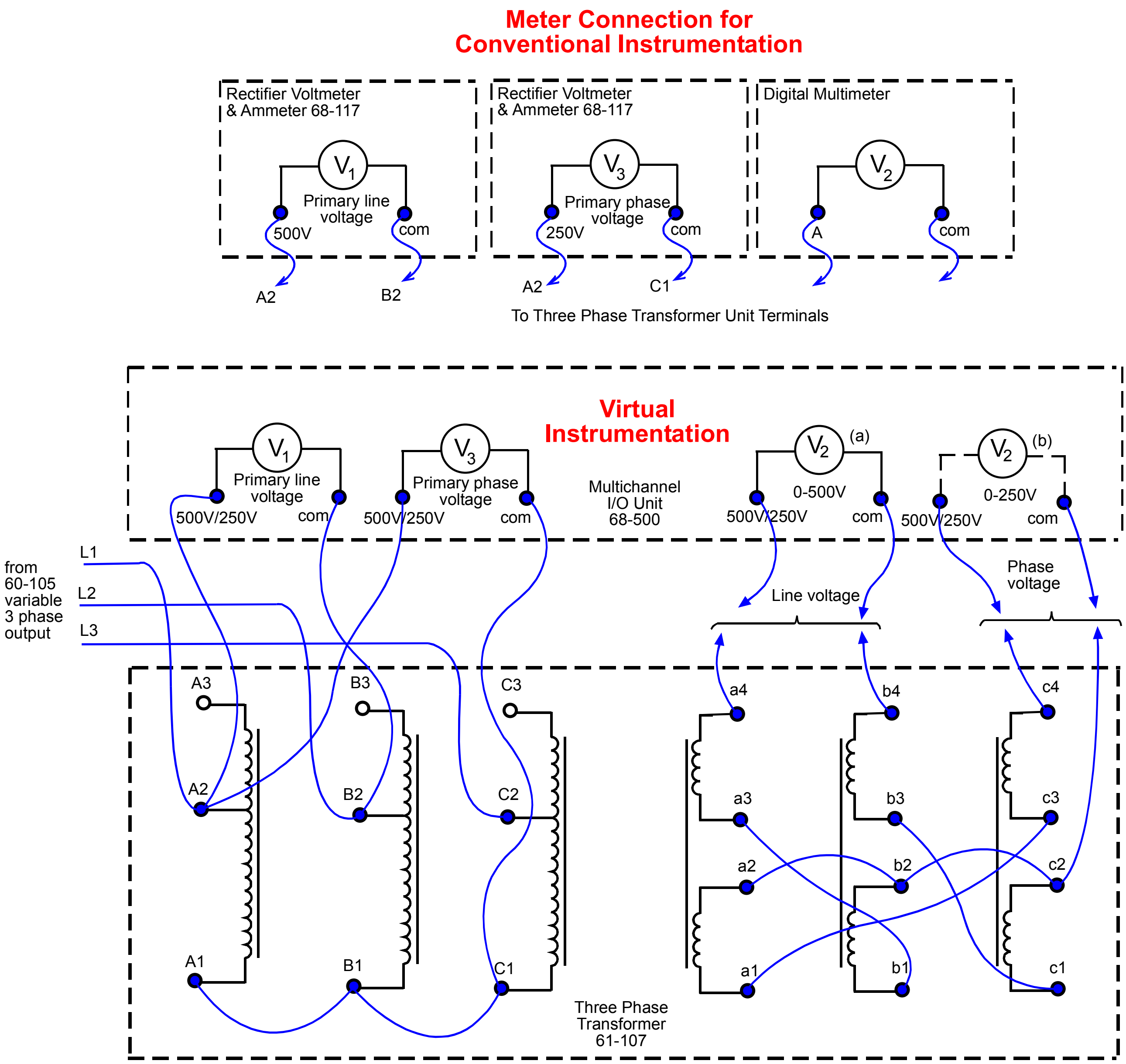


Figure 4-13-3: Practical 13.1 Circuit Diagram

13.6.1 Practical Aspects

Figure 4-13-4 shows one phase of the interconnected star.

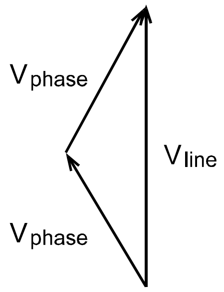


Figure 4-13-4

It can be seen from this that $V_{line} = 2 \times V_{phase} \cos 30$

13.7 Practical 13.2 - Delta to Zigzag Star Transformation

Make the connections shown in Figure 4-13-6. A simplified circuit diagram is shown in Figure 4-13-5.

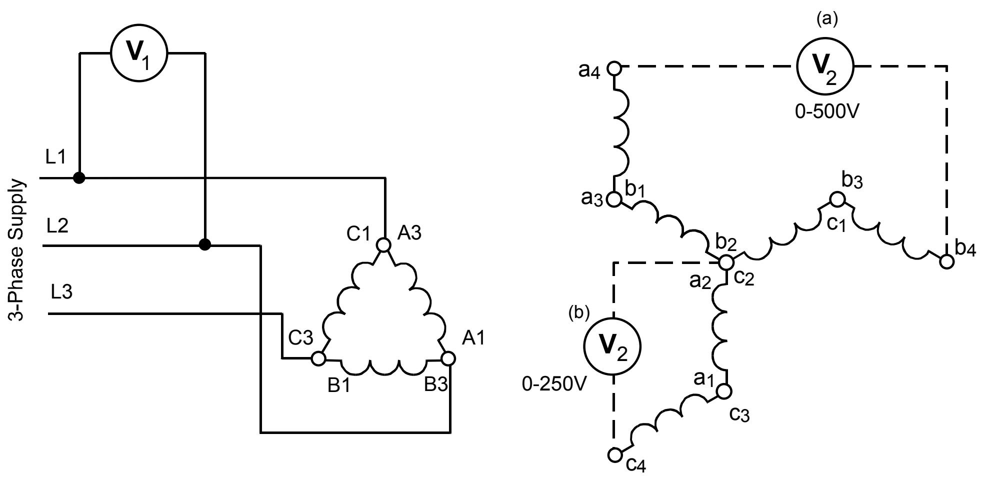


Figure 4-13-5

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.

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.

	Product Version	
	230 V	**120 V**
Turn the dial on the power supply to set the primary voltage V1 to...........	*400 V*	*216 V*

Record the primary line/phase voltage V1, the secondary line voltage V2(a) and the secondary phase voltage V2(b) as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 13.2, Results Table (230 V or 120 V product version).

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

13.7.1 Exercise 13.1

Calculate the percentage difference between the primary and secondary line voltage using the following formulae.

$$100 - \left(\frac{\text{secondary line voltage}}{\text{primary line voltage}} \times 100 \right)$$

13.7.2 Practical Aspects

Zigzag windings are restricted to comparatively low voltage windings and as the phase voltages are composed of half voltages with a 60° displacement, 15% more turns are required for a given phase terminal voltage compared with a normal star configuration.

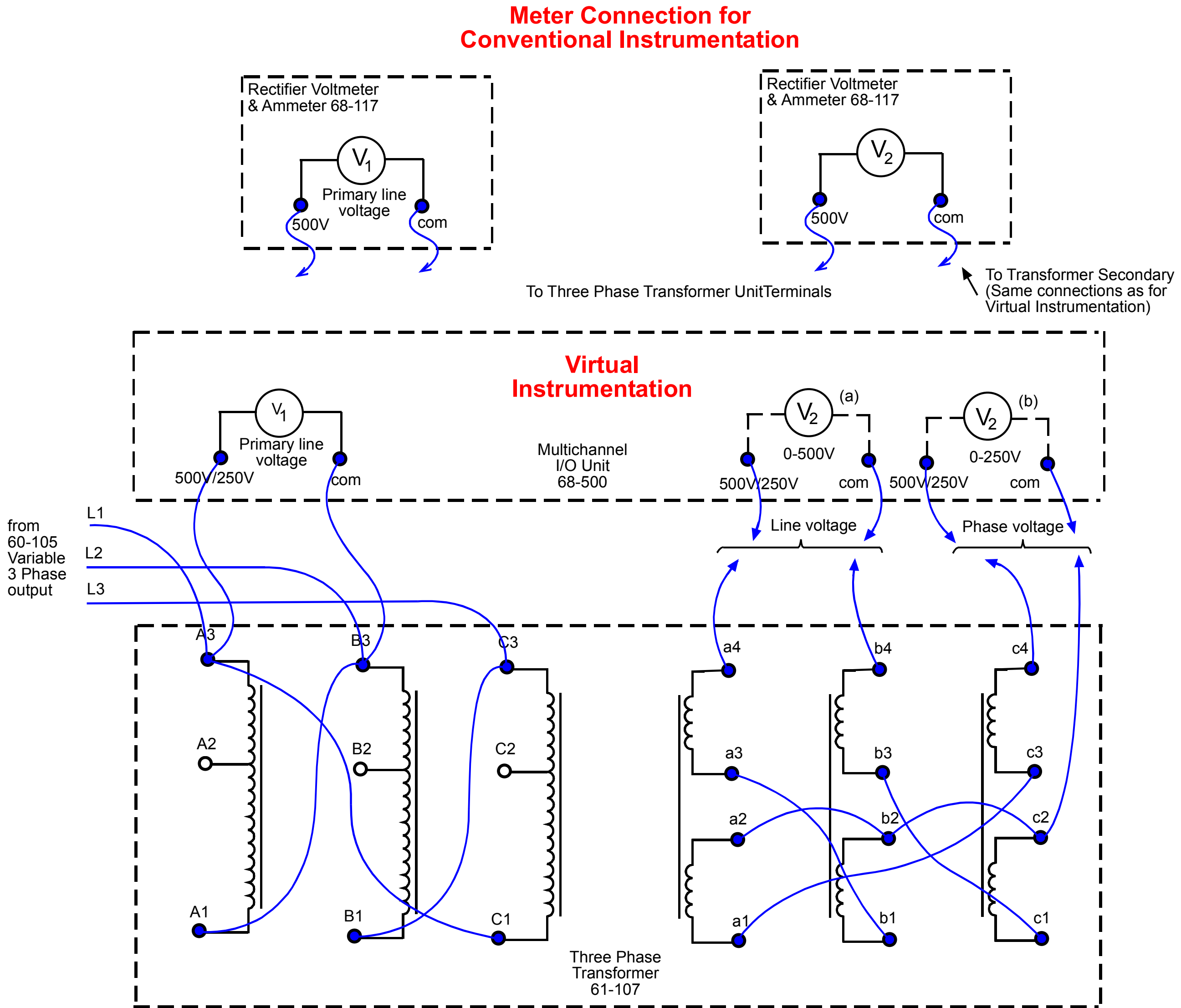


Figure 4-13-6: Practical 13.2 Circuit Diagram

13.8 Practical 13.1 - Results Tables (230 V Product Version)

Primary Line Voltage (V)	Primary Phase Voltage (V)	Secondary Line Voltage (V)	Secondary Phase Voltage (V)

13.9 Practical 13.2 - Results Tables (230 V Product Version)

Primary Line/Phase Voltage (V)	Secondary Line Voltage (V)	Secondary Phase Voltage (V)

13.10 Practical 13.1 - Results Tables (120 V Product Version)

Primary Line Voltage (V)	Primary Phase Voltage (V)	Secondary Line Voltage (V)	Secondary Phase Voltage (V)

13.11 Practical 13.2 - Results Tables (120 V Product Version)

Primary Line/Phase Voltage (V)	Secondary Line Voltage (V)	Secondary Phase Voltage (V)

14 Power in Star Secondary Windings

14.1 Assignment Information

14.1.1 Objectives

When you have completed this assignment you will:

- understand power operation of three phase systems.
- be able to derive the power and phase relationships of commonly used three phase transformers with star connected secondary windings.

14.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignments 11 and 12.
- 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 in a Star Supply Star Load (Single wattmeter measurement)
2. Power in a Star Supply Star Load (Two wattmeter measurement)
3. Power in a Star Supply Delta Load (Single wattmeter measurement)
4. Power in a Star Supply Delta Load (Three phase wattmeter 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.

14.2 Theory

14.2.1 Power Considerations in Three Phase Transformers with Star Connection

14.2.1.1 Star Load

Figure 4-14-1 shows the secondary side of a star-star transformer with star and delta loads.

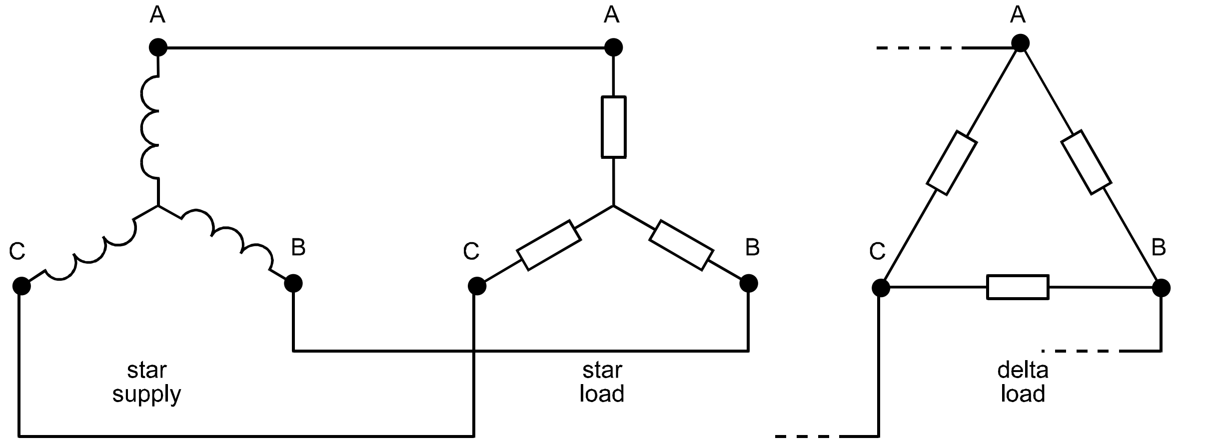


Figure 4-14-1

The operating conditions for the star connected system shown in Figure 4-14-1 are represented in the phasor diagram of Figure 4-14-2, in which ϕ represents the phase difference between the current and the voltage.

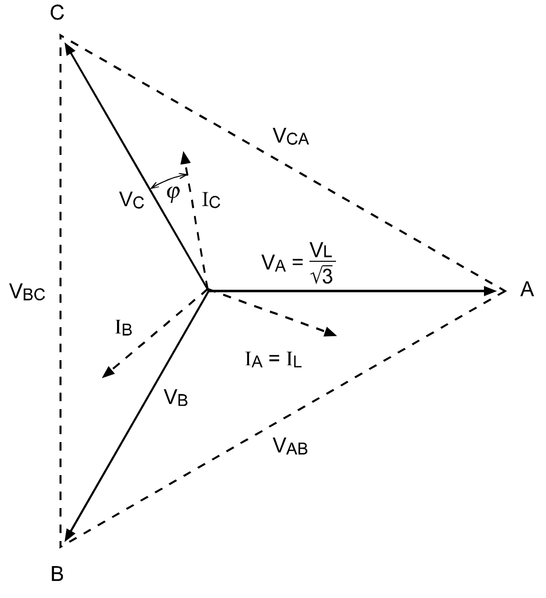


Figure 4-14-2

The conditions are summarised as follows;

$$V_{phase} = \frac{V_{line}}{\sqrt{3}}$$

$$I_{phase} = I_{line}$$

$$\text{Power per phase} = \frac{V_{line}}{\sqrt{3}} I_{line} \cos\phi$$

Hence since total power in the system is the sum of power in all three phases.

$$\text{Total Power} = 3 \times \left(\frac{V_{line}}{\sqrt{3}}\right) I_{line} \cos\phi = \sqrt{3} V_{line} I_{line} \cos\phi$$

14.2.1.2 Delta Load

The voltages in the delta connection are represented by the triangle around the outside of Figure 4-14-2. This is reproduced in Figure 4-14-3, so that the direction of the phasors is clearly shown. These phasors are also drawn in full lines meeting at the centre of Figure 4-14-3.

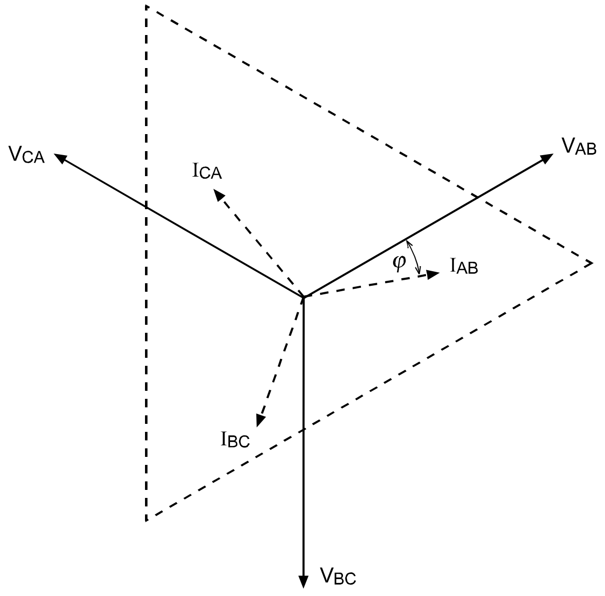


Figure 4-14-3

(Although a phasor has magnitude and direction, like a vector, no meaning is attached to its position, unlike a vector.)

The relationship between I_{line} and I_{phase}, defined to be the current in each phase of a balanced delta load, is shown in Figure 4-14-4.

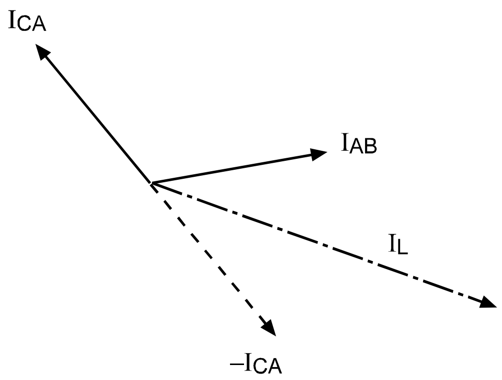


Figure 4-14-4

Notice that the line current is found by adding one I_{phase} phasor to the negative of the other. The resulting line current is $\sqrt{3}$ times the current in each phase.

The conditions for the delta load are summarised as follows;

$$V_{phase} = V_{line}$$

$$I_{phase} = \frac{I_{line}}{\sqrt{3}}$$

$$\text{Power in each phase} = V_{line} \frac{I_{line}}{\sqrt{3}} \cos \phi$$

Hence since total power in the system is the sum of power in all three phases.

$$\text{Total Power} = \sqrt{3} V_{line} I_{line} \cos \phi$$

Note in the practicals used in this assignment the loads used are resistive therefore the power factor (cos ϕ) is always 1.

Hence for both star and delta loads, the total power is given by:

$$\text{Total Power} = \sqrt{3}\, V_{line} I_{line}$$

14.3 Content

The practicals in this assignment examine the power in a three phase transformer with a star connected primary and star connected secondary.

14.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation (60-070-VIP)	• Multichannel I/O Unit • Software Pack CD	68-500 68-912-USB
	or	
Conventional Instrumentation (60-070-CI2)	• Rectifier Voltmeter & Ammeter	68-117
Conventional Instrumentation (60-070-CI1)	• Electrodynamic Wattmeter 68-204	68-100

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® 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 *60-070-VIP, Appendix A).*

14.6 Practical 14.1 - Power in a Star Supply with Star Load, Single Phase Wattmeter Measurements

	Product Version	
	230 V	**120 V**
Make the connections shown in Figure 4-14-6. A simplified circuit diagram is shown in Figure 4-14-5. At this stage, V1 and I1 should be connected in the c3/c4 secondary winding circuit as shown to monitor power (W1) to the appropriate resistor bank.		

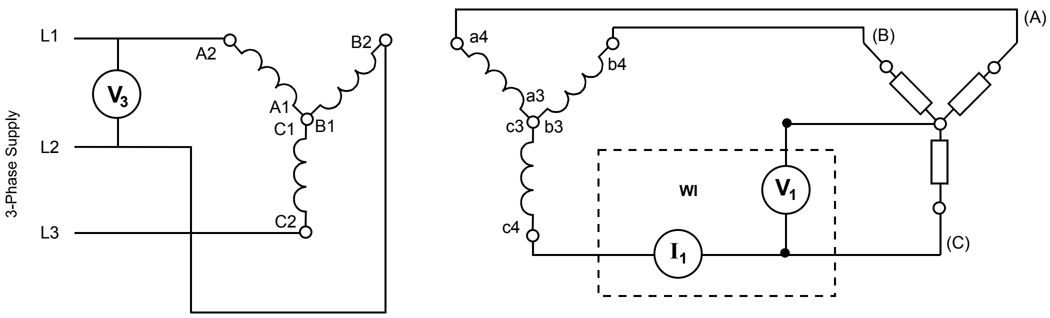


Figure 4-14-5

	230 V	120 V
If virtual instrumentation is being used, set the 250 V/500 V range switch for V1 to '250 V' and V3 to '500 V' on the Multichannel I/O Unit 68-500. 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, the range being software selected.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage to................	*400 V*	*216 V*

Record the primary line voltage and the secondary c3/c4 load power (W1) as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 14.1, Results Table (230 V or 120 V product version).

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

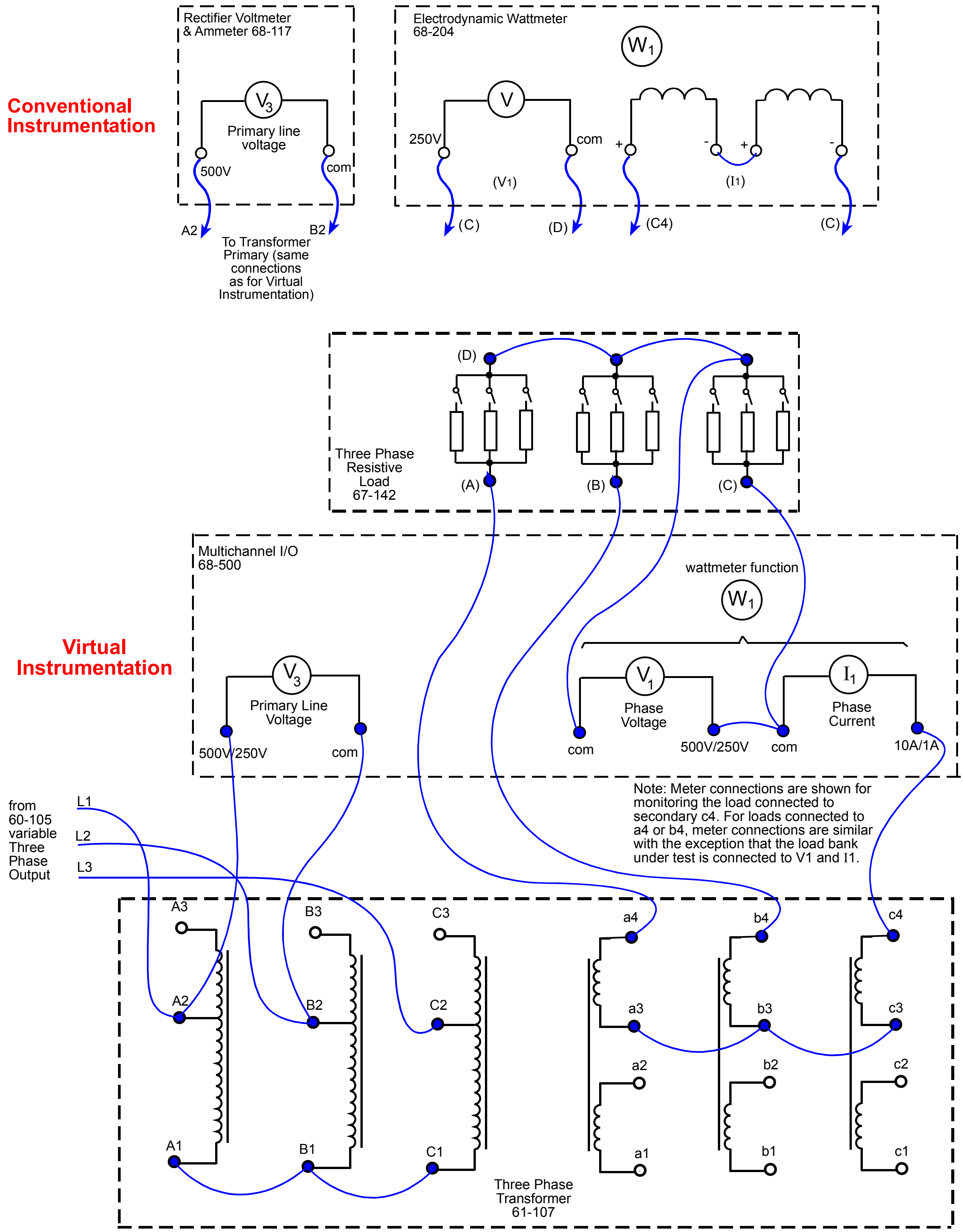


Figure 4-14-6: Practical 14.1 Circuit Diagram

Disconnect V1 and I1 from secondary winding c3/c4 circuit and connect c4 directly to the appropriate resistive load banks, point (C).

Disconnect secondary winding connection, b4 to (B), from its resistive load bank and connect the wattmeter V1 and I1 as shown in Figure 4-14-5 for the second measurement.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary winding b3/b4 (W2) on your copy of the appropriate Practical 14.1, Results Table (230 V or 120 V product version).

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

Disconnect V1 and I1 from secondary winding connection, b4 to (B), and connect b4 directly to the appropriate resistive load bank.

Disconnect secondary winding connection, a4 to (A), from its resistive load bank and connect V1 and I1 as shown in Figure 4-14-5 for the third measurement.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary winding a3/a4 (W3) on your copy of the appropriate Practical 14.1, Results Table (230 V or 120 V product version).

Complete Practical 14.1 Results Table for all values of load listed in the table.

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

14.6.1 Exercise 14.1

From the results recorded in Practical 14.1 Results Table, calculate the total power of the secondary circuit as follows:

$$\text{Total Power} = W1 + W2 + W3$$

Record the result in Practical 14.1 Results Table.

14.7 Practical 14.2 – Power in a Star Supply with Star Load (3-Phase power measurement using two wattmeter method)

In the previous Practical, one single phase wattmeter was used to obtain the total three phase power in the star connected load. We will now use the conventional, or virtual instrumentation to make power measurements using the two wattmeter method and then confirm the result from Practical 14.1.

Make the connections shown in Figure 4-14-8. A simplified circuit diagram is shown in Figure 4-14-7.

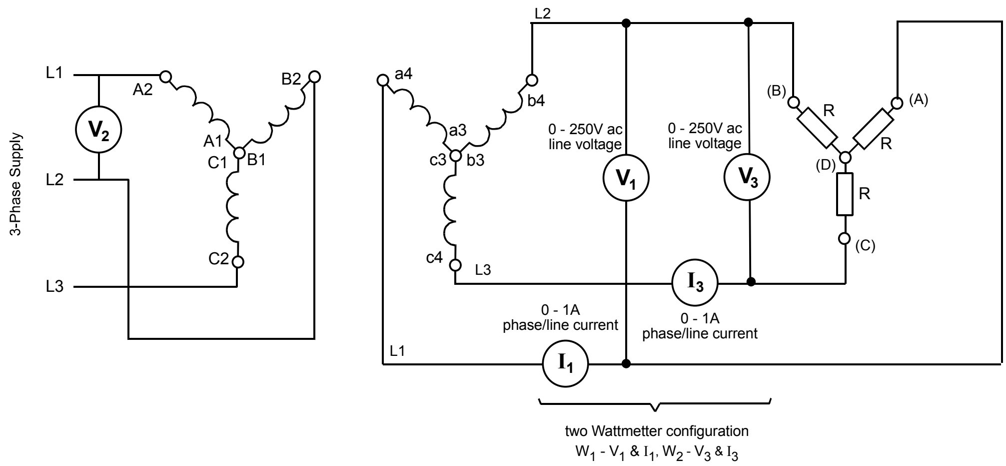


Figure 4-14-7

	Product Version	
	230 V	**120 V**
On the Multichannel I/O Unit 68-500, set the 250 V/500 V range switches for the V1 and V3 channels to '250 V'and the V2 channel to 500 V. 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 and I3 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, the range being software selected.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of ………………	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage to………………	*400 V*	*216 V*

Observe and note the power in the secondary as measured on W1, User Meter 1 (UM1) and W2 (UM3) of the Virtual Instrumentation screen.

Record your results as read on the Virtual or Conventional Instrumentation, on a copy of the appropriate Practical 14.2 Results Table (230 V or 120 V product version).

On the Universal Power Supply 60-105, switch off the *'3 Phase Circuit Breaker'*.

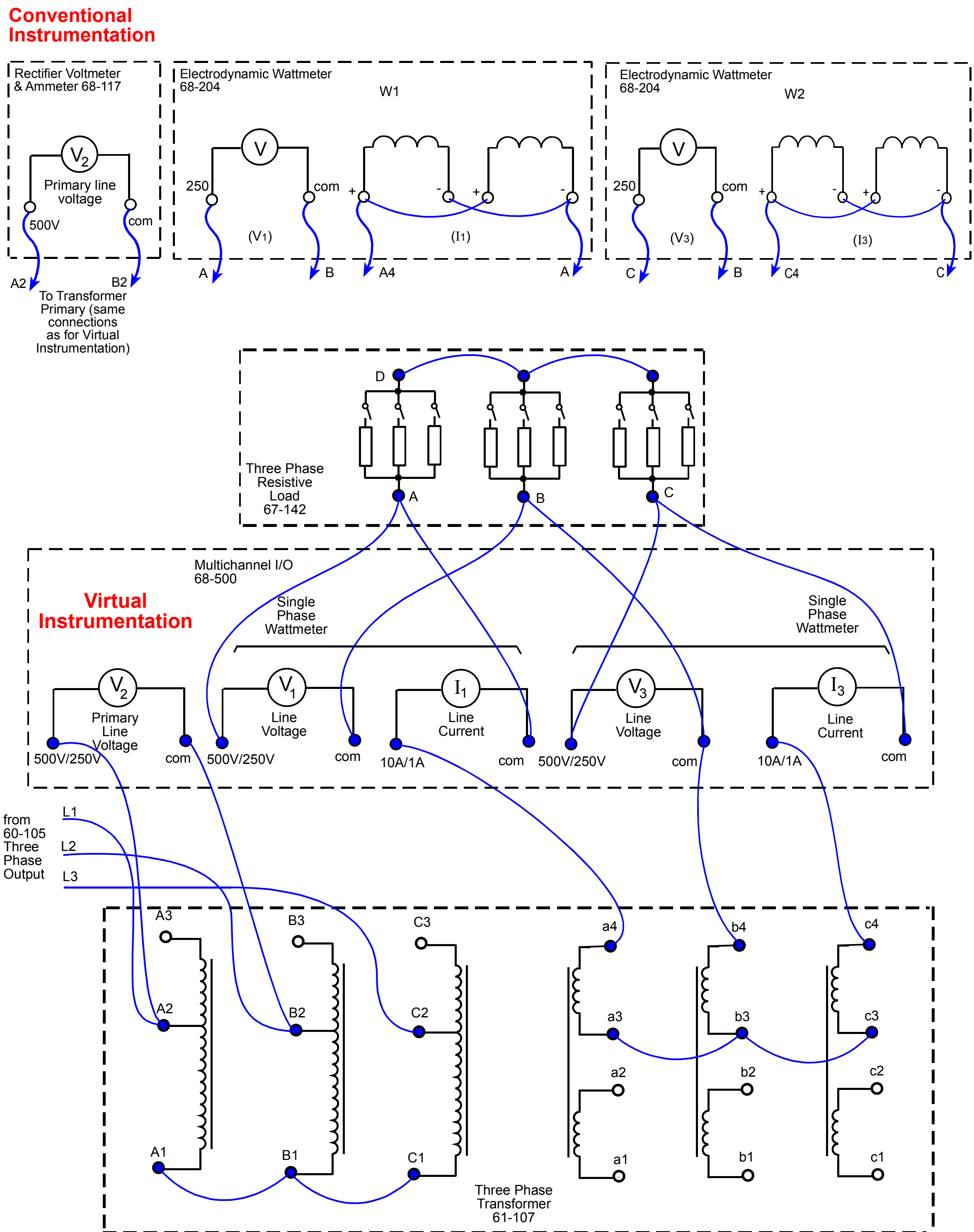


Figure 4-14-8: Practical 14.2 Circuit Diagram

On the Universal Power Supply 60-105, switch off the *'3 phase circuit breaker'*

14.7.1 Exercise 14.2

Compare the secondary power result obtained with the calculated total secondary power recorded in Practical 14.1, Results Table.
Results should be similar.

14.8 Practical 14.3 – Power in a Star Supply with Delta Load, Single Phase Wattmeter Measurement

Make up the connections shown in Figure 4-14-10. A simplified circuit diagram is shown in Figure 4-14-9. At this stage, V1 and I1 (shown drawn solid) should be connected in the a4/b4 secondary windings load circuit, RA, shown in Figure 4-14-9 to monitor power (W1) in the appropriate resistor bank.

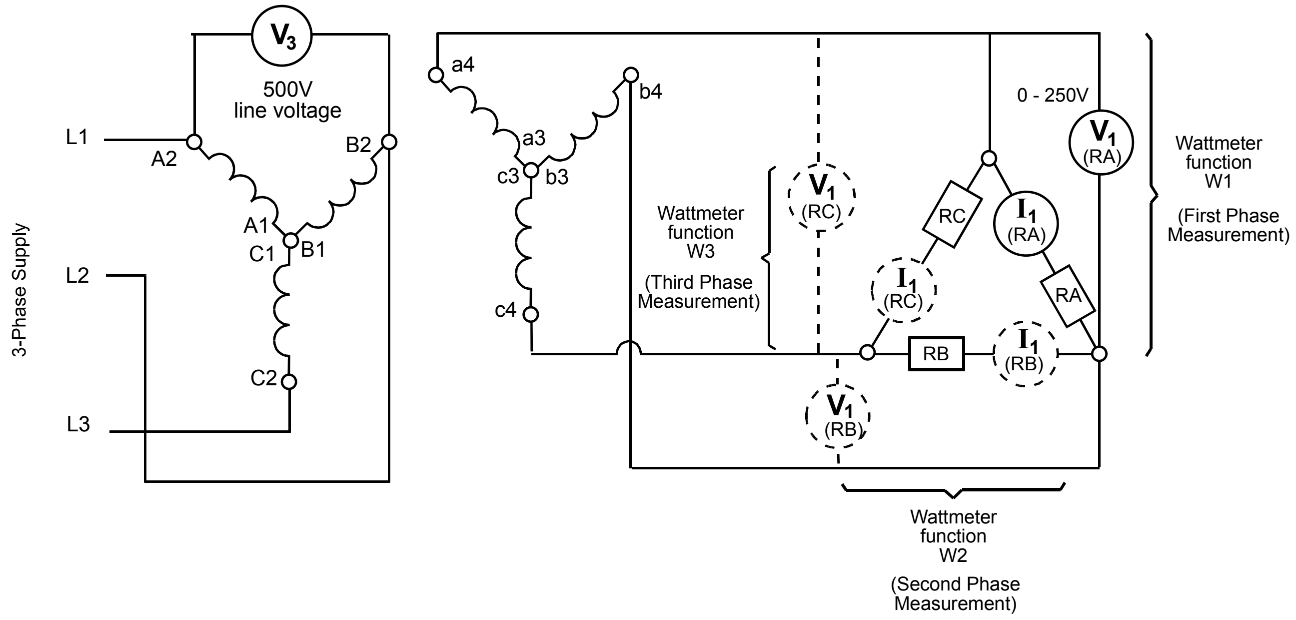


Figure 4-14-9

	Product Version	
	230 V	**120 V**
If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1 and V3 channels to '250 V' and V3 to '500 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, the range being software selected.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of ………………	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V3 to…………	*400 V*	*216 V*

Record the primary line voltage and the secondary load (RA) power (W1) as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 14.3, Results Table (230 V or 120 V product version).

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

Disconnect V1 and I1 from the secondary load RA circuit and connect a link in place of I1 to the appropriate resistive load bank.

Now connect I1 and V1 into the load circuit of RB, as shown in Figure 4-14-9 for the second measurement.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary winding b4/c4 (W2) on your copy of the appropriate Practical 14.3, Results Table (230 V or 120 V product version).

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

Disconnect V1 and I1 from the secondary load RB and connect a link in place of I1 to the appropriate resistive load bank.

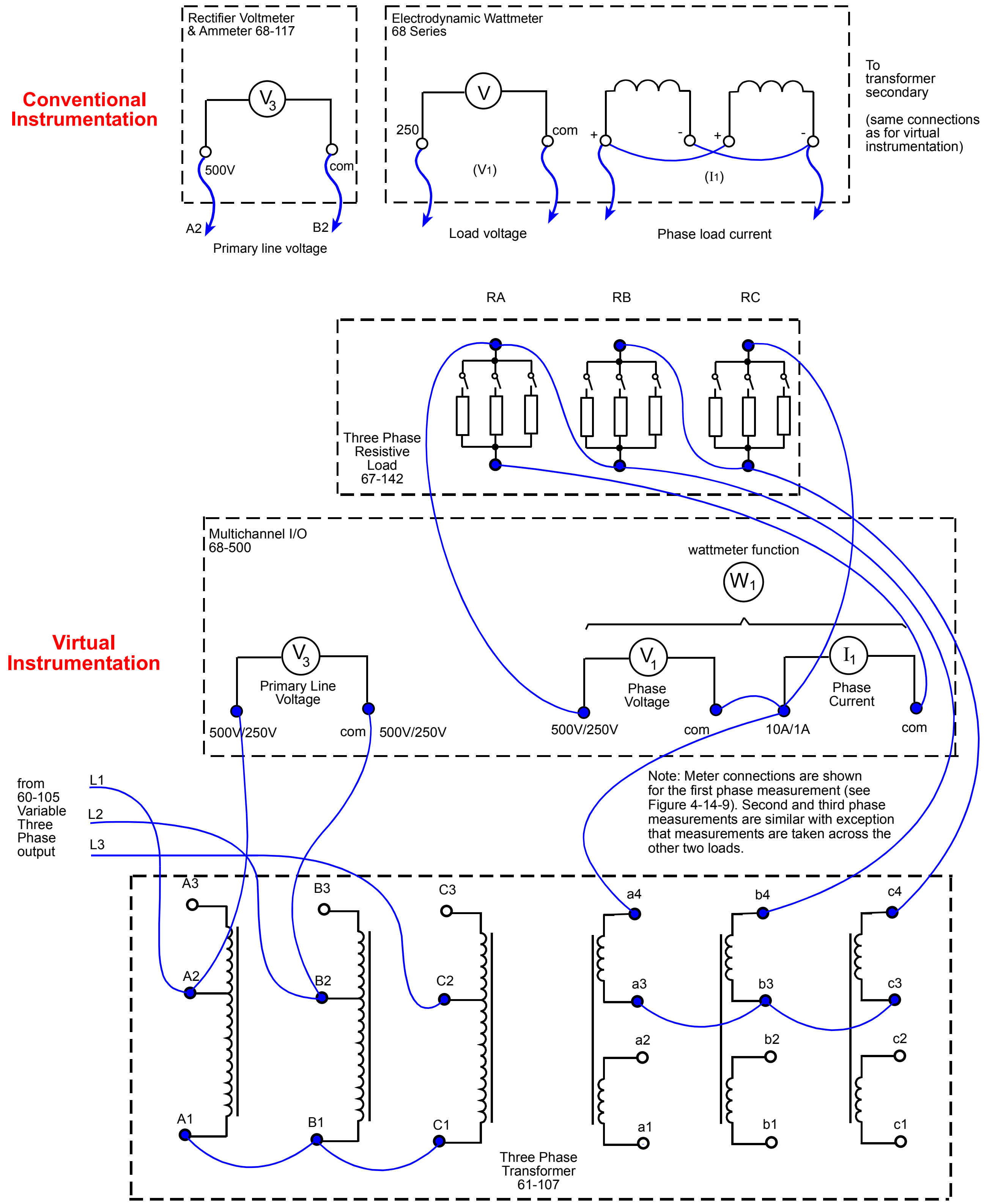


Figure 4-14-10: Practical 14.3 Circuit Diagram

Now connect I1 and V1 into the load circuit of RC, as shown in Figure 4-14-9 for the third measurement.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary winding a4/b4 (W3) on your copy of the appropriate Practical 14.3, Results Table (230 V or 120 V product version).

Complete Practical 14.3 Results Table for all values of load listed in the table.

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

14.8.1 Exercise 14.3

From the results recorded in Practical 14.3 Results Table, calculate the total power of the secondary circuit as follows:

$$\text{Total Power} = W1 + W2 + W3$$

Record the result in Practical 14.3 Results Table.

14.9 Practical 14.4 - Power in a Star Supply with Delta Load (3-Phase Wattmeter Measurement)

In the previous practicals we used a single, single phase wattmeter and then two wattmeters to measure the total three phase power, applying the two wattmeter method.

Make up the connections shown in Figure 4-14-12. A simplified circuit diagram is shown in Figure 4-14-11.

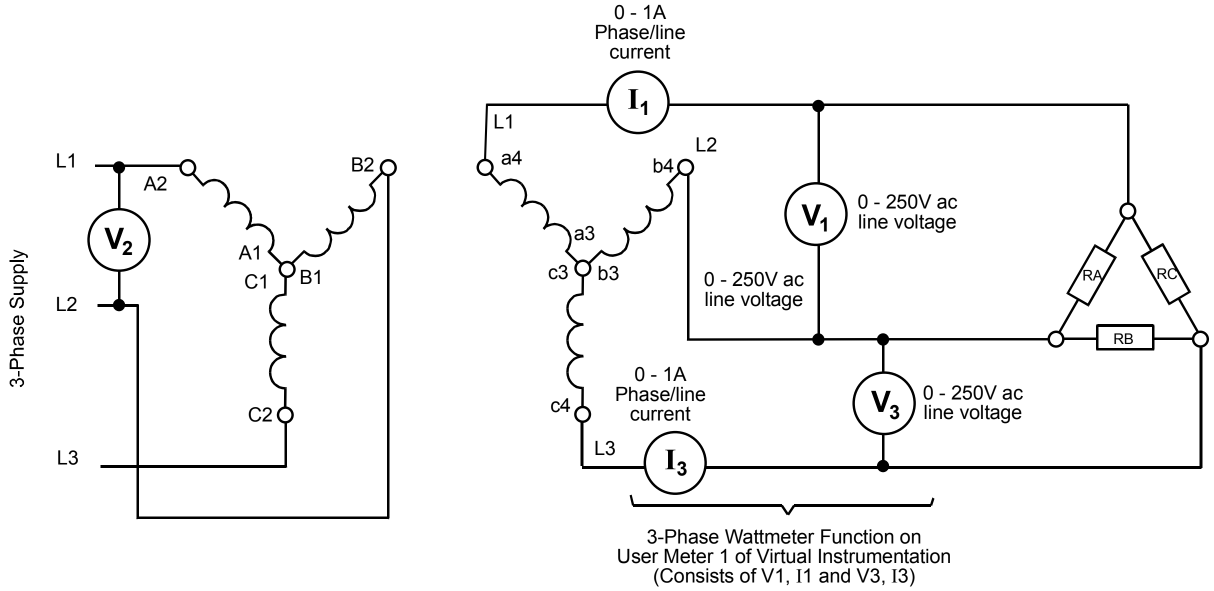


Figure 4-14-11

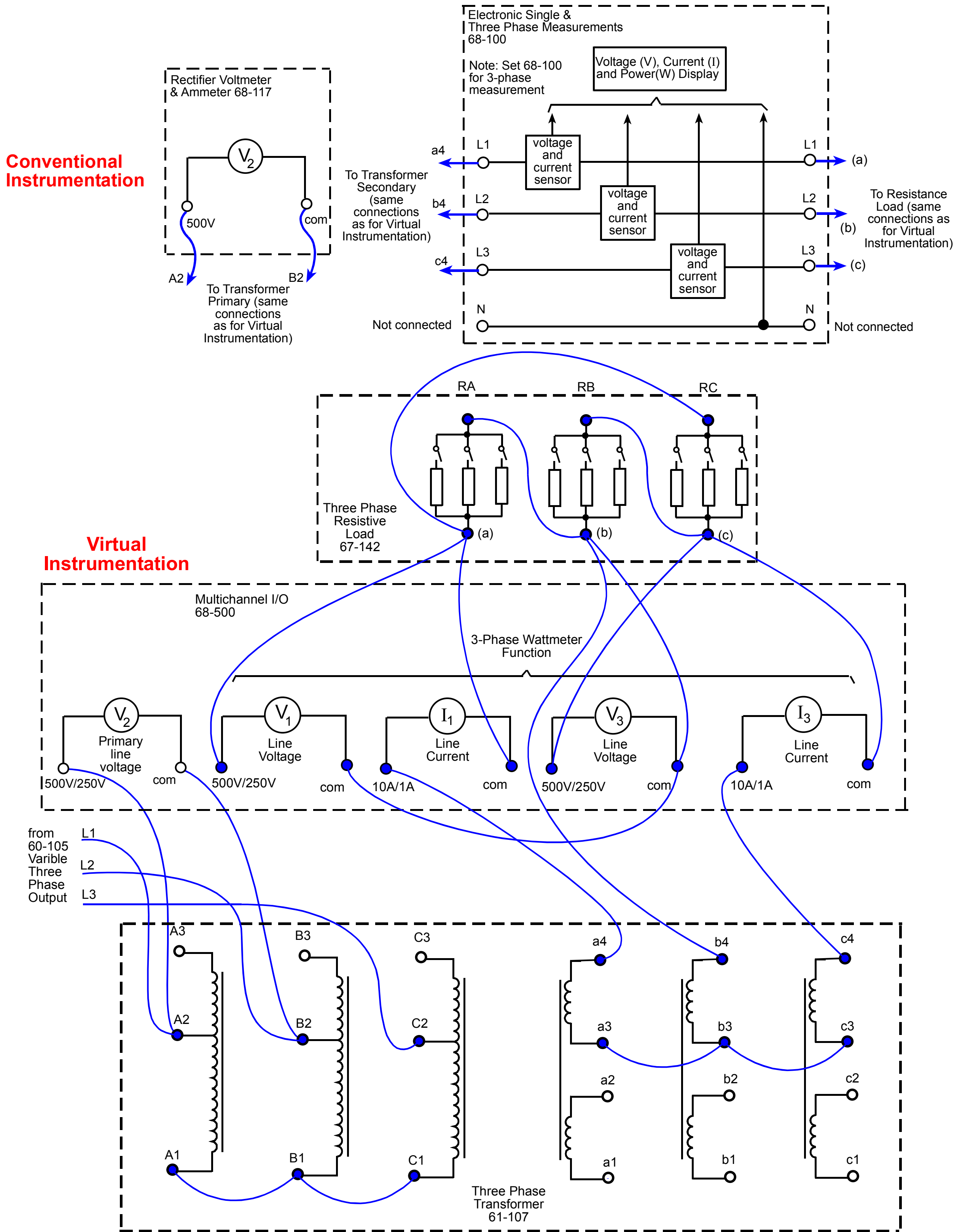


Figure 4-14-12: Practical 14.4 Circuit Diagram

Instruction	Product Version 230 V	Product Version 120 V
If Virtual Instrumentation is being used, the total three phase power will be measured using the three phase wattmeter function, or in the case of Conventional Instrumentation the total power is measured using the 68-100 three phase function. On the Multichannel I/O Unit 68-500, set the 250 V/500 V range switches for V1 to '250 V' and V3 to '500 V'. Additionally, set the 1 A/10 A range switches for I1 and I3 to '1A'. 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, the range being software selected.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of ………………	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V2 to………..	*400 V*	*216 V*

Record the secondary power as measured on User Meter 1 of Virtual Instrumentation screen, or the Single and Three Phase Measurements 68-100 unit, if conventional instruments are being used,.in a copy of practical 14.4 results table (230 V or 120 V product version).

Complete Practical 14.4 Results Table for all values of load listed in the table.

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

14.9.1 Exercise 14.4

Compare the secondary power result obtained with the calculated total secondary power recorded in Practical 14.3, Results Table.
Results should be similar.

14.10 Practical Aspects

In a balanced three phase system, a star connected device (transformer or load) carries the whole line current, and $1/\sqrt{3}$ times the line voltage appears across each of the three individual loads.

A star connected secondary 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 appears across each of the three individual loads.

A delta connected secondary has no neutral point.

In a balanced four wire (three phases plus neutral) system, line voltages are $\sqrt{3}$ times larger than line-to-neutral voltages. In each case the power is:

$$\sqrt{3} V_{line} I_{line} \cos \phi$$

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).

14.11 Practical 14.1 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary c3/c4 Load Power (W1)	Secondary b3/b4 Load Power (W2)	Secondary a3/a4 Load Power (W3)	Secondary Total Power (W1+W2+W3)
548 (all resistance switches on)					
640 (3770 switches off)					
760 (1950 switches off)					

14.12 Practical 14.1 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary c3/c4 Load Power (W1)	Secondary b3/b4 Load Power (W2)	Secondary a3/a4 Load Power (W3)	Secondary Total Power (W1+W2+W3)

14.13 Practical 14.2 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary a4/D Load Power (W1)	Secondary c4/D Load Power (W2)	Secondary Total Power (W1+W2)
548 (all resistance switches on)				
640 (3770 switches off)				
760 (1950 switches off)				

14.14 Practical 14.2 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary a4/D Load Power (W1)	Secondary c4/D Load Power (W2)	Secondary Total Power (W1+W2)
548 (all resistance switches on)				
640 (3770 switches off)				
760 (1950 switches off)				

14.15 Practical 14.3 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary a4/b4 Load Power (W1)	Secondary b4/c4 Load Power (W2)	Secondary c4/a4 Load Power (W3)	Secondary Total Power (W1+W2+W3)
548 (all resistance switches on)					
640 (3770 switches off)					
760 (1950 switches off)					

14.16 Practical 14.4 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Total Three Phase Secondary Power
548 (all resistance switches on)		
640 (3770 switches off)		
760 (1950 switches off)		

14.17 Practical 14.3 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary a4/b4 Load Power (W1)	Secondary b4/c4 Load Power (W2)	Secondary c4/a4 Load Power (W3)	Secondary Total Power (W1+W2+W3)

+

14.18 Practical 14.4 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Total Three Phase Secondary Power
548 (all resistance switches on)		
640 (3770 switches off)		
760 (1950 switches off)		

15 Power in Delta Secondary Windings

15.1 Assignment Information

15.1.1 Objectives

When you have completed this assignment you will:

- understand power operation of three phase systems,
- be able to derive the power and phase relationships of commonly used three phase transformers with delta connected secondary windings.

15.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignments 11, 12 and 14.
- 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. Power in a Delta Supply Star Load
2. Power in a Delta Supply Star Load (Use of 3-Phase Wattmeter)
3. Power in a Delta Supply Delta Load
4. Power in a Delta Supply Delta Load (Use of 3-Phase Wattmeter)

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 Power Considerations in Three Phase Transformers with Star Connection

15.2.1.1 Delta Load

In the previous assignment it was mentioned that the current in each phase of a delta connected load differed from the line current. This assignment will verify that difference, both in the load and in the supply transformers.

Figure 4-15-1 shows the delta connected secondary side of a star-delta transformer, with star or delta loads.

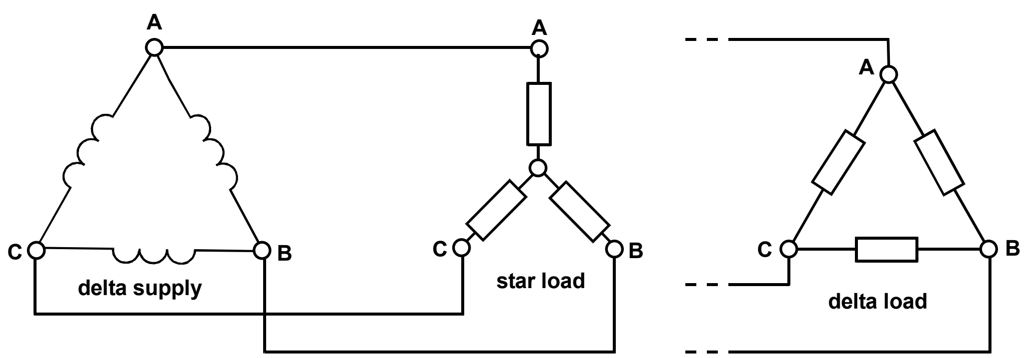


Figure 4-15-1

A similar analysis of the operating conditions may be made. The phasor diagram of Figure 4-15-2 shows the secondary current conditions for a closed load, and confirms that $I_{line} = \sqrt{3}\, I_{phase}$.

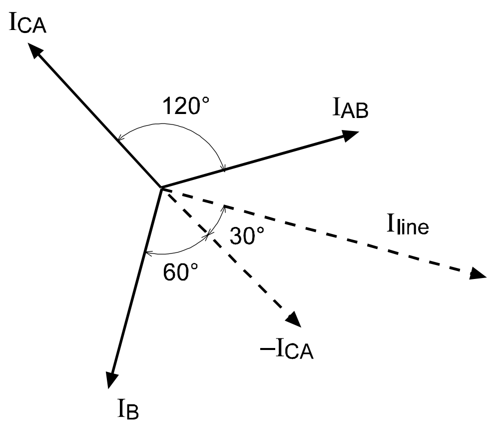


Figure 4-15-2

15.3 Content

The practicals in this assignment examine the power in a three phase transformer with a star connected primary and delta connected secondary.

15.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation 60-070-VIP	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation 60-070-CI1	• Electronic Single & Three Phase Measurements	68-100
Conventional Instrumentation 60-070-CI2	• Rectifier Voltmeter & Ammeter	68-117
	• ac/dc electrodynamic wattmeter	68-204

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® 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 - Power in a Delta Supply with Star Load - Single Phase Wattmeter Measurements

Make up the connections shown in Figure 4-15-4. A simplified circuit diagram is shown in Figure 4-15-3. At this stage, the wattmeter V1 and I1 connections should be connected in the load (A) circuit as shown to measure the power (W1).

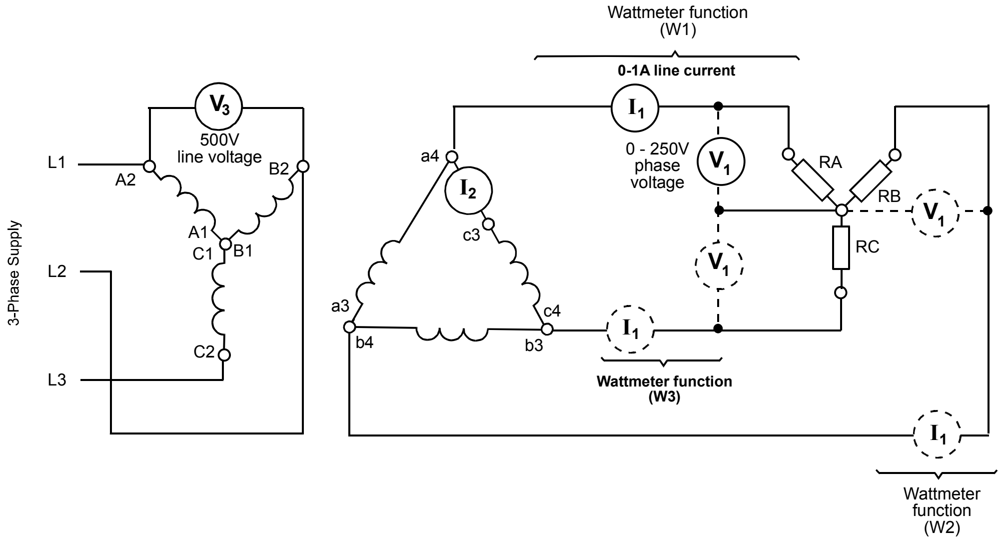


Figure 4-15-3

	Product Version	
If virtual instrumentation is being used, set the 250 V/500 V range switches for channels V1 to '250 V' and V3 to 500 V on the Multichannel I/O Unit 68-500. This allows voltages of up to 250 V or 500 V to be monitored when the '500 V/250 V' sockets are connected. Additionally, set the 1 A/10 A range switch for I1 and I2 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 and selected within the software.	**230 V**	**120 V**
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V3 to	*400 V*	*216 V*

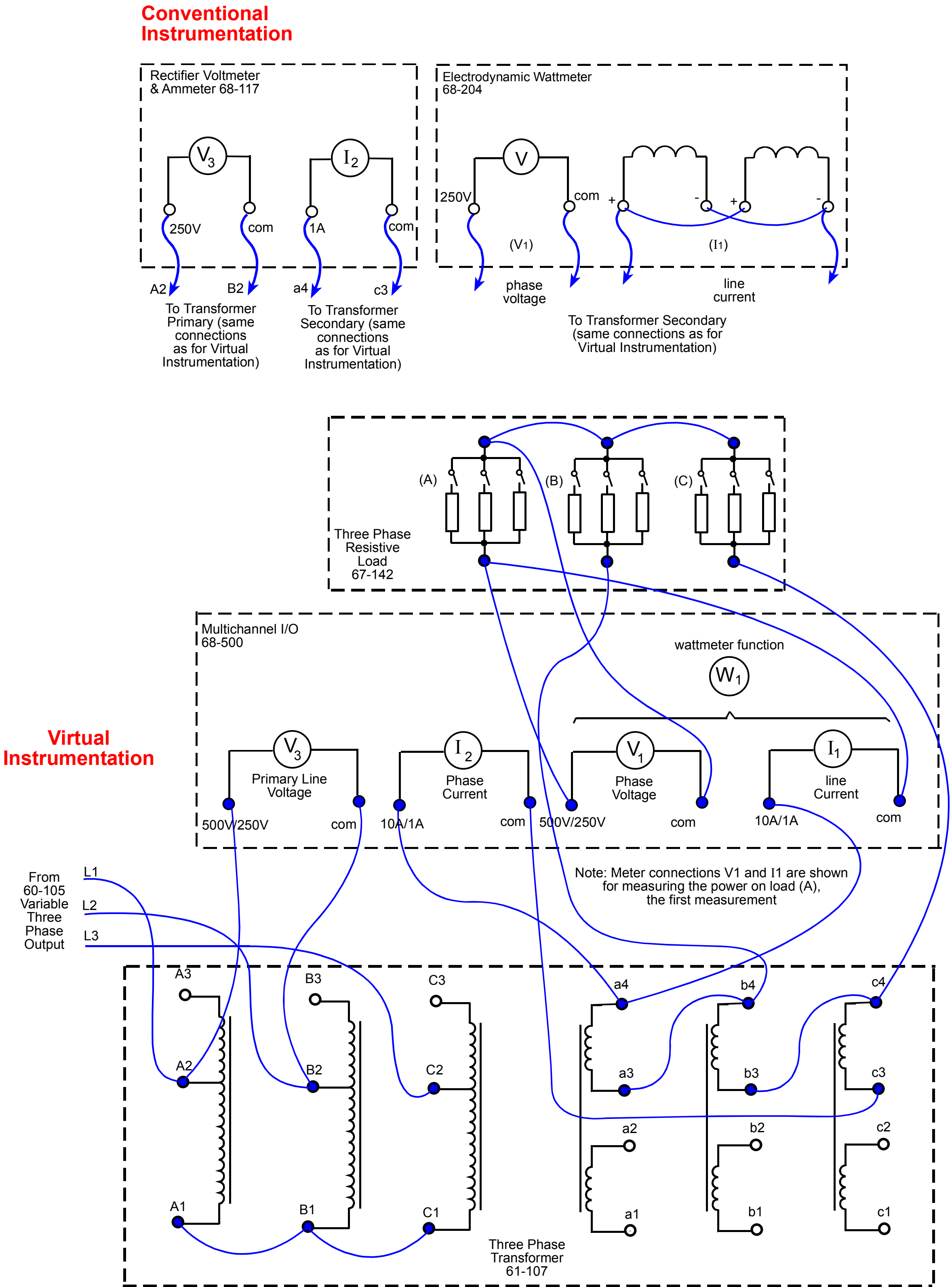


Figure 4-15-4: Practical 15.1 Circuit Diagram

Record the primary line voltage, secondary load (RA) power (W1) as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 15.1, Results Table (230 V or 120 V product version). Continue to record values of W1 for all resistance load settings as show in the table of 15.1. (Note, switch settings apply to all three load banks).

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

Disconnect V1 and I1 from the load (A) circuit and make a connection to replace the ammeter I1 between a4/c3 and load resistor (RA).

Connect V1 and I1 into the load (B) circuit as shown in Figure 4-15-3 for the second measurement, W2. Set all the load switches to the on position.

On the Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary, load (RB) power (W2) on your copy of the appropriate Practical 15.1, Results Table (230 V or 120 V product version). Continue to record values of W2 for all the load settings as show in the table of 15.1. (Switch settings apply to all three load banks)

On the Supply 60-105, switch off the *'3 phase circuit breaker'.*

Disconnect V1 and I1 from the load (B) circuit and make a connection to replace the ammeter between a3/b4 and load resistor (B).

Connect V1 and I1 into the load (C) circuit as shown in Figure 4-15-3 for the third measurement, W3. Set all the load switches to the on position

On the Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary load (RC) power (W3) on your copy of the appropriate Practical 15.1, Results Table (230 V or 120 V product version).

Complete Practical 15.1 Results Table for all values of resistance load listed in the table.

On the Supply 60-105, switch off the *'3 phase circuit breaker'.*

15.6.1 Exercise 15.1

From the results recorded in Practical 15.1 Results Table, calculate the total power of the secondary circuit as follows: Total power = W1 + W2 + W3.

Record the result in Practical 15.1 Results Table.

15.7 Practical 15.2 - Power in a Delta Supply with Star Load - 3-Phase Wattmeter Measurement

In the previous Practical one single phase wattmeter was used to obtain the total three phase power in the star connected load. We will now use the conventional or virtual instrumentation three phase wattmeter function to make the measurement and confirm the result from Practical 15.1.

Make up the connections shown in Figure 4-15-6. A simplified circuit diagram is shown in Figure 4-15-5.

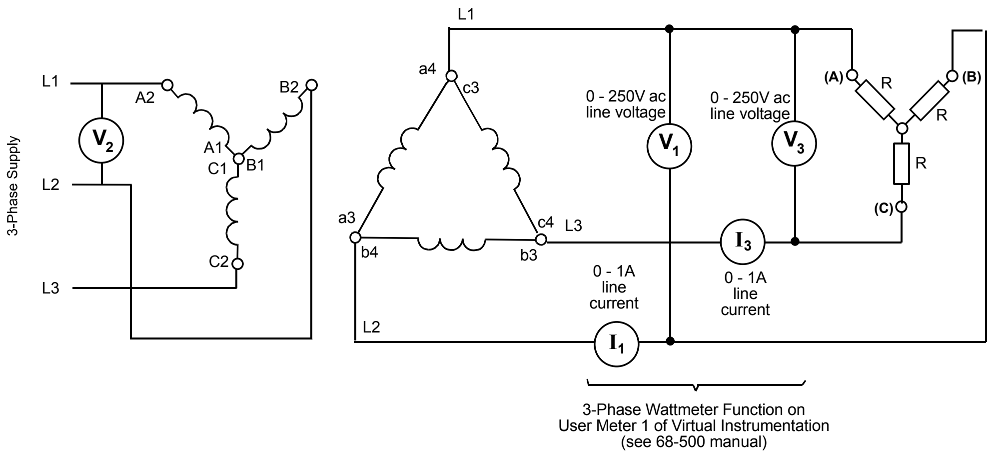


Figure 4-15-5

	Product Version	
	230 V	**120 V**
On the Multichannel I/O Unit 68-500, set the 250 V/500 V range switches for the V1 and V3 channels to '250 V', V3 to 500 V. This allows voltages of 250 V and 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 and I3 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 and selected within the software.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V2 to..............	*400 V*	*216 V*

Record the secondary total three phase power as measured on User Meter 1 of Virtual Instrumentation or the 68-100 Measurements Unit, in Practical 15.2 Results Table (230 V or 120 V product version).

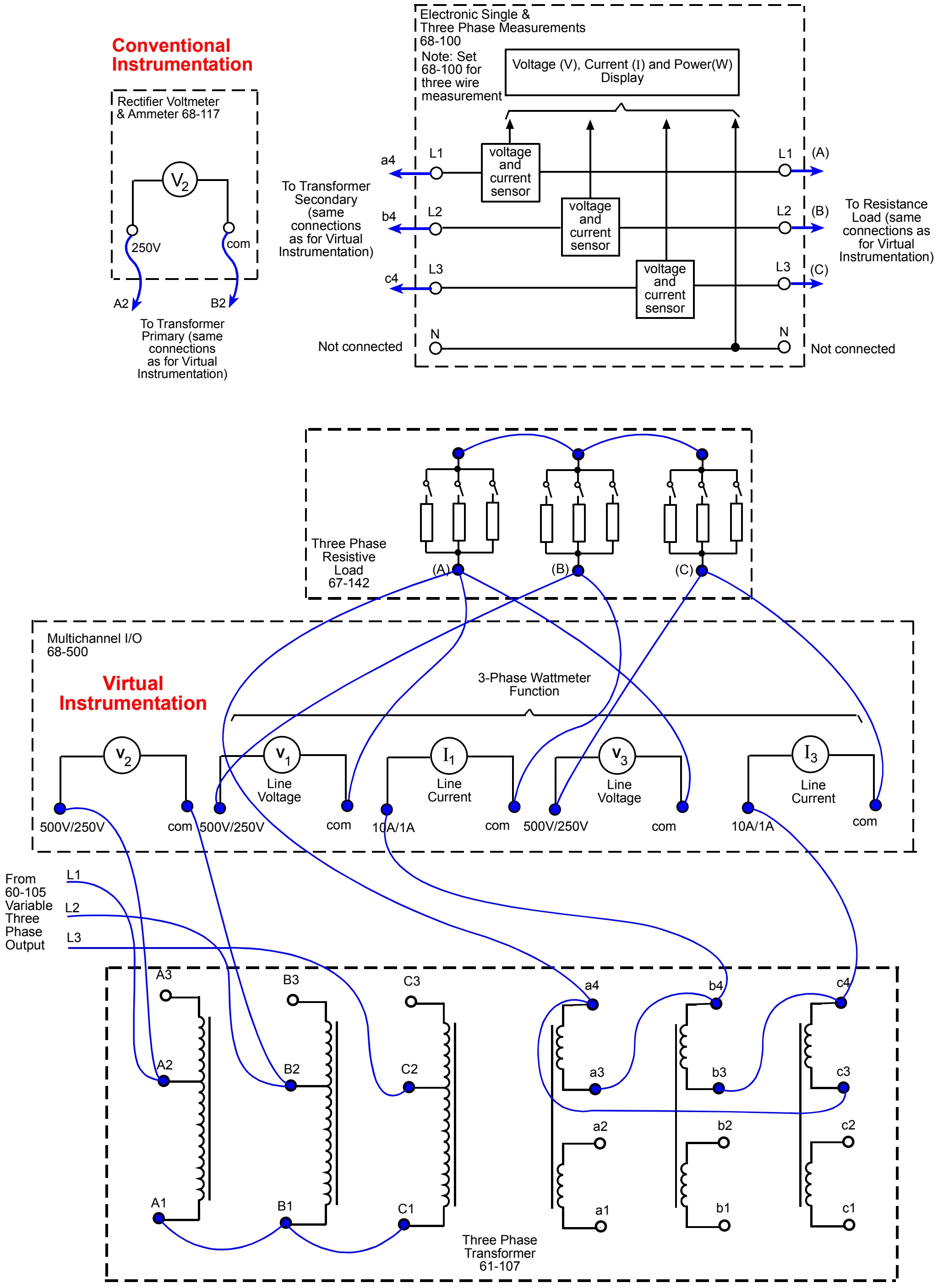


Figure 4-15-6: Practical 15.2 Circuit Diagram

Complete Practical 15.2 Results Table for all values of resistance load listed in the table.

On the Universal Power Supply 60-105, switch off the *'3 phase circuit breaker'*

15.7.1 Exercise 15.2

Compare the secondary power result obtained with the calculated total secondary power recorded in Practical 15.1, Results Table.
Results should be similar.

15.8 Practical 15.3 - Power in a Delta Supply with Delta Load - Single Wattmeter Measurement

Make up the connections shown in Figure 4-15-8. A simplified circuit diagram is shown in Figure 4-15-7. At this stage, V1 and I1 for the wattmeter should be connected in the load (A) secondary circuit shown in Figure 4-15-7 to monitor power (W1) in the resistor bank.

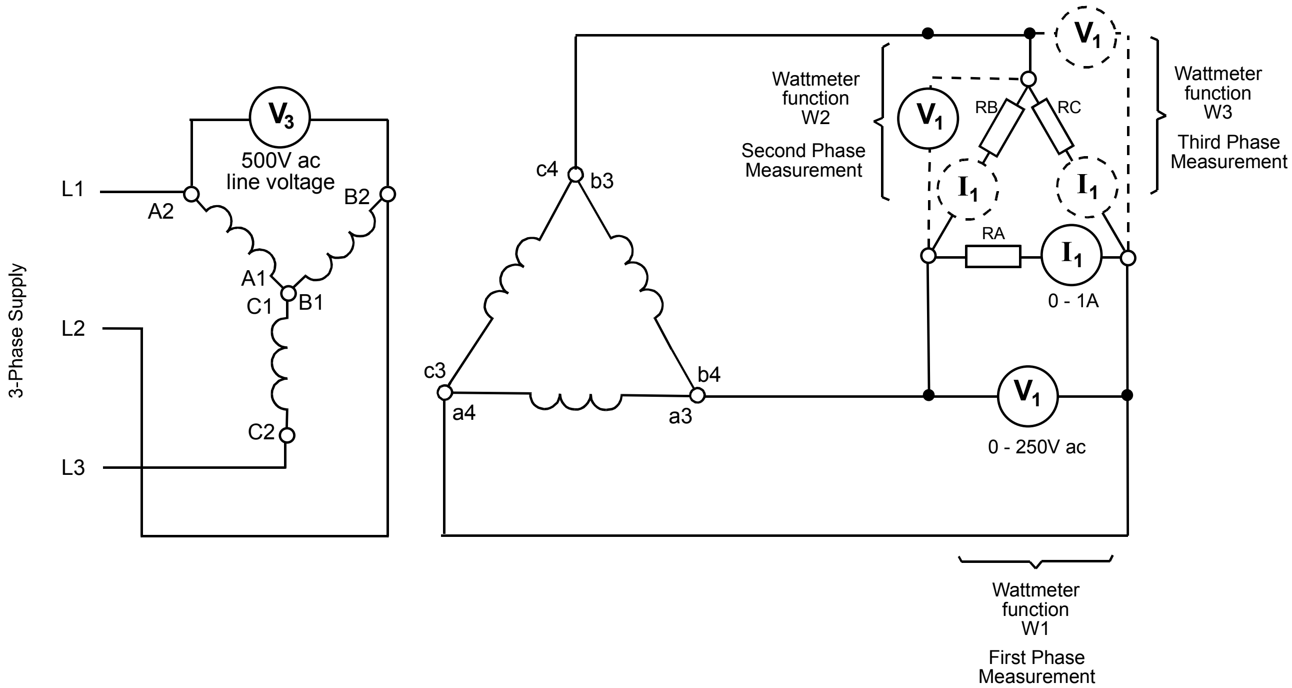


Figure 4-15-7

	Product Version	
	230 V	**120 V**
If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1 and V3 channels to '250 V', V3 to 500 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 and I2 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 and selected within the software.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' (up) position. This corresponds to a total resistance of ………………	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V3 to…………..	*400 V*	*216 V*

Record the primary line voltage and the secondary a3/a4 load (RA) power (W1) as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 15.3, Results Table (230 V or 120 V product version).

Repeat the measurement and recording procedure for the various settings of Resistance Load as shown in the results table for Practical 15.3. Note that all three resistance banks should to be set to the appropriate value.

On the Universal Power Supply 60-105, switch off the *'3 phase circuit breaker'.* On the resistance load 67-142, set all the switches to 'on' (up).

Disconnect V1 and I1 of the wattmeter from secondary winding a3/a4 load (RA), and make a connection from a4 to load (A) in place of the I1 meter.

Connect the wattmeter V1 and I1 into the b3/b4 load (RB) circuit as shown in Figure 4-15-7 for the second measurement.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary winding b3/b4 (W2) on your copy of the appropriate Practical 15.3, Results Table (230 V or 120 V product version).

Repeat the measurement and recording procedure for the various settings of Resistance Load as shown in the results table for Practical 15.3. Note that all three resistance banks should to be set to the appropriate value.

On the Universal Power Supply 60-105, switch off the *'3 phase circuit breaker'.* On the resistance load 67-142, set all the switches to 'on' (up)..

Disconnect the wattmeter V1 and I1 from secondary winding b3/b4 load (RB) and make a connection from b4 to replace the ammeter I1 directly to the resistive load bank RB.

Connect the wattmeter V1 and I1 into the c3/c4 load (RC) circuit, as shown in Figure 4-15-7 for the third measurement.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the power reading for secondary winding c3/c4 (W3) on your copy of the appropriate Practical 15.3, Results Table (230 V or 120 V product version).

Complete Practical 15.3 Results Table for all values of load listed in the table.

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

15.8.1 Exercise 15.3

From the results recorded in Practical 15.3 Results Table, calculate the total power of the secondary circuit as follows:

$$\text{Total power} = W1 + W2 + W3$$

Record the result in Practical 15.3 Results Table.

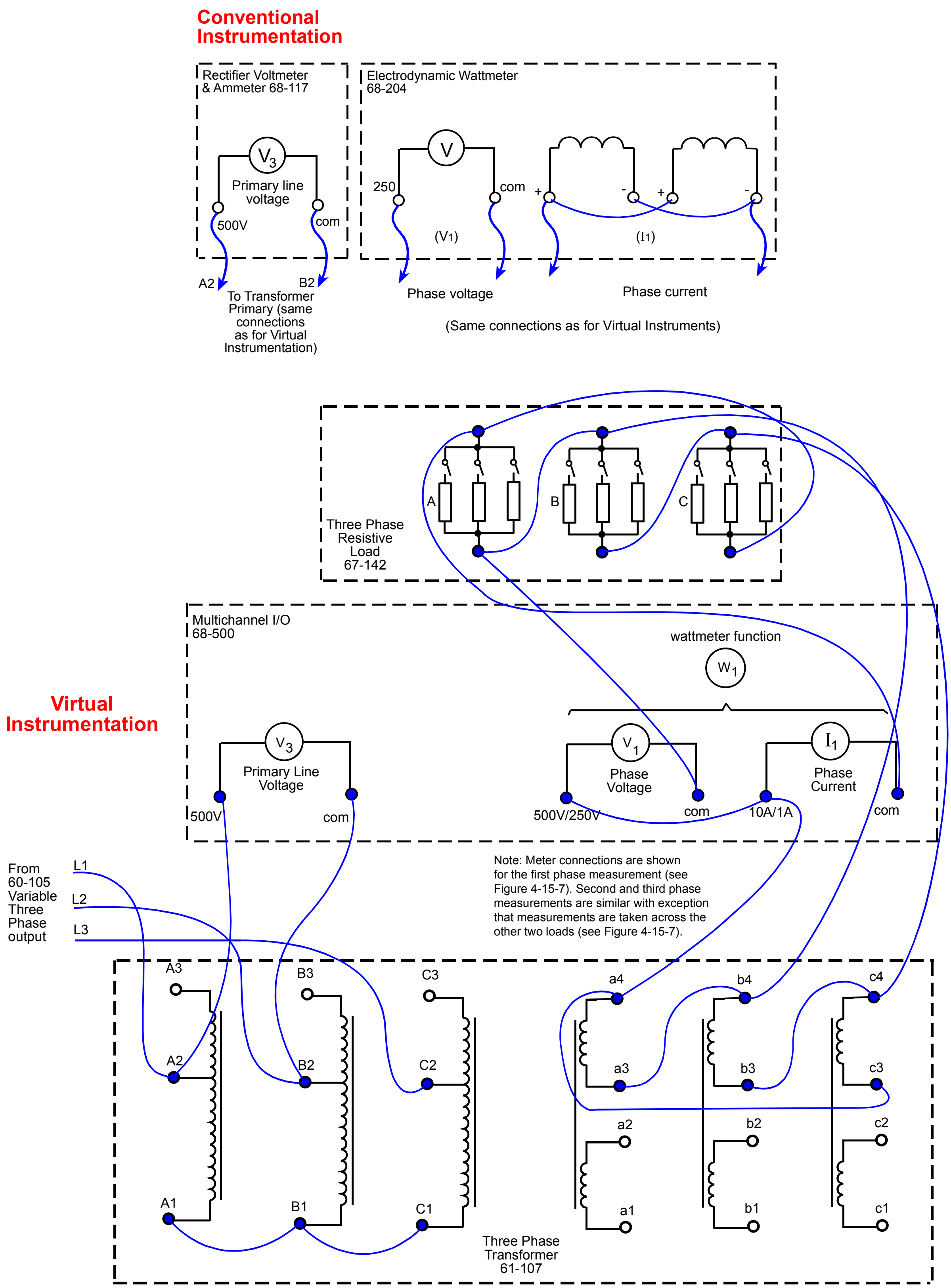


Figure 4-15-8: Practical 15.3 Circuit Diagram

15.9 Practical 15.4 - Power in a Delta Supply with Delta Load - 3-Phase Wattmeter Measurement

In the previous Practical one wattmeter was used to obtain the total three phase power in the Delta connected load. We will now use the conventional or virtual instrumentation three phase wattmeter function to make the measurement and confirm the result of Practical 15.3.

Make up the connections shown in Figure 4-15-10. A simplified circuit diagram is shown in Figure 4-15-9.

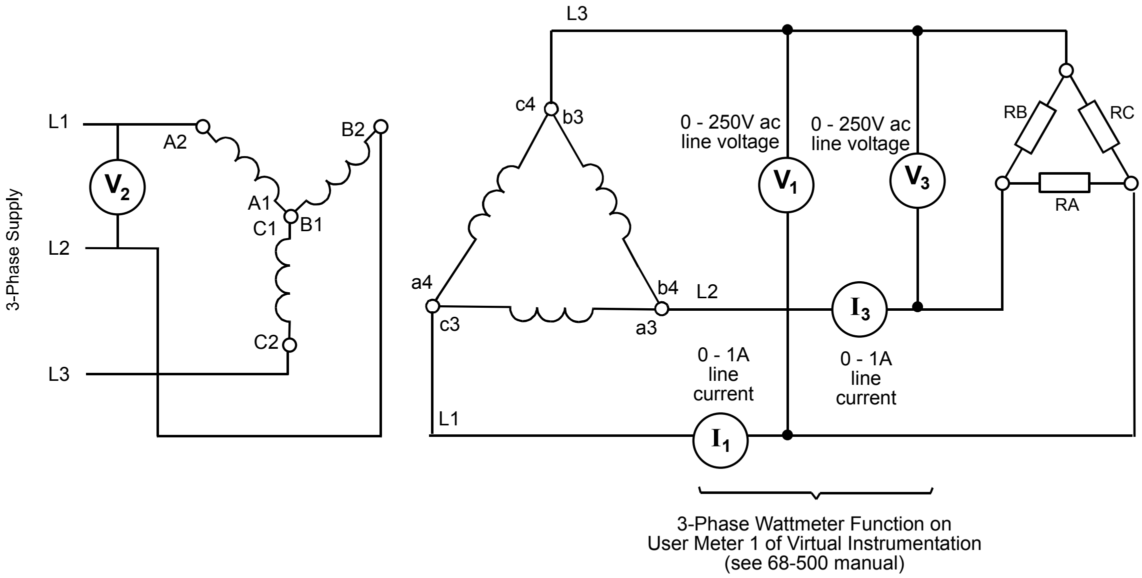


Figure 4-15-9

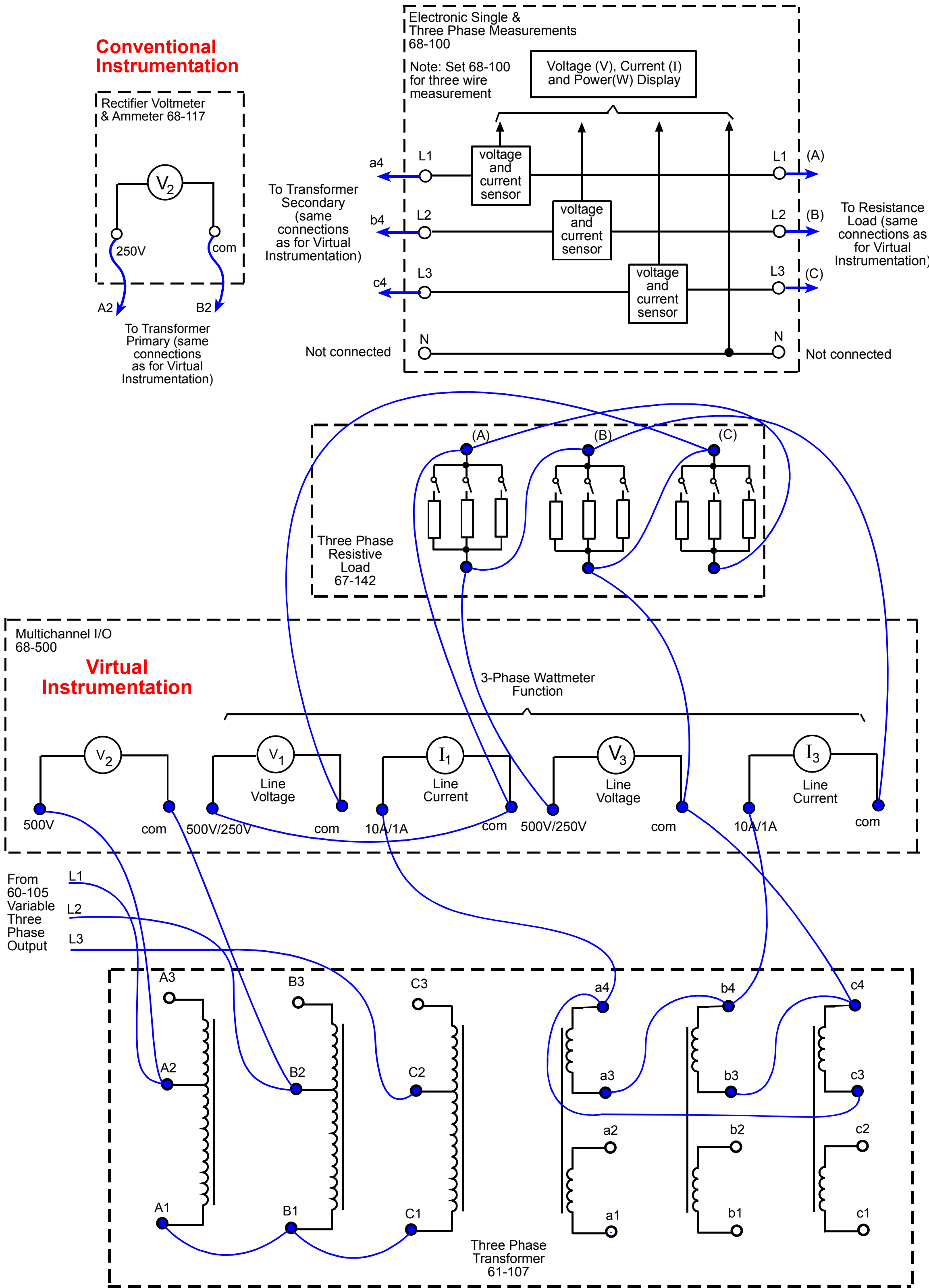


Figure 4-15-10: Practical 15.4 Circuit Diagram

Instruction	Product Version 230 V	Product Version 120 V
On the Multichannel I/O Unit 68-500, set the 250 V/500 V range switches for the V1 and V3 channels to '250 V'. This allows voltages of up to 250 V to be monitored when the '500 V/250 V' sockets are connected. Set V2 for 500 V and set the 1 A/10 A range switches for I1 and I3 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 and selected within the software.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of ………………	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V2 to……………	*400 V*	*216 V*

Observe and note the secondary power as measured on User Meter 1 (UM1) of the Virtual Instrumentation screen or on the 68-100 Single and Three Phase Measurements unit, if conventional instrumentation is being used.

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

15.9.1 Exercise 15.4

Compare the secondary power result obtained with the calculated total secondary power recorded in Practical 15.3, Results Table.
Results should be similar.

15.10 Practical Aspects

A delta connected secondary has no neutral point.

In comparison with a star-connected secondary; if one winding of a delta-connected secondary fails, the three phase voltage is maintained, and it remains possible to supply a three phase load, although at reduced power.

In a balanced three phase system, a delta connected device carries $1/\sqrt{3}$ times the line current and the whole line voltage.

The power is:

$$\sqrt{3}V_{line}I_{line}\cos\phi$$

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.)

15.11 Practical 15.1 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary Star Load (RA) Power (W1)	Secondary Star Load (RB) Power (W2)	Secondary Star Load (RC) Power (W3)	Secondary Total Power (W1+W2+W3)
548 (all resistance switches on)					
640 (3770 switches off)					
760 (1950 switches off)					
1280 (950 switches off)					
1950 (3770 and 950 switches off)					

15.12 Practical 15.2 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Total Three Phase Secondary Power
548 (all resistance switches on)		
640 (3770 switches off)		
760 (1950 switches off)		
1280 (950 switches off)		
1950 (3770 and 950 switches off)		

15.13 Practical 15.1 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary Star Load (RA) Power (W1)	Secondary Star Load (RB) Power (W2)	Secondary Star Load (RC) Power (W3)	Secondary Total Power (W1+W2+W3)

15.14 Practical 15.2 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Total Three Phase Secondary Power
548 (all resistance switches on)		
640 (3770 switches off)		
760 (1950 switches off)		
1280 (950 switches off)		
1950 (3770 and 950 switches off)		

15.15 Practical 15.3 - Results Tables (230 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary a3/a4 Load (RA) Power (W1)	Secondary b3/b4 Load (RB) Power (W2)	Secondary c3/c4 Load (RC) Power (W3)	Secondary Total Power (W1+W2+W3)
548 (all resistance switches on)					
640 (3770 switches off)					
760 (1950 switches off)					
1280 (950 switches off)					
1950 (3770 and 950 switches off)					

15.16 Practical 15.3 - Results Tables (120 V Product Version)

Resistance Load (Ω)	Primary Line Voltage (V)	Secondary a3/a4 Load (RA) Power (W1)	Secondary b3/b4 Load (RB) Power (W2)	Secondary c3/c4 Load (RC) Power (W3)	Secondary Total Power (W1+W2+W3)

16 Six Phase Transformers

16.1 Assignment Information

16.1.1 Objectives

When you have completed this assignment you will:

- understand the operation of transformers with six phase secondary windings.

16.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignment 11 and 12.
- 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.)

16.1.3 Practicals

1. Star to Double Star Transformation
2. Star to Double Delta Transformation

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.

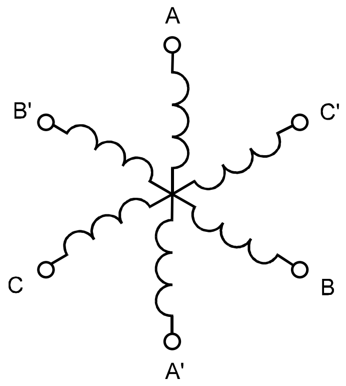
16.2 Theory

16.2.1 Introduction

Transformers with six phase secondary windings are used to supply ac to dc rotary converters and heavy duty current ac to dc static rectifying systems. Either a double-star or a double-delta connection may be used.

16.2.1.1 Star to Double-Star Connection

Figure 4-16-1 shows the double-star connection; two three phase stars have a common neutral, making in effect a star with six arms. In this arrangement, the voltages are determined by the transformer. The voltage between adjacent phases equals the phase-neutral voltage.



Double-star

Figure 4-16-1

16.2.1.2 Star to Double-Delta Connection

Figure 4-16-2 shows the double-delta connection. In this case, there are in effect two separate delta secondaries. While these can produce a balanced set of six phase voltages, the relationship between potentials in the two deltas is affected by the external circuit.

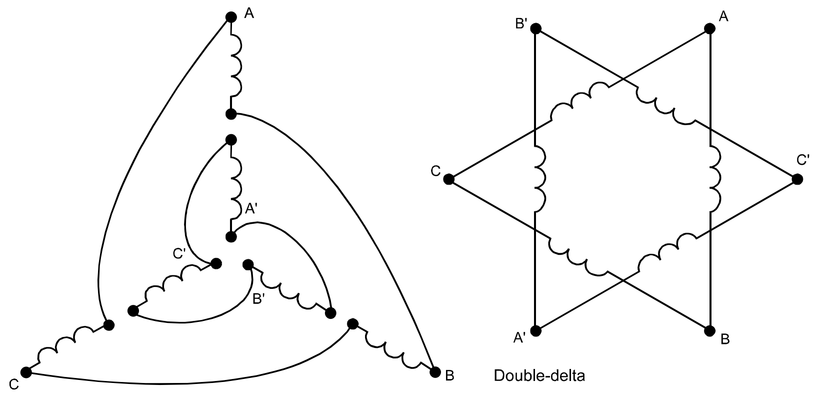


Figure 4-16-2

16.3 Content

The practicals in this assignment examine six phase transformers.

16.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation 60-070-VIP	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation 60-070-CI1	• Rectifier Voltmeter & Ammeter	68-117
Auxiliary Equipment	• Oscilloscope, 2 Channel, 20 MHz, such as Feedback CS4125 (not supplied)	
	• Differential Voltage Probe (2 off)	68-151

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.

16.5 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).*

16.6 Practical 16.1 - Star to Double-Star Transformation

Make up the connections shown in Figure 4-16-4. A simplified circuit diagram is shown in Figure 4-16-3.

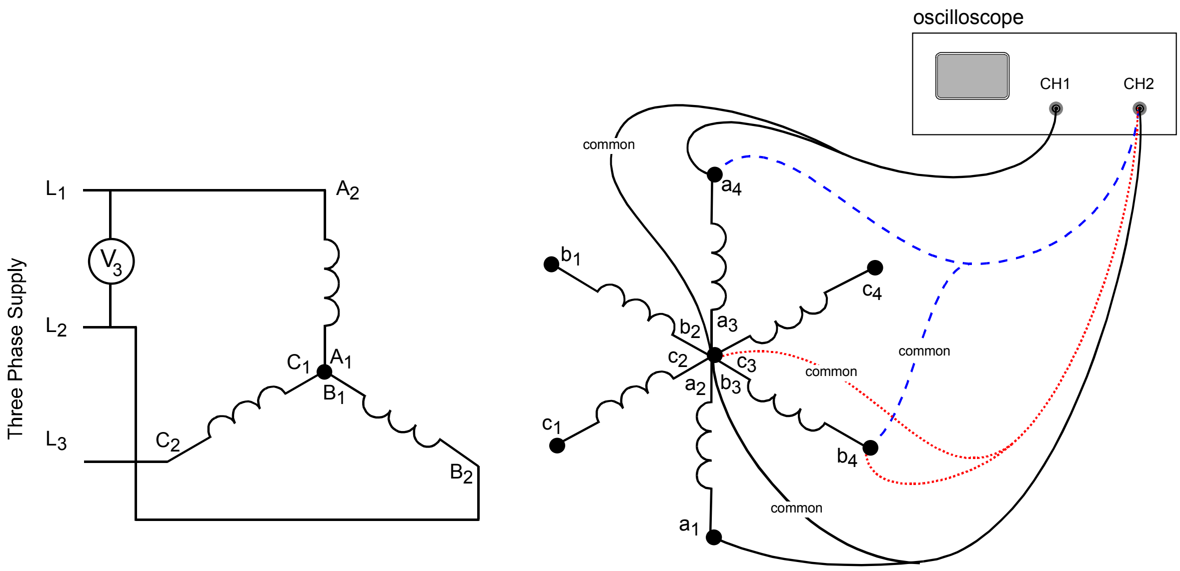


Figure 4-16-3

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.

Switch on the oscilloscope, set the timebase to 5 ms/div and the channel amplifiers to 0.5 V/div.

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.

	Product Version	
	230 V	**120 V**
Turn the dial on the power supply to set the primary voltage V3 to…………	*400 V*	*216 V*

Sketch and label the opposing phase voltage waveforms (Ch1 V_{a4a3} and Ch2 V_{a1a2}) observed on a copy of Figure 4-16-7 located in the 'Results' section at the end of this assignment.

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

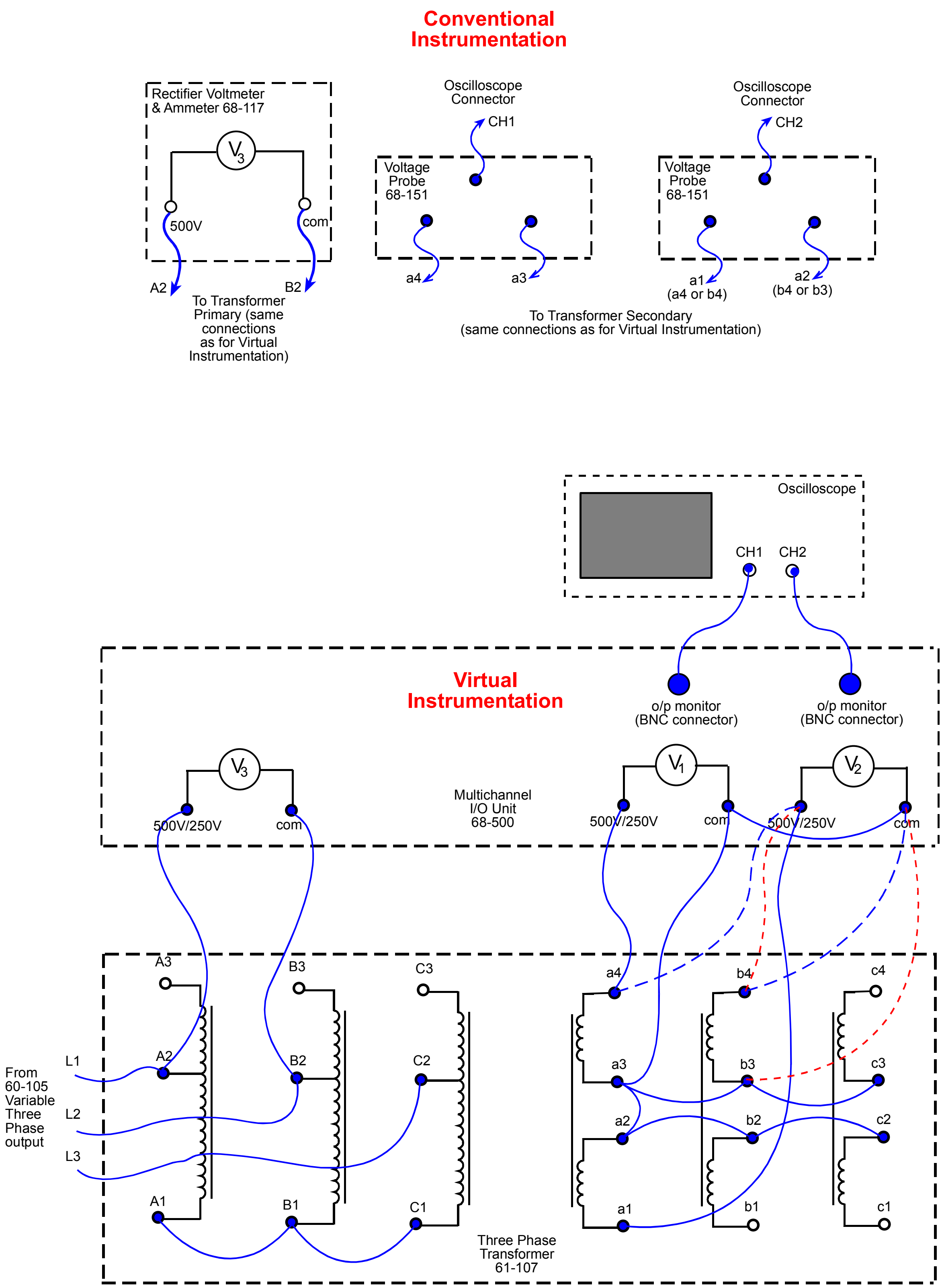


Figure 4-16-4: Practical 16.1 Circuit Diagram

On the oscilloscope, disconnect Channel 2 connections and connect to transformer secondary terminals a4 and b4 as shown in Figure 4-16-4 (long dashed connections).

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Add a sketch of the line voltage waveform observed on the copy of Figure 4-16-7 and label it V_{a4b4}.

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

On the oscilloscope, disconnect Channel 2 connections and connect to transformer secondary terminals b4 and b3 as shown in Figure 4-16-4 (dotted connections).

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Add a sketch of the line voltage waveform observed on the copy of Figure 4-16-7 and label it V_{b4b3}.

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

16.7 Practical 16.2 - Star to Double-Delta Transformation

Make up the connections shown in Figure 4-16-6. A simplified circuit diagram is shown in Figure 4-16-5.

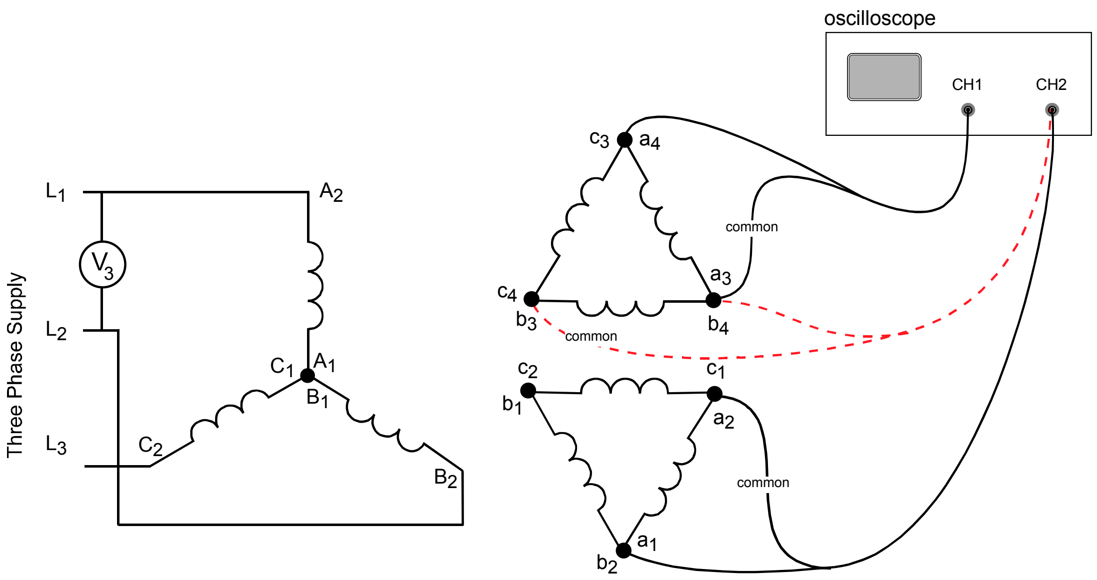


Figure 4-16-5

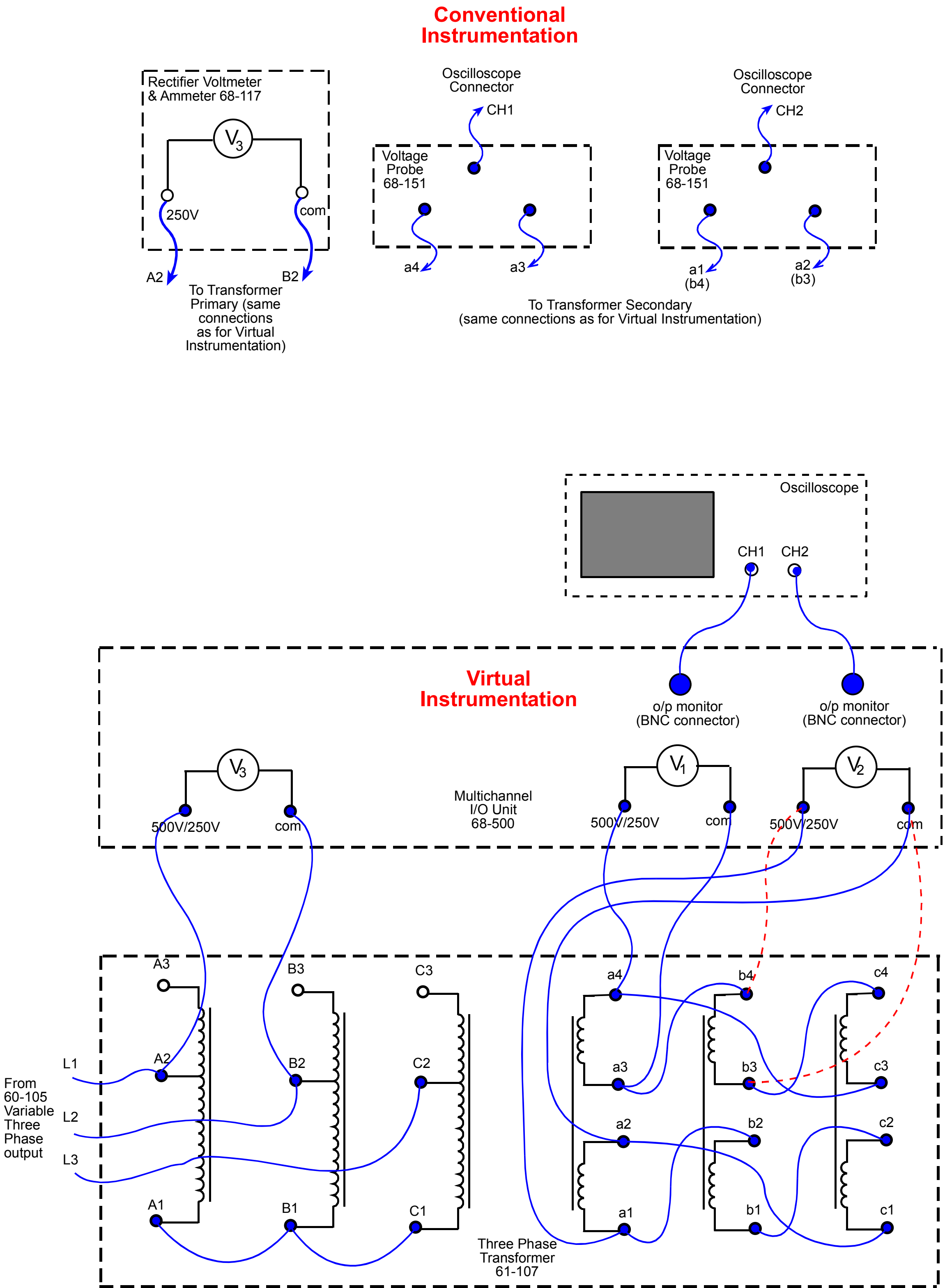


Figure 4-16-6: Practical 16.2 Circuit Diagram

Product Version	
230 V	120 V

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.

Switch on the oscilloscope, set the timebase to 5 ms/div and the channel amplifiers to 0.5 V/div.

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.

	230 V	120 V
Turn the dial on the power supply to set the primary voltage V3 to………	*400 V*	*216 V*

Sketch and label the opposing phase voltage waveforms (V_{a4a3} and V_{a1a2}) observed on a copy of Figure 4-16-8 located in the 'Results' section at the end of this assignment.

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

On the oscilloscope, disconnect Channel 2 and connect transformer secondary terminals b4 and b3 as shown in Figure 4-16-5 (dashed connections) to Channel 2.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Add a sketch of the phase voltage waveform observed on the copy of Figure 4-16-8 and label it V_{b4b3}.

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

16.8 Practical Aspects

In a double star connection, two three phase stars have a common neutral, making in effect a star with six arms. In this arrangement, the voltages are determined by the transformer. The voltage between adjacent phases equals the phase to neutral voltage.

In the double delta connection, there are two separate deltas. While these can produce a balanced set of six phase voltages, the relation between potentials in the two deltas is affected by the external circuit.

16.9 Practical 16.1 - Graphs (230 V & 120 V Product Versions)

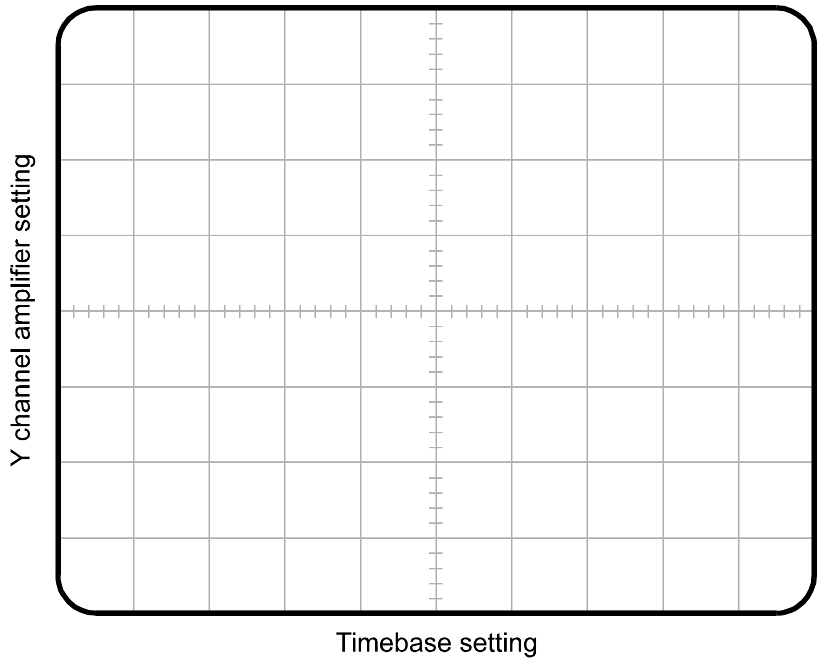


Figure 4-16-7: Star to Double Star Transformation

16.10 Practical 16.2 - Graphs (230 V & 120 V Product Versions)

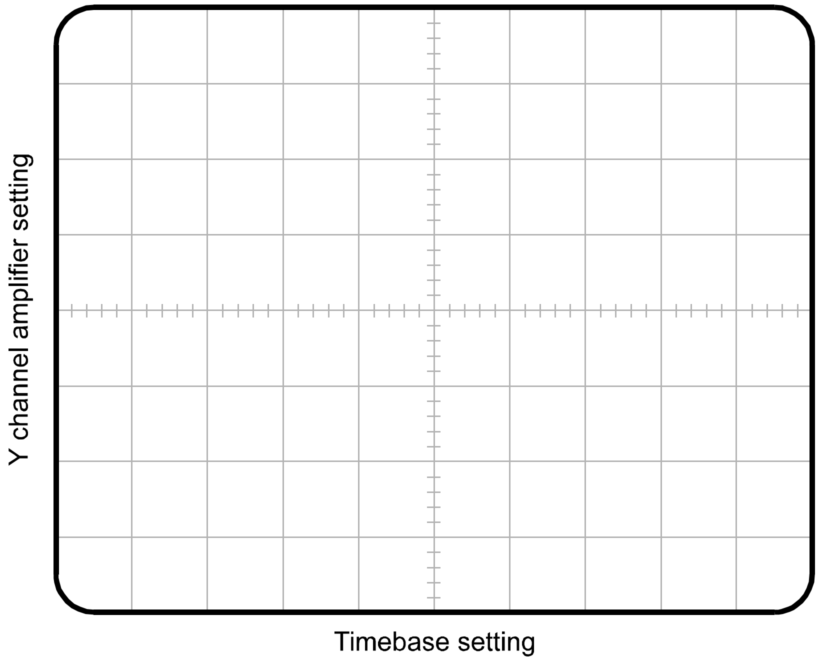


Figure 4-16-8: Star to Double Delta Transformation

17 Four-Wire Systems

17.1 Assignment Information

17.1.1 Objectives

When you have completed this assignment you will:

- understand the practical benefits of three phase, four-wire systems.

17.1.2 Knowledge Level

Before you start this assignment:

- you should have read Appendix A General Information.
- you should have completed Assignments 11, 12, 14 and 15.
- 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.)

17.1.3 Practicals

1. Four-Wire System on Load
2. Observing Fourth Wire Operation

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.

17.2 Theory

17.2.1 Introduction

Most domestic loads and many industrial loads require single phase power, which are to be fed from the three phase supply. Although the loads are distributed between the three phases as evenly as practicable, the system is rarely balanced because individual single phase loads can be switched on and off.

For this reason, a four-wire system is used as shown in Figure 4-17-1.

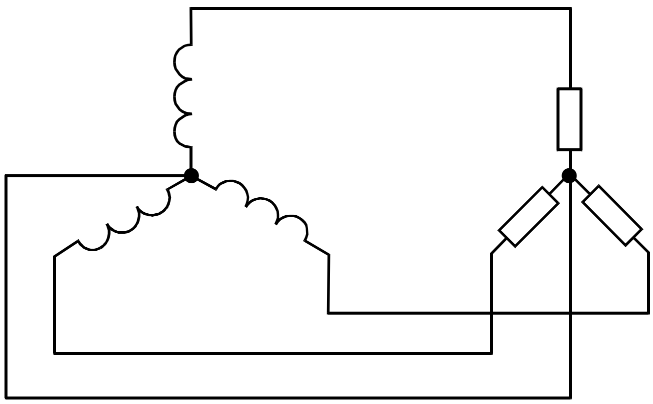


Figure 4-17-1

If the loads are balanced, then the phasor sum of currents entering the neutral wire is zero. If the loads are not balanced, there will be current in the neutral wire that serves to keep the system voltages balanced.

17.3 Content

The practical in this assignment introduces the four-wire system.

17.4 Equipment Required

- Universal Power Supply 60-105.
- Three Phase Transformer Unit 61-107
- Switched Three Phase Resistance Load 67-142
- System Frame 91-200
- Standard Set of Patch Leads 68-800
- Either:

Virtual Instrumentation 60-070-VIP	• Multichannel I/O Unit	68-500
	• Software Pack CD	68-912-USB
	or	
Conventional Instrumentation 60-070-CI1	• Electronic Single & Three Phase Measurements	68-100
Conventional Instrumentation 60-070-CI2	• Rectifier Voltmeter & Ammeter (two off)	68-117
	• Electronic Wattmeter (two off)	68-204

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.

17.5 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).*

17.6 Practical 17.1 - Four-Wire System on Load

Make up the connections shown in Figure 4-17-3. A simplified circuit diagram is shown in Figure 4-17-2. If using virtual instrumentation V2 and I2 should be connected in the c3/c4 secondary winding load circuit as shown to monitor current and phase voltage across the appropriate load resistor bank. If using conventional instrumentation, the 68-100 is used to monitor all the phase currents and phase voltages simultaneously. These values can be displayed using the menu facility and recorded for each of the loads RA, RB and RC.

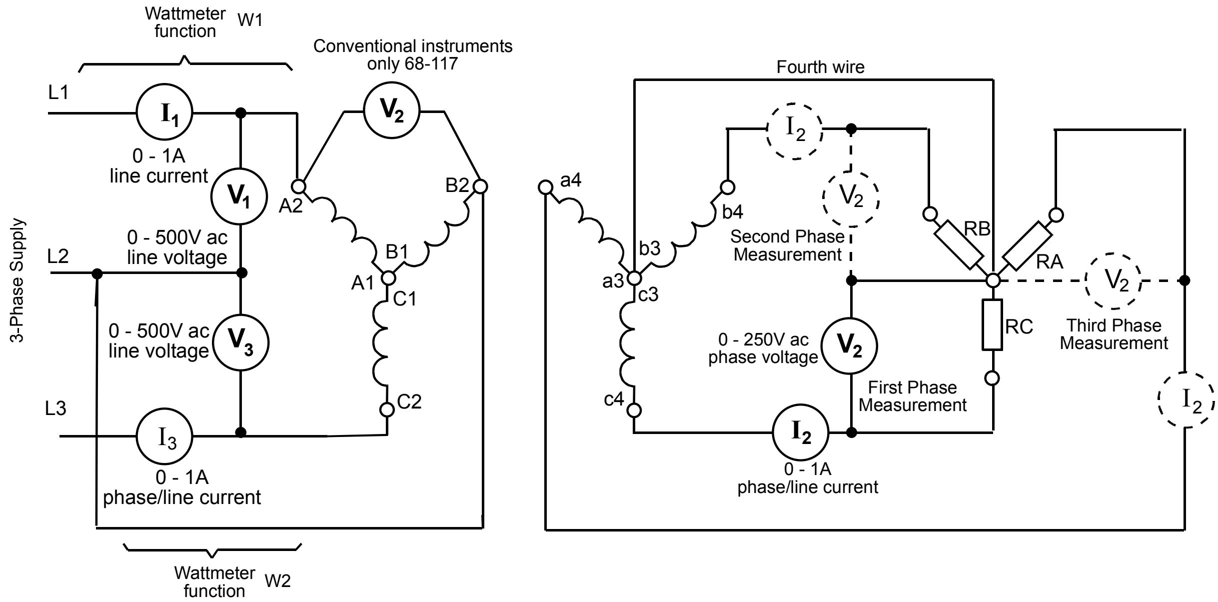


Figure 4-17-2

	Product Version	
	230 V	**120 V**
If virtual instrumentation is being used, set the 250 V/500 V range switches for V1, V2 and V3 channel 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 switch 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 socket is connected or 200 mA to be monitored when the 200 mA socket is connected and selected within the software.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of ……………….	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V1 to…………	*400 V*	*216 V*

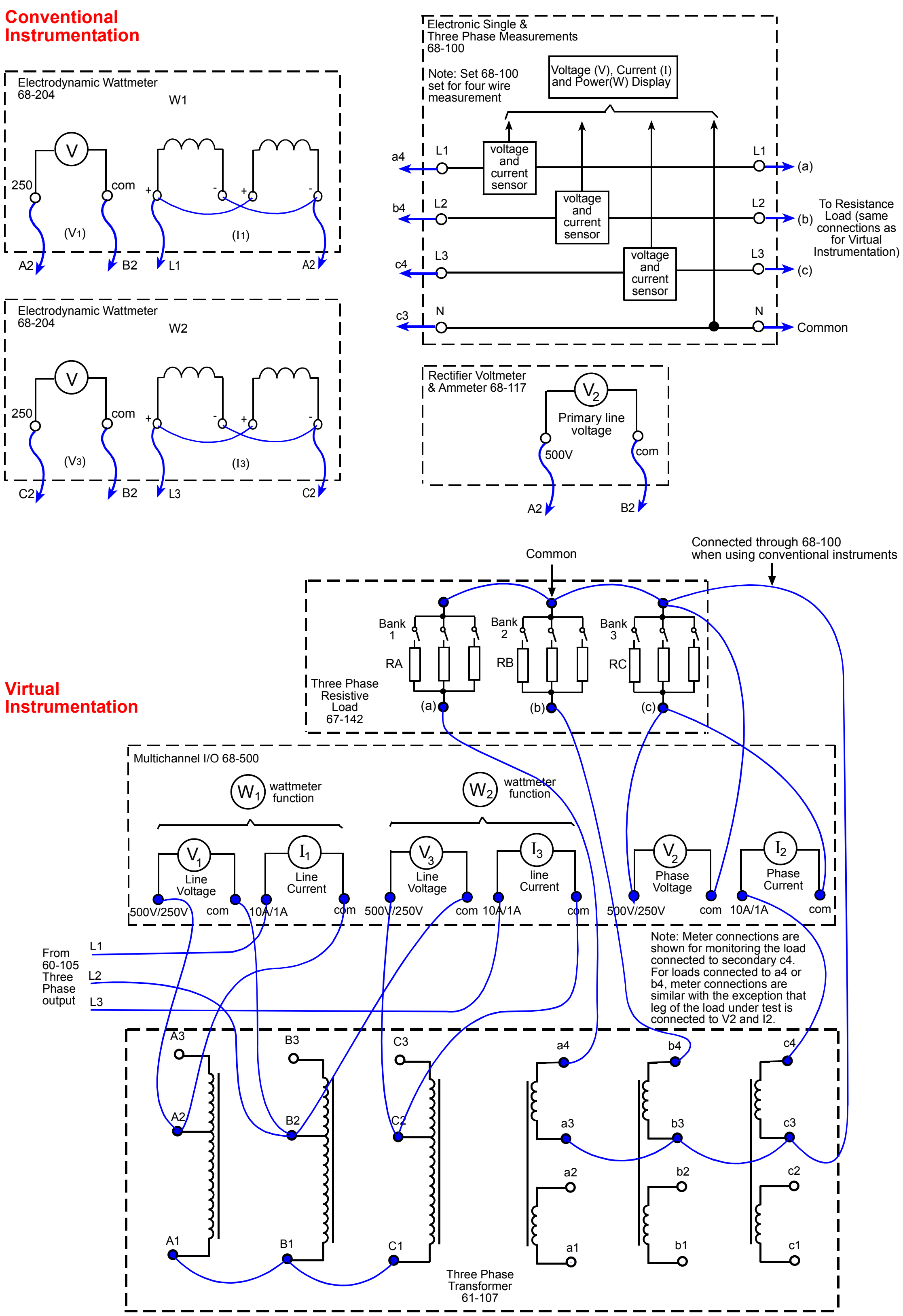


Figure 4-17-3: Practical 17.1 Circuit Diagram

Record the following, as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 17.1, Results Table (230 V or 120 V product version).:

- the primary power for L1/L2 (W1),
- the primary power for L3/L2 (W2)
- total primary power (W1 + W2)

NOTE:

When recording the value of primary power using conventional instrumentation, one of the 68-204 wattmeters may read a negative value. If this should happen, switch off the 60-105 power supply and reverse the connections to the wattmeter current coil. On the power supply, restore power to the system. To obtain the value of the power reading, the value indicated on the wattmeter with the reversed connection should be subtracted from the value indicated on the other wattmeter.

- secondary c3/c4 (RC) phase current as read on ammeter I_2.when using virtual or on the 68-100 if using conventional instrumentation.
- Secondary c3/c4 (RC) phase voltage as read on voltmeter V_2 when using virtual or on the 68-100 for conventional instrumentation.

If Conventional Instruments are being used then the above measurements can all be made on the 68-100 without the need to disconnect or reconnect the circuit. Use the 68-100's menu facility to obtain the appropriate results.

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

The following procedure applies to the use of virtual instrumentation only:

Disconnect V2 and I2 from secondary winding load RC circuit and make a link in place of I2 to connect c4 directly to the resistive load bank RC.

Disconnect secondary winding b4 from its resistive load bank and connect V2 and I2 as shown in Figure 4-17-2 for the second measurement.

On the supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the parameters listed above for secondary winding load circuit RB, on your copy of the appropriate Practical 17.1 Results Table (230 V or 120 V product version).

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

Disconnect V2 and I2 from secondary winding load circuit RB and make a link in place of I2 to connect b4 directly to the resistive load bank RB.

.

Disconnect secondary winding a4 from its resistive load bank RA and connect V2 and I2 as shown in Figure 4-17-2 for the third measurement

Record the parameters listed for secondary winding load circuit RA on your copy of the appropriate Practical 17.1, Results Table (230 V or 120 V product version).

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

17.6.1 Exercise 17.1

From the results recorded in your copy of the Practical 17.1, Results Table, calculate the total power of the secondary circuit as follows:

Total power = RC phase power + RB phase power + RA phase power

Record the result in your copy of the Practical 17.1, Results Table.

Refer to Assignment 4 for power considerations in three phase transformers with star connection.

17.7 Practical 17.2 - Observing Fourth Wire Operation

Make up the connections shown in Figure 4-17-5. A simplified circuit diagram is shown in Figure 4-17-4. At this stage, V2 should be connected across the secondary winding load circuit RC as shown to monitor phase voltage across the appropriate load resistor bank.

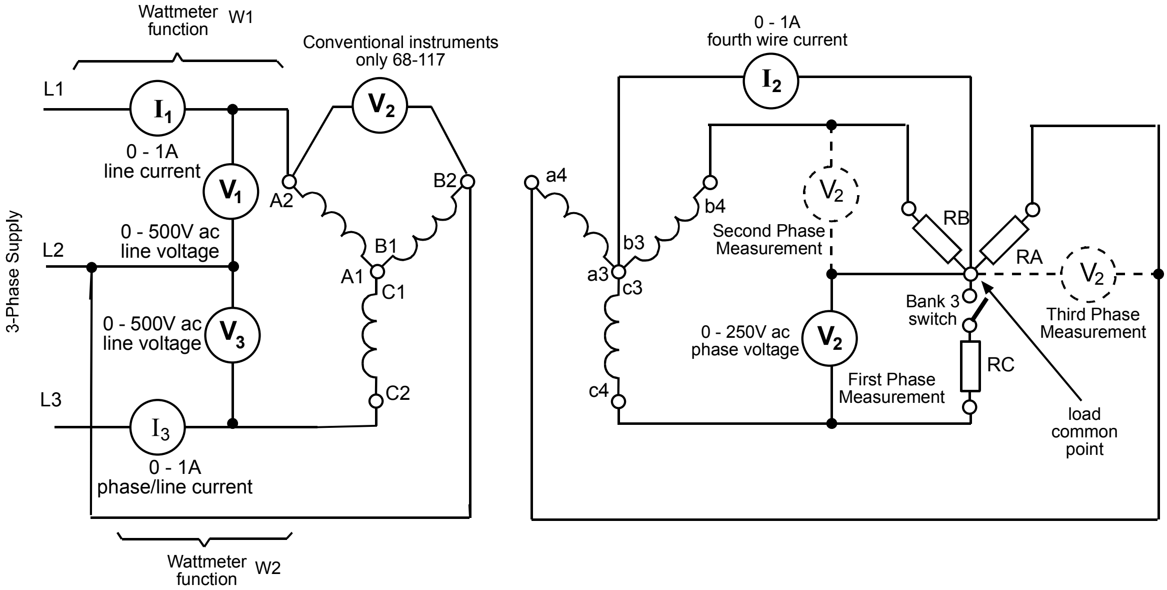
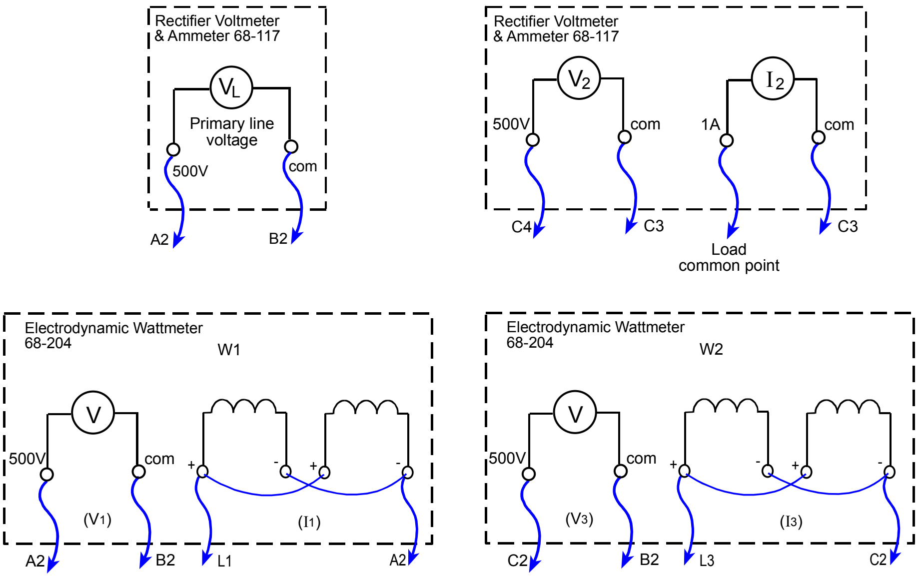


Figure 4-17-4

	Product Version	
	230 V	**120 V**
If virtual instrumentation is being used, set the 250 V/500 V range switches for the V1, V3 and to '500 V' and V2 to 250 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 switch 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 socket is connected or 200 mA to be monitored when the 200 mA socket is connected and selected within the software.		
Set all the resistance switches on the Three Phase Resistive Load 67-142 to the 'on' position. This corresponds to a total resistance of ……………….	*548 Ω per phase*	*140 Ω per phase*
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.		
Turn the dial on the power supply to set the primary voltage V1 to………..	*400 V*	*216 V*

Conventional Instrumentation



Virtual Instrumentation

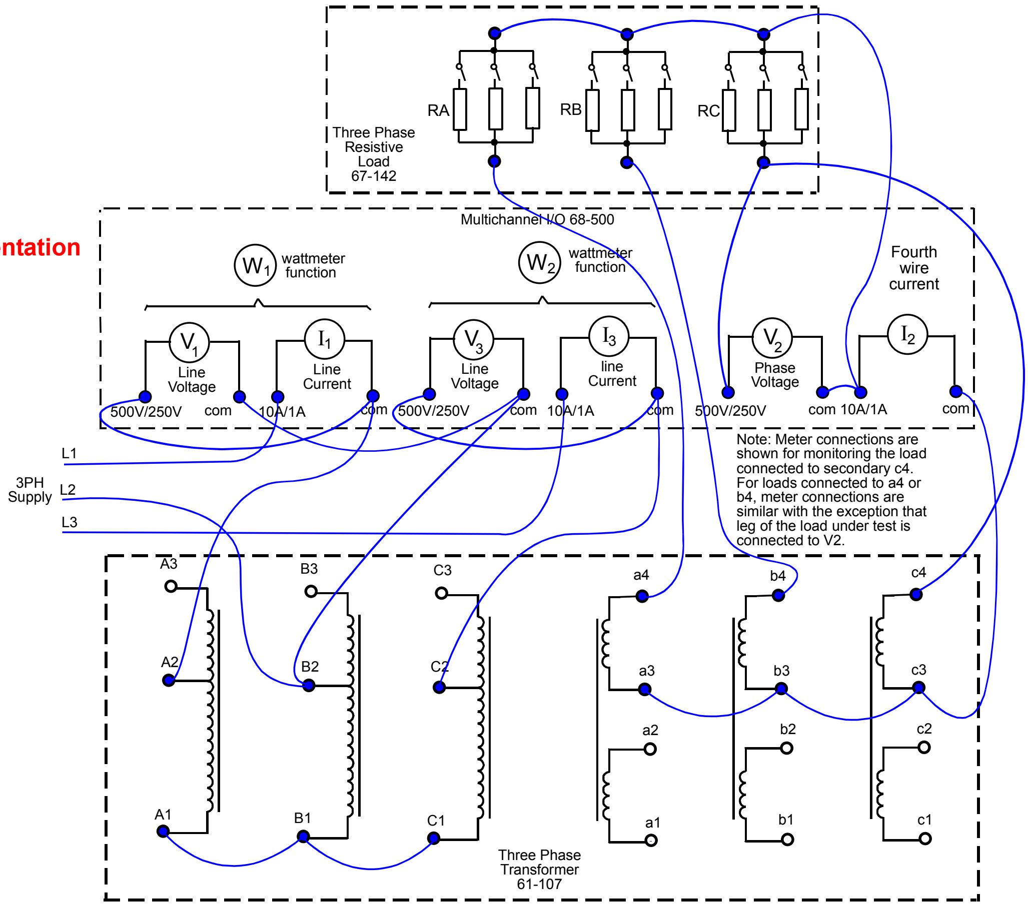


Figure 4-17-5: Practical 17.2 Circuit Diagram

Record the following, as read on virtual or conventional instrumentation, on a copy of the appropriate Practical 17.2, Results Table (230 V or 120 V product version) for secondary winding c3/c4 (RC).

- the primary power for L1 and L2 (W1),
- the primary power for L3 and L2 (W2)
- total primary power (W1 + W2)
- the fourth-wire current as read on ammeter I_2.
- phase load voltage as read on voltmeter V_2.

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

Disconnect the V2 lead from secondary winding terminal c4 circuit and connect it directly to the secondary winding terminal b4, for the second phase measurement, as shown in Fig 4-17-4.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the parameters listed above for secondary winding load circuit b3/b4 (RB) on your copy of the appropriate Practical 17.2, Results Table (230 V or 120 V product version).

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

Disconnect the V2 lead from secondary winding terminal b4 and connect it to the secondary winding terminal a4, for the third phase measurement, as shown in Fig 4-17-4.

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the parameters listed for third winding load circuit a3/a4 (RA) on your copy of the appropriate Practical 17.2, Results Table (230 V or 120 V product version).

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

Product Version	
230 V	**120 V**

Disconnect V2 lead from secondary winding a3/a4 (RA) circuit and connect it to c3/c4 (RC) resistive load bank.

Three phase supply with unbalanced load

	230 V	120 V
On the Three Phase Resistive Load 67-142, set all 'bank 3' resistance switches to the 'off' position. This corresponds to a resistance load of ……. for banks 1 and 2 whilst bank 3 is open circuit.	*548 Ω*	

On the Universal Power Supply 60-105, switch on the *'3 phase circuit breaker'.*

Record the parameters for c3/c4 (RC) on your copy of the second Practical 17.2, Results Table.

Now follow the procedure as for the previous set of measurements and complete the results table.

It should be observed that whilst bank 3 is open circuit, current flows in the fourth wire. Additionally, the voltage measured across the two resistor banks in circuit should remain balanced.

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

17.7.1 Exercise 17.1

From the results recorded in your copies of the Practical 17.2, Results Tables, explain why the system is still balanced when a resistive load bank is disconnected.

17.8 Practical Aspects

A four-wire system is used when single phase loads are to be supplied from a three phase source, because a neutral wire is necessary to carry the unbalance of currents between the line currents. If there is no neutral wire, then the load unbalance disturbs the system voltages, possibly dangerously.

The neutral wire need not carry more current than any one of the line wires. The amount of current is given by the phasor sum of the line currents.

To measure power in a four-wire system, three power readings are required.

17.9 Practical 17.1 - Results Tables (230 V Product Version)

Circuit Load (548Ω/ Phase)	Primary			Secondary		
	L1–L2 Power (W1)	L3–L2 Power (W2)	Total Primary Power (W1+W2)	Phase/Line Current (A)	Phase Voltage (V)	Phase Power (I^2R)
1 RC (c3/c4)						
2 RB (b3/b4)						
3 RA (a3/a4)						
Total Secondary Power (sum of Phase Power)						

17.10 Practical 17.1 - Results Tables (120 V Product Version)

Circuit Load	Primary			Secondary		
	L1–L2 Power (W1)	L3–L2 Power (W2)	Total Primary Power (W1+W2)	Phase/Line Current (A)	Phase Voltage (V)	Phase Power (I^2R)
1 RC (c3/c4)						
2 RB (b3/b4)						
3 RC (a3/a4)						
Total Secondary Power (sum of Phase Power)						

17.11 Practical 17.2- Results Tables (230 V Product Version)

Secondary Winding Circuit	Primary			Secondary	
	L1–L2 Power (W1)	L3–L2 Power (W2)	Total Primary Power (W1+W2)	Phase Voltage (Load Voltage) (V)	Fourth Wire Current (A)
1 c3/c4(RC)					
2 b3/b4(RB)					
3 a3/a4(RA)					

Circuit Readings with all Resistive Load Bank Switches Closed

Secondary Winding Circuit	Primary			Secondary	
	L1–L2 Power (W1)	L3–L2 Power (W2)	Total Primary Power (W1+W2)	Phase Voltage (Load Voltage) (V)	Fourth Wire Current (A)
1 c3/c4(RC)					
2 b3/b4(RB)					
3 a3/a4(RA)					

Circuit Readings with Resistive Load Banks 1 and 2 Switches Closed and 3 Open

17.12 Practical 17.2- Results Tables (120 V Product Version)

Secondary Winding Circuit	Primary			Secondary	
	L1–L2 Power (W1)	L3–L2 Power (W2)	Total Primary Power (W1+W2)	Phase Voltage (Load Voltage) (V)	Fourth Wire Current (A)
1 c3/c4(RC)					
2 b3/b4(RB)					
3 a3/a4(RA)					

Circuit Readings with all Resistive Load Bank Switches Closed

Secondary Winding Circuit	Primary			Secondary	
	L1–L2 Power (W1)	L3–L2 Power (W2)	Total Primary Power (W1+W2)	Phase Voltage (Load Voltage) (V)	Fourth Wire Current (A)
1 c3/c4(RC)					
2 b3/b4(RB)					
3 a3/a4(RA)					

Circuit Readings with Resistive Load Banks 1 and 2 Switches Closed and 3 Open

A General Information

A.1 History

The transformer effect was first observed by Michael Faraday in 1831 when experimenting with two coils wound on an iron core. He found that on applying a voltage to one of the coils a voltage was induced in the second coil although there was no electrical connection between them.

It was not until the 1880's that transformers were used for the distribution of electrical power. They are now among the most widely used of all types of electrical machine. Transformers range in size from the very large 3-phase types used in power stations to step up the generator voltage to the level required for transmission over long distances, down to the small single phase transformers used in audio frequency work, which may weigh only a few grammes.

Figure A-1: Typical Transformer

A.2 The Transformer As An Electrical Machine

A machine may be defined as an apparatus which accepts energy in some form and transfers that energy, possibly in an alternative form, to a load. Mechanical machines include pulleys, gear drives and various types of engine. Some typical electrical machines are described below:

- A synchronous generator, driven from a mechanical source of power at a fixed rotational speed will supply electrical power at a fixed frequency.
- A direct-current motor connected to an electrical power supply will produce torque over a range of shaft speeds.
- A frequency convertor accepts power at a given frequency and supplies power at another set frequency.
- A power transformer accepts electrical power at a given ac voltage and supplies electrical power at a higher or lower ac voltage. It may also be used electrically to isolate one electrical circuit from another, possibly using the same input and output voltage.

A transformer is analogous to a gear drive, which changes shaft speed, usually by a fixed ratio, without changing the form of energy transferred from the input to the output shaft.

The transformer provides an excellent introduction to the general study of electrical machines, since its construction is relatively simple and having no rotating parts its assembly and testing is not complicated. Despite its relative simplicity it can be used as a means of understanding the significance of the magnetic circuit, losses, efficiency, temperature rise, phasor diagrams and equivalent circuits. All of these concepts are relevant to the study of motors, generators and other electromagnetic machines.

A.3 Transformer Principles

A transformer in its basic form consists of two coils fitted over a magnetic steel core, as shown in Figure A-2.

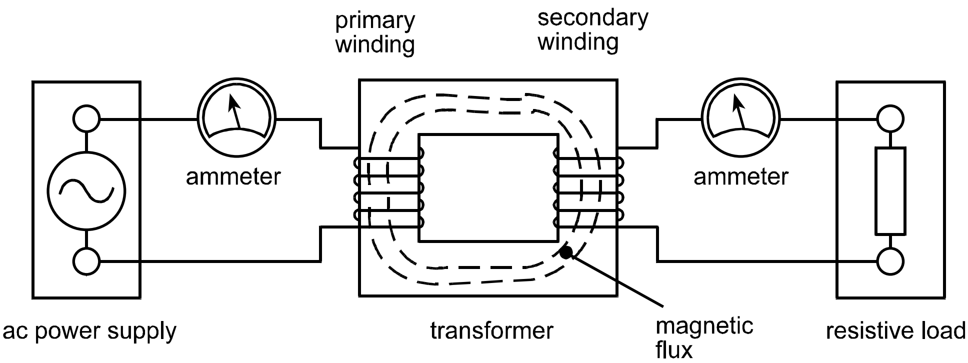


Figure A-2

If one of these coils, which we will call the primary winding, is connected to an ac power supply it will be found that an alternating voltage will also be present across the terminals of the other, or secondary winding. If we connect the secondary winding to an electrical load it will supply current to it and a corresponding current will be drawn into the primary from the supply.

The transformer therefore transfers ac voltage and current from the primary circuit to the secondary with no electrical connection between them. This is a useful facility but, more important, by having a different number of turns on the secondary to those on the primary we can change, or transform the secondary voltage to whatever level we require. In other words, we can step up or step down the mains supply voltage, but the product of voltage and current, or volt-amperes, in the primary is the same as the volt-amperes in the secondary, apart from some losses within the transformer itself.

Although there is no electrical connection between the two windings, there is a magnetic flux which links them through their common core and which alternates at the same frequency as the ac mains supply. It is this changing flux which causes a voltage to be induced in the secondary winding.

The voltage per coil turn will be the same for the primary and secondary windings. To take an example, consider a transformer which has 500 primary turns and 250 secondary turns.

If we apply 100 volts to the primary winding, the volts per turn will be:

$$\frac{100}{500} = 0.2$$

From this we can say that the secondary voltage will be:

$$0.2 \times 250 = 50 \text{ Volts}$$

This shows that the voltage ratio of the transformer is the same as the turns ratio.

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}$$

where V_1 = primary voltage

V_2 = secondary voltage

N_1 = primary turns

N_2 = secondary turns

If now the secondary winding is connected to an electrical load, current will flow from the secondary to the load and this will cause current to be drawn from the mains supply into the primary.

Ignoring transformer losses at this stage, we can equate the primary and secondary volt-amperes:

$$V_1 I_1 = V_2 I_2$$

where: I_1 = primary current

I_2 = secondary current

Therefore, for an ideal transformer from this equation and that relating to the voltage and turns ratio, we can write:

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

A.4 Transformer Construction

There are three principal forms of construction which cover all except very specialised transformers. These are the core, shell and toroidal types.

A.4.1 Single-Phase Core Type

In this construction, U- and I-shaped steel laminations are built up to form a rectangular core with the windings supports on two of its limbs as shown in Figure A-3.

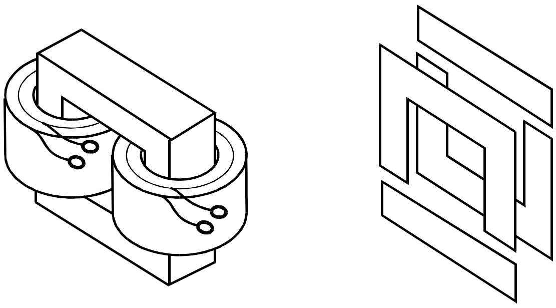


Figure A-3

It is usual for each winding to be split so that each limb supports half of the primary turns and half of the secondary turns, which are wound concentrically. The low voltage windings are placed nearer to the core to reduce the voltage gradient across the insulation (see notes under 'Transformer Windings' later in this chapter). The U- and I-laminations are fitted alternately to distribute the small air gaps and the core structure is held rigid by bolts or rivets. Large three phase power and distribution transformers are generally of the core type, whereas small single phase transformers use shell-type construction.

A.4.2 Single-Phase Shell Type

The laminated magnetic core in this case has a central limb which supports all the windings and two outer limbs to complete the flux path, as shown in Figure A-4.

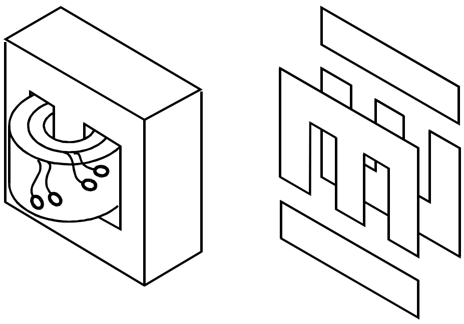


Figure A-4

This construction is most widely used for small power transformers as it is compact and economical to produce. The magnetic core is built up from either U and T-sections or E and I-sections, fitted alternately.

A.4.3 Single-Phase Toroidal Type

This has a ring-shaped core, often formed from helically wound steel strip, resin bonded to form a rigid structure. The primary and secondary are wound over the whole of the ring surface with the low-voltage winding nearer to the core, as shown in Figure A-5.

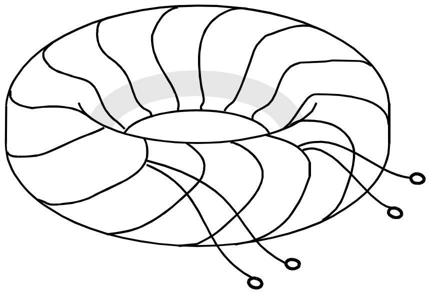


Figure A-5

Because of the setting up time and special coil winding equipment which is required, this type of transformer is only economical when made in fairly large production quantities. However it has two features which may sometimes cause it to be preferred to conventional types: there is no flux leakage outside the magnetic path and it has an inherently low profile, or pancake shape, which can be advantageous where space is limited.

A.4.4 Transformer Windings

Although a designer's first concern is with the electrical requirements of the windings, it must also be ensured that they have adequate mechanical strength and that the heat developed internally is carried away to the outside air or other cooling medium. Figure A-6 shows some of the winding arrangements used in large and small transformers.

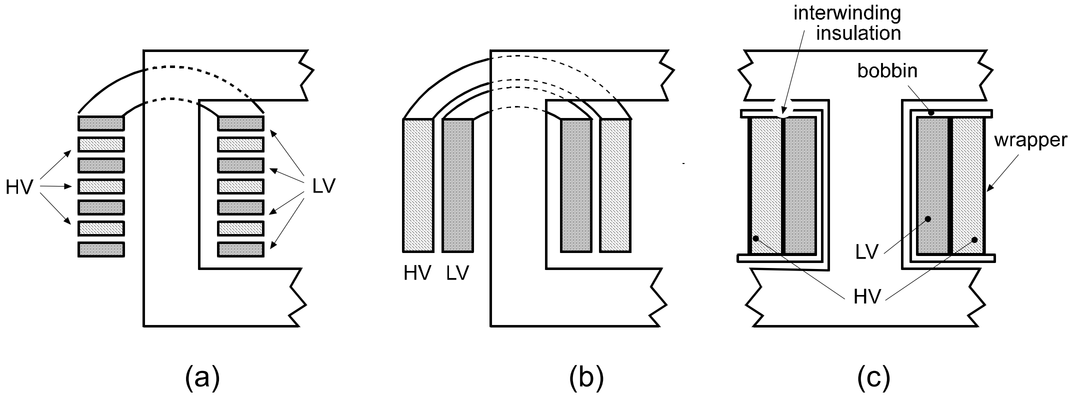


Figure A-6

In large power system transformers, the copper conductors will usually be of rectangular cross-section covered with impregnated paper or fabric as an insulant. The coils are wound on to resin bonded mica, glass fibre or pressboard cylinders.

Disc and cylindrically wound coils, Figure A-6(a) and (b) have their turns distributed so that cooling air, gas or oil can circulate within the winding. Rigid separators prevent voltage breakdown between adjacent layers and give the mechanical support needed to withstand the large forces which can be applied under fault conditions.

In small power transformers, Figure A-6(c) enamel-covered round copper wire is used for the windings. This may be wound on a bobbin made from a resin bonded fabric or a thermally stable plastic material such as Nylon. Alternatively the coils may be wound directly on to a sleeve consisting of several layers of impregnated paper.

To prevent voltage breakdown within the winding, a paper or fabric sheet is inserted between layers of turns as the winding proceeds. Additional insulation is placed between the primary and secondary windings.

To isolate further the two sets of windings, sheet copper can be fitted between the primary and secondary to act as a screen which is then connected to an external earth. This must not be closed upon itself as it would then act as a shorted turn of low resistance which would cause the transformer to over heat.

Table A-1 gives an extract from a wire manufacturer's table, showing the relationship between wire diameter, current rating and electrical resistance.

Conductor Diameter			*Sectional Area (mm^2)*	*Weight per km (kg)*	*Nominal Resistance at 20°C*		*Current Rating at 4.65 amp per mm^2 (A)*
Nom (mm)	*Max (mm)*	*Min (mm)*			*per metre Ω*	*per kg Ω*	
1.600	*1.616*	*1.584*	*2.011*	*17.87*	*0.008575*	*0.4799*	*9.349*
1.500	*1.515*	*1.485*	*1.767*	*15.71*	*0.0097575*	*0.6211*	*8.217*
1.400	*1.414*	*1.386*	*1.539*	*13.69*	*0.01120*	*0.8181*	*7.158*
1.320	*1.333*	*1.307*	*1.368*	*12.17*	*0.01260*	*1.035*	*6.364*
1.250	*1.263*	*1.237*	*1.227*	*10.91*	*0.01405*	*1.288*	*5.706*
1.180	*1.192*	*1.168*	*1.094*	*9.722*	*0.01577*	*1.622*	*5.085*
1.120	*1.131*	*1.109*	*0.9852*	*8.758*	*0.01750*	*1.998*	*4.581*

Table A-1

The temperature at which a winding can operate is largely determined by the properties of the insulation materials used. Manufacturers work to a classification system from which the list given in Table A-2 is extracted.

Classification	Max. Continuous Operating Temperature	Typical Materials	Typical Dielectric Strength
Class A	105°	Impregnated Cotton, Silk, Paper	4 to 18kV/mm
Class B	130°	Bonded mica, glass fibre	8 to 30 kV/mm
Class H	180°	Silicone and epoxy resins, fluorchemicals e.g. polytetrafluoroethylene, bonded mica	12 to 30 kV/mm

Table A-2

In this table, the dielectric strength is the maximum voltage gradient that can be applied to an insulation material without breakdown, expressed as volts per mm thickness of material. Measured values of dielectric strength are dependent on the thickness of the sample material and the test conditions. The figures given are for guidance only.

A.4.5 Transformer Core

The magnetic core in large and most small transformers is built up from steel laminations normally using two of the shapes shown in Figure A-7.

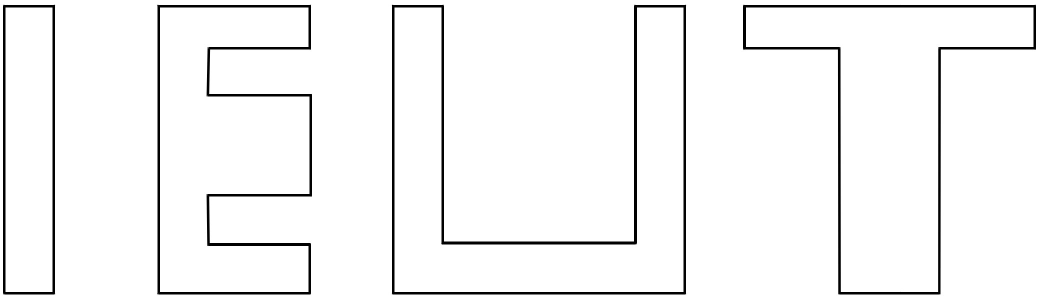


Figure A-7

Steels used for transformer cores are special alloys of Iron and Carbon with the addition of a small percentage of Silicon, or in some special cases, of Nickel — typically a cold-rolled Carbon steel containing up to 3% Silicon would be used.

The subject of power loss in the transformer core is treated in greater detail in Assignment 6 of this manual, but briefly we can say that Silicon steels are used to reduce the hysteresis component of total core loss and a laminated structure is employed to reduce the eddy-current component. The lamination thickness is dependent on the power supply frequency — for 50 or 60 Hz applications this would be typically 0.3 mm (0.014 in). Each lamination has an insulating coating applied to one surface.

Lamination stacks for large transformers are held rigid by insulated bolts which pass through the core and an insulated clamping frame. In the smaller transformers the core is riveted or simply held together by an insulated clamp.

A.4.6 Impregnation

To assist the transfer of heat from the inner parts of the winding and to improve the overall insulation, small transformers are taken through an impregnation process after assembly of the core and windings.

The impregnant is a synthetic resin which may contain a solvent to thin the resin and improve penetration. The impregnate must have good dielectric strength, good mechanical strength when set and be capable of acting as a barrier to moisture and dirt. It should also be a relatively good conductor of heat and of course be capable of operating well above the transformer running temperature.

In one typical impregnation process the transformer is first dried in an oven, then cooled under vacuum in a tank. The transformer is then completely immersed in the impregnant for up to ten minutes, after which it is removed from the tank and allowed to drain and dry off. A baking period follows, terminating at the cure temperature of the resin. In addition to the impregnation process, transformers which are to operate in tropical conditions are given an envelopment dip. This provides a relatively thick coating over the windings and core to make doubly sure that there is no moisture penetration and to resist fungus growth.

A.4.7 Windings Connections

Conventional transformers are double wound — the primary and one or more secondaries are separate with no electrical connection between them.

To enable the primary to be connected to a number of different mains supply voltages, or to allow some variation in the secondary terminal voltage, it is usual to provide either tapped connections to the main windings or to have separate tapping coils which may be connected so that the voltage across a particular winding can be increased or decreased.

Typical tapped windings for small power transformers are shown in Figure A-8. In dealing with tapped windings we should keep in mind that the volts per turn on all windings is constant.

In Figure A-8(a) the primary winding is tapped so that it can accept mains supply voltages or 240, 200, 120 and 100 volts. Note that if the volt-ampere rating of the transformer is to be the same for all connections, the primary current on the 100 or 120 volt tappings will be approximately twice that at 200 or 240 volts and therefore the wire size must be increased proportionately.

In Figure A-8(b), the secondary has tapping points so that when operating from a fixed mains supply the transformer can provide an output of 10, 15 or 20 volts.

In Figure A-8(c), the primary consists of two separate coils which may be connected in series for a 240 volt supply or in parallel for a 120 volt supply. This arrangement is more economical than the tapped primary of Figure A-7(a), since irrespective of the connection used each primary winding need only be designed to carry half the rated volt-amperes of the transformer.

In Figure A-8(d), both the primary and secondary have two separate coils, giving a choice of mains supply voltage and of secondary output voltage. In this example the transformer can accept a mains supply of 240 or 120 volts and can provide an output of 20 volts at 1 A or 10 volts at 2 A.

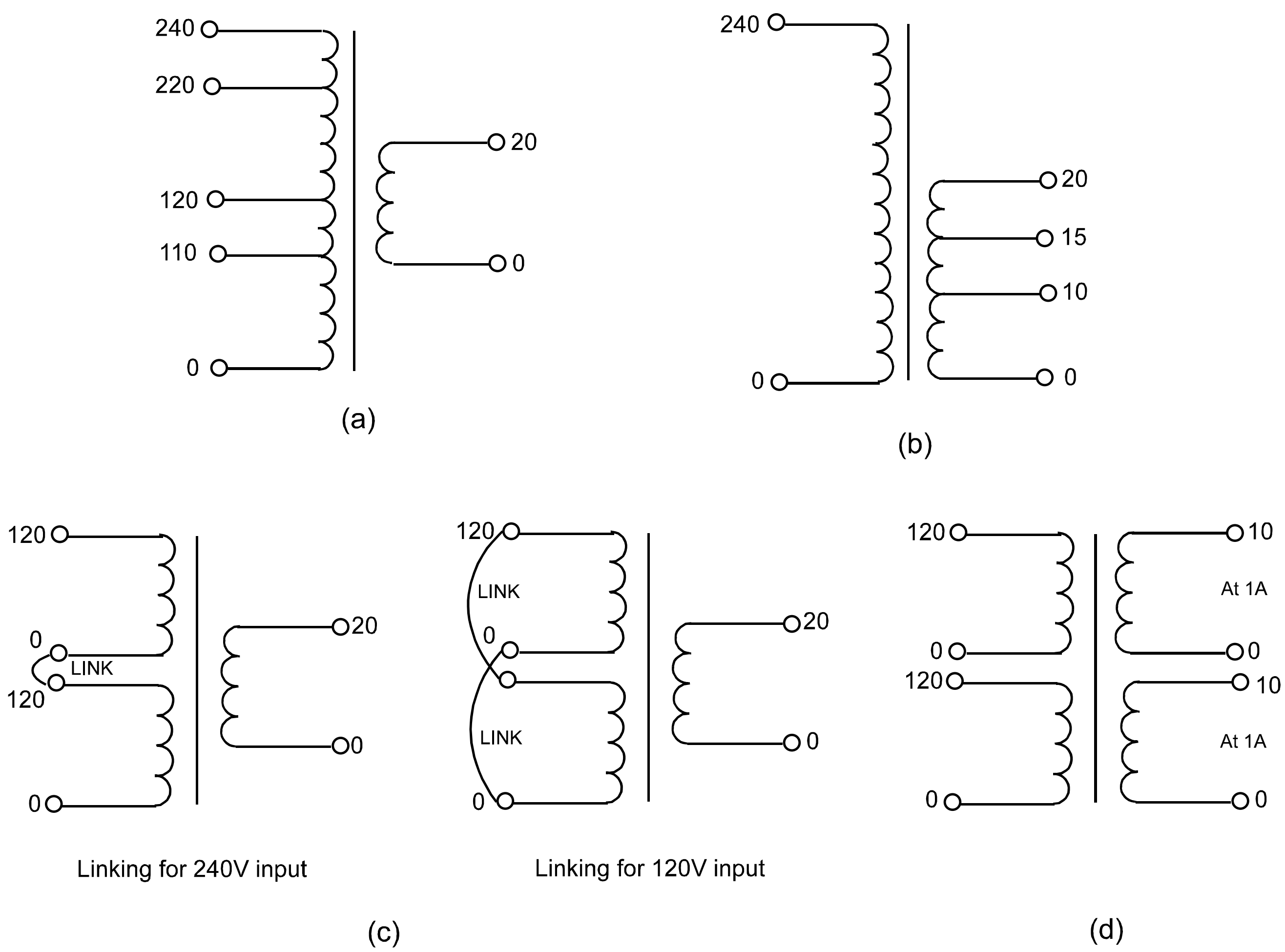

240
220
120
110
0
20
0
(a)
240
0
20
15
10
0
(b)
120
0
LINK
120
0
20
0
120
LINK
0
LINK
0
20
0
120
0
120
0
10
At 1A
0
10
At 1A
0
Linking for 240V input
Linking for 120V input
(c)
(d)

Figure A-8

A.5 Three Phase Transformer Principles

A.5.1 Introduction

Three phase transmission and distribution of electrical power is almost universally employed, because it saves conductor costs and is more efficient when compared to other ac systems (mathematical proof of this is given in Appendix B). As the name implies, it is a system which uses simultaneously alternating (sinusoidal) voltages having different phases. Ideally these alternating voltages are identical in magnitude but are equally displaced from each other in phase by 120°.

Figure A-9 shows the three voltages graphically.

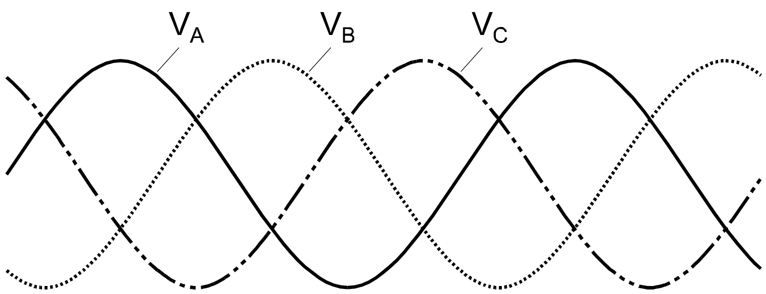


Figure A-9: Three Phase Voltages

A.5.2 Phasors

Any sinusoidal quantity can be represented 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. The 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 in time.

One cycle of the sine wave is equal to a phasor rotation of 360° or 2π radians. 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 as ω and the total swept angle after time t is ωt radian.

Figure A-10 shows the phasor diagram for a single phase sine wave. The amplitude of the sine wave at any time t can be found from the equation:

$$a = A \sin \theta$$

where a = amplitude

A = maximum value

$\theta = \omega t$

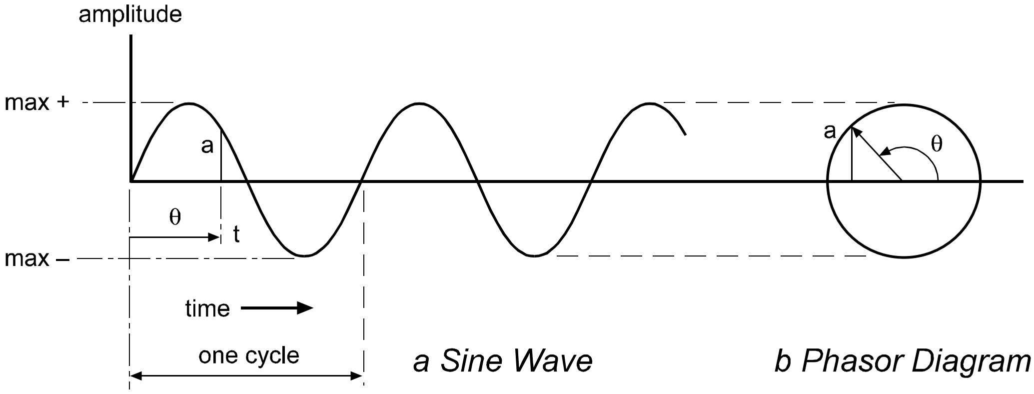


Figure A-10: Phasor Diagram for a Single Phase Sine Wave

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 the sine wave of Figure A-11 shows the amplitudes of the voltages in a three phase system of constant frequency at one instant in time.

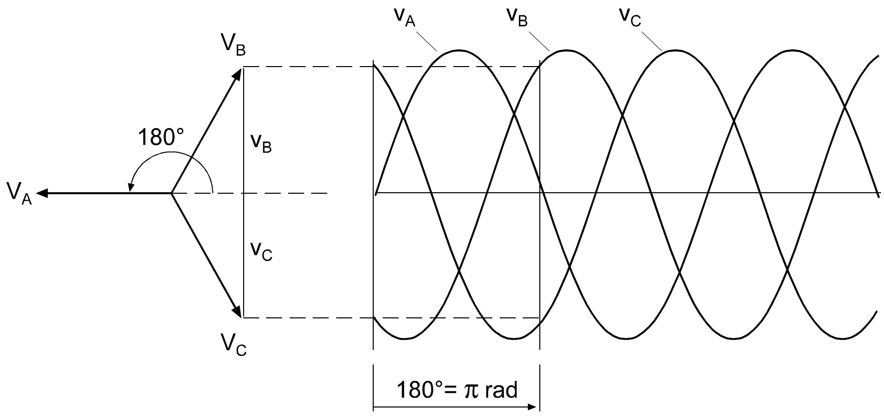


Figure A-11: Phasor Diagram for a Three Phase System

In any three phase system, the three supply voltage phasors rotate at a uniform angular velocity and maintain the same angular relationship to one another. V_B lags V_A by 120° and V_C lags V_A by 240°.

Consequently, the amplitude in each case is:

$$v_A = V_A \sin\theta$$

$$v_B = V_B \sin\left(\theta - 120^\circ\right)$$

$$v_C = V_C \sin\left(\theta - 240^\circ\right)$$

At the instant shown in Figure A-11, assume the maximum values V_A, V_B and V_C are 200 volts where V_A has swept through one half cycle or 180°. From zero:

$$v_A = V_A \sin(180°) = 0 \text{ volts}$$

$$v_B = V_B \sin(180 - 120) = 173 \text{ volts}$$

$$v_C = V_C \sin(180 - 240) = -173 \text{ volts}$$

Voltages and currents can also be shown on the same phasor diagram. The circuit in Figure A-12 shows a single phase supply connected to a load containing resistance and inductance in series.

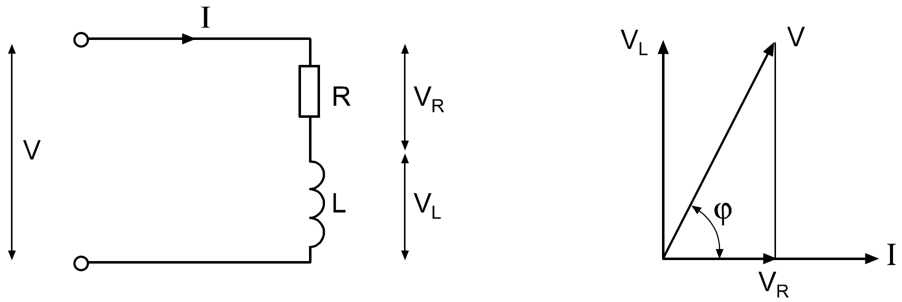


Figure A-12: Single Phase Supply Connected to a Resistive/Inductive Load

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°.

From the phasor diagram, we can find the angle φ by which the current lags the applied voltage V, since:

$$\frac{V_L}{V_R} = \tan\varphi$$

$$\varphi = \tan^{-1}\frac{V_L}{V_R}$$

A.5.3 Root Mean Square Values

Up to now 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:

$$\text{RMS} = \frac{\text{max. value}}{\sqrt{2}} = 0.707 \text{ max. value.}$$

The application of phasor diagrams is therefore unaffected by the use of RMS values.

A.5.4 Three-Phase Transformers

Three identical single phase transformers are shown in Figure A-13, The primary windings of the transformers are connected to a three phase supply, each winding is connected across a pair of lines.

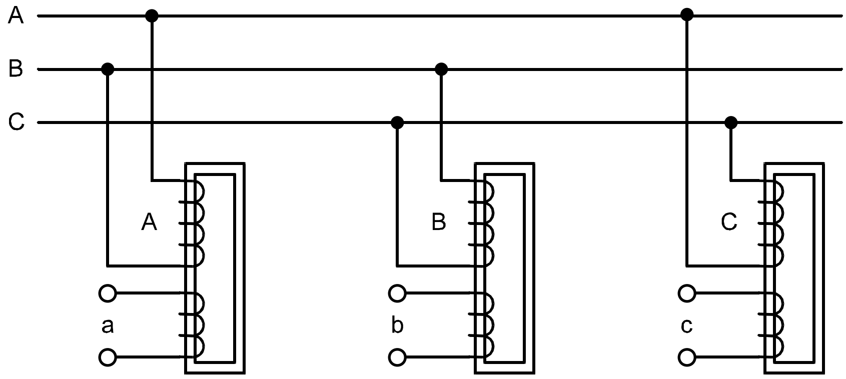


Figure A-13: Three Phase Transformers(Separate Cores)

The fluxes produced in the individual units ϕ_1, ϕ_2 and ϕ_3 will be equal in magnitude but will be phase displaced by 120° to each other. The secondary voltages will therefore be similar. The three transformers are spoken of as a three phase bank.

Since at any instant the total flux $\phi_1 + \phi_2 + \phi_3 = 0$ if the three transformers are placed side by side with a common yoke top and bottom (see Figure A-14), there is no need for a return path for the flux. This type of transformer is widely used for power system applications.

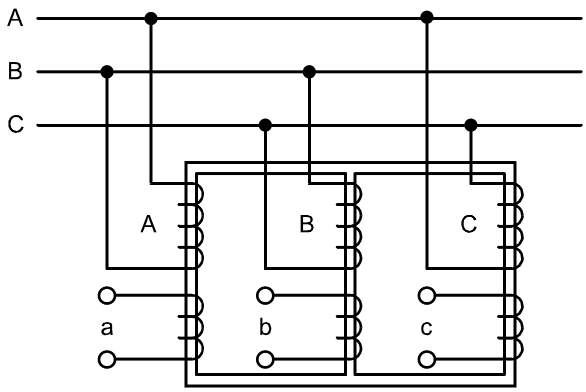


Figure A-14: Three Phase Transformer (Single Core)

Some large three phase transformers have five limb cores (see Figure A-15) the winding being confined to the middle three limbs. This device is adopted to reduce the height of the yoke and hence the overall height of the transformer.

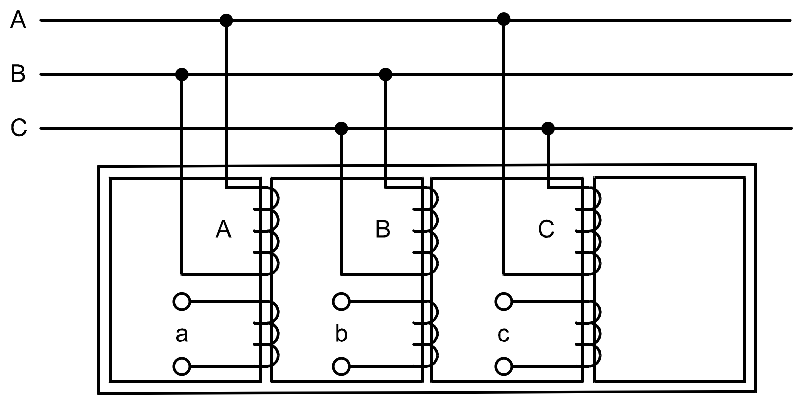


Figure A-15 Three Phase Transformer (Five Limbed Core)

A.5.4.1 Winding Connections

The method of marking and Identifying the terminals of a three phase transformer is as follows;

The supply lines between connections are generally denoted as L_1, L_2, and L_3.

The standard lettering for the phases is A, B C. Capital letters denote the primary or (high voltage) windings and lower case letters a, b, c for the secondary (or low voltage) windings.

In general, the two ends of a winding will be given suffixes and marked for example A_1 and A_2.

A.5.4.2 Three Phase Transformer Applications

The main application of three phase transformers is in the supply of electrical power, through a three phase transmission system to industrial and domestic equipment. The alternators that generate this power operate at a relatively low voltage which must be stepped up by transformers for economic transmission over long distances. The voltage must then be stepped down to the lower values required for local distribution.

There are a variety of different designs and constructions of three phase transformers used for conventional distributions and for special purposes.

A.6 Other Transformer Types

A.6.1 Auto-transformers

In some transformer applications it is not necessary to provide separate primary and secondary windings. In this case a single tapped winding is used which will act as the equivalent of a double wound transformer, as shown in Figure A-16.

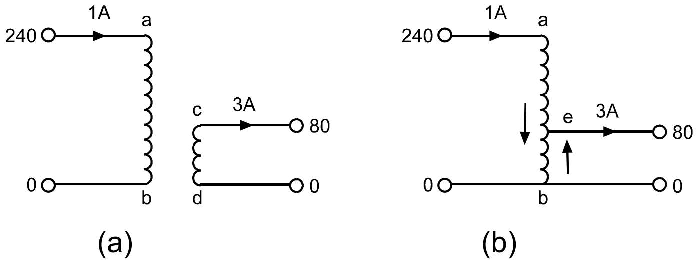


Figure A-16

In this figure, we have taken as an example a step-down transformer whose secondary voltage is $\frac{1}{3}$ that of the primary.

For the double wound transformer, Figure A-9(a).

$$V_{ab} = 3V_{cd} \text{ and } I_{ab} = \frac{1}{3} I_{cd}$$

also $N_{ab} = 3N_{cd}$

where:
- V_{ab} = primary volts
- V_{cd} = secondary volts
- I_{ab} = primary current
- I_{cd} = secondary current
- N_{ab} = turns on winding ab
- N_{cd} = turns on winding cd

In the auto transformer, we fix the tapping point to give the same turns ratio as in the double wound version, Figure A-9(b).

Then: $V_{ab} = 3V_{eb}$ $\quad\quad I_{ab} = \frac{1}{3} I_{eb}$

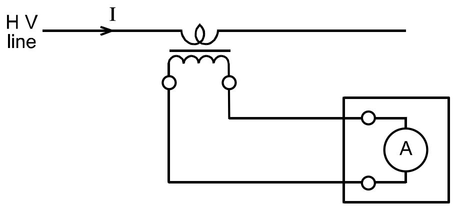
and $N_{ab} = 3N_{eb}$

where:
- V_{eb} = secondary volts
- I_{eb} = secondary current
- N_{a} = turns on winding ab
- N_{eb} = turns on winding eb

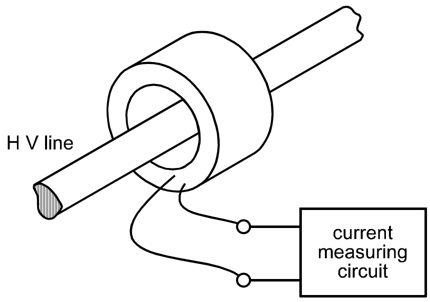
The auto wound transformer has one important advantage over the double wound version. The currents I_{ab} and I_{eb} flow in opposite directions through the common winding eb. This part of the winding therefore carries 3 – 1 = 2A, whereas in the double wound version the whole primary carries 1A and the secondary carries 3A. There is, therefore, a substantial saving in copper, leading to a reduction in cost and weight. Despite this, the auto-transformer is not very widely used since it provides no isolation between the supply and the output.

A.6.2 Current Transformers

In power system protection and metering circuits, it is necessary to measure the currents in high-voltage lines and convey this information to a control or switching station. It would be obviously impracticable to connect the measuring equipment directly to the high-voltage line, and for this reason a transformer is interposed between the line and the measuring circuit, as in Figure A-17(a). Apart from safety considerations this has the advantage that by suitable choice of turns ratio the current in the low-voltage winding may be made many times lower than the high voltage line current.



(a)



(b)

Figure A-17

A good current transformer will have adequate insulation to isolate the high-voltage and low-voltage circuits, it will have a linear high voltage to low voltage current relationship (low current ratio error), and the phase angle of the measured current should be close to that of the line current (low phase angle error).

In power system work, the current transformer may consist of a single heavily insulated bar conductor which is connected in series with the line. This bar will pass through the centre of a toroidally wound secondary winding, as shown in Figure A-17(b). When the secondary terminals are not connected to the measuring circuit, they should be shorted out. Otherwise, dangerously high voltages can be produced across the terminals due to the high turns ratio involved.

B Three Phase Systems

B.1 Three Phase Transmission

In the generation, transmission and utilisation of electric power, three phase systems are predominant for both economic and operational reasons.

A three phase system has two distinct advantages over the single phase system:

- A three phase system requires much less copper 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.2 Efficiency of a Three Phase System

To compare the economy of three phase transmission lines, we calculate the copper loss in the lines for the same mass of copper in each transmitting the same total power.

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.

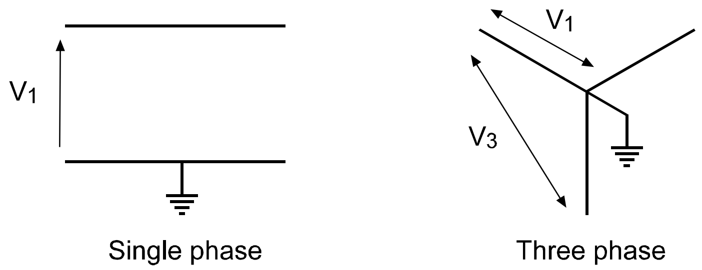


Figure B-1

Let:

V_1 = single phase voltage

P_1 = single phase power

V_3 = three phase voltage

P_3 = three phase power

Figure B-1 demonstrates the single and three-phase system. From this it can be seen that;

$$V_3 = 2 \times V_1 \cos 30 = \sqrt{3}\, V_1$$

Since the same total power is transmitted to the load;

$$P_1 = P_3$$

where $P_1 = V_1 I_1$

and $P_3 = V_3 I_3 = \sqrt{3} V_1 I_1$

Hence $\frac{I_1}{I_3} = 3$

The resistance R of a conductor of length l is inversely proportional to its mass M, since if it has resistivity ρ, density σ and cross sectional area a.

$$R = \frac{\rho l}{a} \qquad M = \sigma l a$$

Consider M the mass of copper in each system:

$$2M_1 = 3M_3$$

$$2\frac{\sigma \rho l}{R_1} = 3\frac{\sigma \rho l}{R_3}$$

Consider the copper loss in both systems:

$$p_1 = 2{I_1}^2 R_1$$

$$p_2 = 3{I_3}^2 R_3$$

Since $I_3 = \frac{I_1}{3}$ and $R_3 = \frac{3}{2} R_1$

$$\frac{p_1}{p_2} = 4$$

Therefore, the copper loss in the single phase system is four times that for three phase when transmitting the same power.

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 in order to carry out of balance current. Its current carrying 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.

In more detail:

$$\frac{\text{total single phase mass}}{\text{total three phase mass}} = \frac{2(\text{wires}) \times M_1}{4(\text{wires}) \times M_3}$$

since $M_1 = 6M_3$

$$\frac{\text{total single phase mass}}{\text{total three phase mass}} = 3$$

B.3 Invariance of Three Phase Power

At any instant, the power transmitted by a conductor carrying a 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:

$$v_A = V\sin\theta$$

$$v_B = V\sin(\theta - \frac{\pi}{3})$$

$$v_C = V\sin(\theta - \frac{2\pi}{3})$$

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 ϕ, the line currents will be:

$$i_A = I\sin(\theta - \phi)$$

$$i_B = I\sin(\theta - \phi - \frac{\pi}{3})$$

$$i_C = I\sin(\theta - \phi - \frac{2\pi}{3})$$

where I is the peak current.

The total power is therefore:

$$W = VI\left[\sin(\theta)\sin(\theta - \phi) + \sin\left(\theta - \frac{\pi}{3}\right)\sin\left(\theta - \phi - \frac{\pi}{3}\right) + \sin\left(\theta - \frac{2\pi}{3}\right)\sin\left(\theta - \phi - \frac{2\pi}{3}\right)\right]$$

$$W = \frac{1}{2}VI\left[\cos(-\theta) - \cos(2\theta - \phi) + \cos(-\phi) - \cos\left(2\theta - \phi - \frac{2\pi}{3}\right) + \cos(-\phi) - \cos\left(2\theta - \phi - \frac{4\pi}{3}\right)\right]$$

But for any angle α (i.e. $\alpha \equiv 2\theta - \phi$)

$$\cos\alpha + \cos\left(\alpha - \frac{2\pi}{3}\right) + \cos\left(\alpha - \frac{4\pi}{3}\right) = \cos\alpha + 2\cos\left[\frac{(2\alpha - 2\pi)}{2}\right]\cos\frac{2\pi}{3}$$

$$= \cos\alpha - 2\cos\left(\frac{2\alpha}{2}\right) = \cos\alpha - \cos\alpha = 0$$

Hence the power can be seen to be:

$$W = \frac{1}{2}VI3\cos(-\phi) = \frac{3}{2}VI\cos\phi$$

Since this expression does not contain θ (or any other reference to time) the power is shown to have constant value.

If V_{rms} and I_{rms} are the rms values of voltage and current,
(since $V_{rms} = V/\sqrt{2}$ and $I_{rms} = I/\sqrt{2}$) the power can be expressed as:

$$W = 3VI\cos\phi$$

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.

C The Magnetic Circuit

C.1 Units and Definitions Comparison with Electrical Circuit

The symbols, units and definitions most often used when dealing with the magnetic circuit are listed below. In many cases, there is a similarity between the terms used in a magnetic circuit and those of an electric circuit.

Flux Φ

The flux in a magnetic circuit can be taken to consist of a number of continuous lines which form closed loops round a current-carrying coil. In a power transformer, the flux is set up in the magnetic core which links the primary and secondary windings.

Unit of flux : weber (Wb)

Flux density *B*

The flux density in any part of the magnetic circuit is the flux divided by the cross-sectional area of that part.

Unit of flux density : tesla or webers per square metre (Wb/m^2)

Field strength *H*

This is a measure of the magnetic field produced by current flowing in a coil or conductor. The field strength within a coil is proportional to the value of current and the number of turns per unit length of flux path.

Unit of field strength : ampere-turns per metre (At/m)

Note: As 'turns' is a non-dimensional quantity, the unit of field strength is strictly 'ampere per metre (A/m)' but this form is not often used in practical calculations.

Permeability μ

This is the ratio of flux density to field strength $\mu = \frac{B}{H}$ for a given core material. H is defined in such a way that for a vacuum $\mu = \frac{4\pi}{10^7}$ webers per (ampere-turn metre) and is denoted by μ_o. For other materials, μ is greater by a factor μ_r called the 'relative permeability'; thus $\mu = \mu_0\mu_r$. For iron, cobalt, nickel and their alloys the value of μ_r may be many thousands. For copper, aluminium, air and many other 'non-magnetic' materials μ_r is very close to unity.

Magnetomotive force or MMF

It is the magnetomotive force (MMF) which causes a flux to be set up in magnetic circuit. It is expressed as the product of current flow and number of turns in a coil and is similar in its effect to the applied voltage in an electrical circuit.

Unit of magnetomotive force : ampere-turns (A/t)

Reluctance R_m

This is the magnetomotive force (MMF) which causes a flux to be set up in a magnetic circuit. It is expressed as the product of current flow and number of turns in a coil and is similar in its effect to the applied voltage in an electrical circuit. Unit of reluctance : ampere-turns per weber (At/Wb)

C.2 Comparison between Electrical and Magnetic Circuits

In Table C-1, the terms used in magnetic circuits are listed alongside similar terms used in electrical circuits.

Electrical Circuit	Magnetic Circuit
Electric Current I	Magnetic Flux Φ
Current Density J	Flux Density B
Voltage V	Magnetomotive Force MMF
Conductivity σ	Permeability μ
Resistance R	Reluctance R_m

Table C-1

It is of interest to compare the electrical equation for resistance with its magnetic counterpart, reluctance.

$$R = \frac{\rho\lambda}{a}$$

Reluctance of a magnetic material of length 'λ', cross-sectional area 'a' and permeability μ.

$$R = \frac{1}{\mu}\frac{\lambda}{a}$$

Voltage required to pass current I through the resistor in Figure C-1:

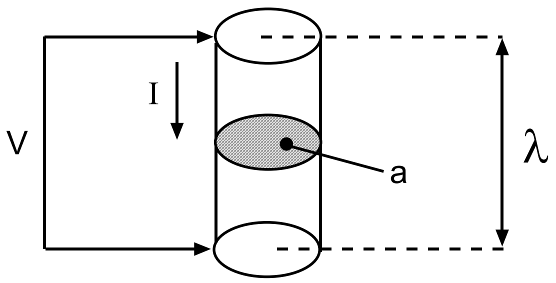


Figure C–1

$$V = \frac{\rho\lambda}{a} I \quad \therefore V = I \times R \text{ Volts}$$

where: ρ is the resistivity
λ is the length
a is the cross sectional area

Magnetomotive force required to set up flux f in the magnetic material of Figure C-2:

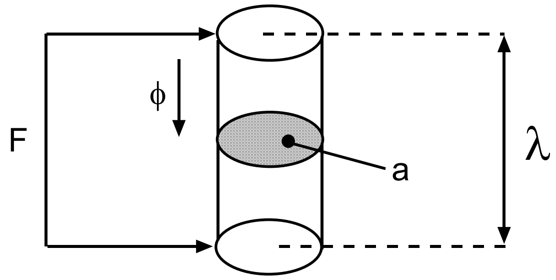


Figure C–2

$$F = \frac{\lambda}{\mu a}\Phi$$

$$\therefore\ F = \Phi \times R_m \text{ ampere turns}$$

where: μ is the permeability
ℓ is the length of the conductor
a is the cross sectional area of the conductor.

For an electrical circuit consisting of a number of resistors in series, Figure C-3, the voltage required to pass current I is:

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

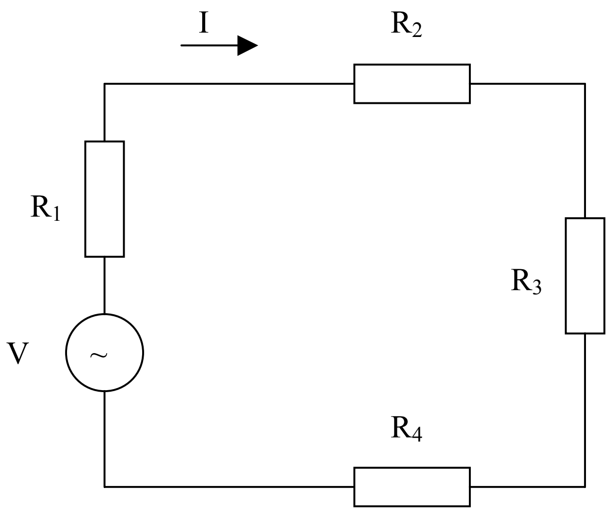


Figure C–3

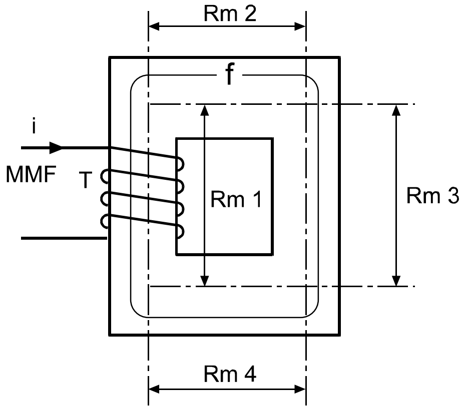


Figure C–4

In a typical magnetic circuit (Figure C-4) which contains sections of different length and cross-sectional area but having the same permeability and carrying the same flux f, the MMF or total ampere-turns required is:

$$MMF = \left(\frac{\ell_1}{\mu a_1}\right)\Phi + \left(\frac{\ell_2}{\mu a_2}\right)\Phi + \left(\frac{\ell_3}{\mu a_3}\right)\Phi + \dots$$

$$MMF = \Phi(R_{m1} + R_{m2} + R_{m3} + \dots)$$

It should be remembered that unlike resistance, reluctance is not a constant and consequently the relationship between F and f is not linear.

If there is an air gap in the magnetic circuit, the reluctance can be calculated as before but since the relative permeability of air is near unity (as compared with tens of thousands for steel), the MMF required to produce a given flux is increased many times.

The actual values of flux and magnetomotive force in a magnetic circuit will depend on the size and shape of the core and on the magnetic material used. However, the manufacturers of transformer core steel issue standard curves of flux density, B (expressed as weber/square meter) against field strength, H (expressed as ampere-turns per metre of core path) which apply to any form of magnetic structure. With this type of curve we can calculate the number of turns and the current in a coil to produce a required flux in a core of given dimensions.

C.3 Magnetic Materials

The transformer core is constructed from one of the ferromagnetic materials, so called because they are either alloys of iron (carbon steel, silicon steel) or alloys with similar magnetic properties (cobalt, nickel, etc). Apart from its magnetic function, the core of a power transformer must be structurally strong so that it can support the windings.

The majority of power transformer cores are made from 'electrical' steel laminations. This is a carbon steel alloy with up to 3% silicon and is chosen partly because it produces a high flux density B for a given field strength H. Also, the power losses due to alternating flux in a core made from silicon steel laminations are relatively low. This is discussed in greater detail in Assignment 6.

The manufacturers of electrical steels provide the user with magnetisation curves for their range of alloys. These are plotted from tests carried out in the company's laboratory using specialised measuring equipment and show the variation of flux density B against field strength H over the full working range. A typical example for a silicon steel is shown in Figure C-5 curve (a).

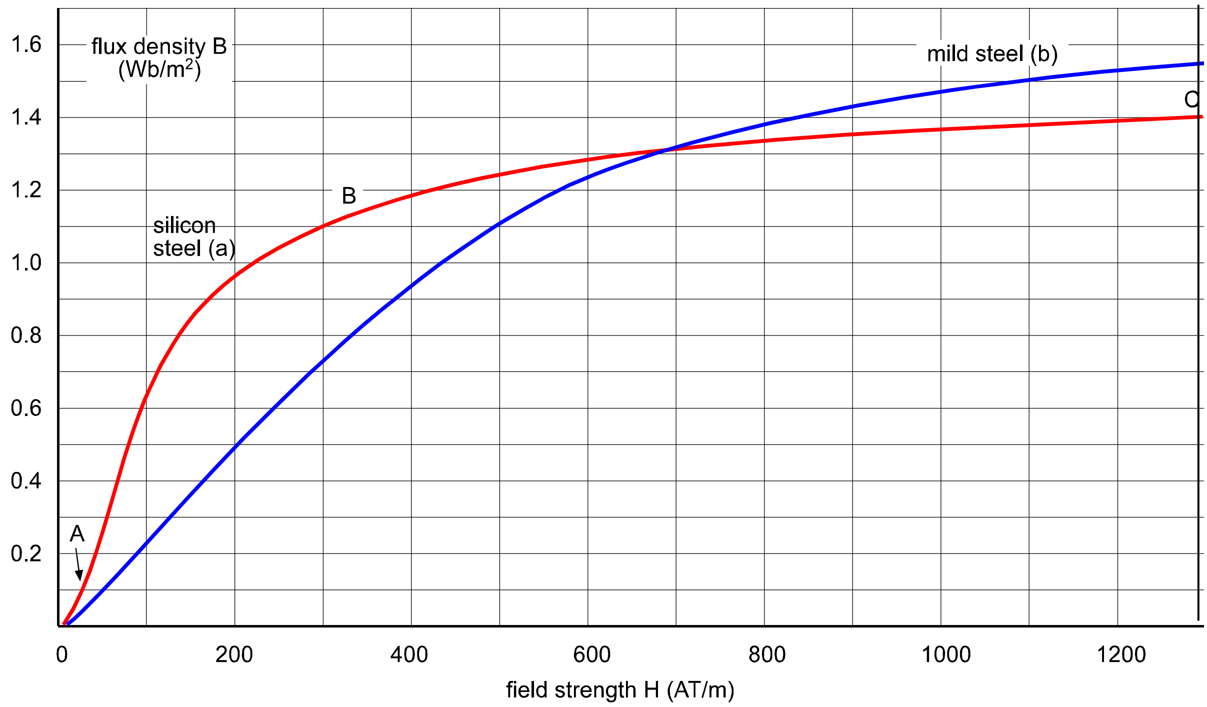


Figure C–5

The initial slope O–A is relatively low and is of little interest in electrical machines. The almost linear portion A–B is the working region, and the mean flux density with the transformer on full load will normally lie near the upper part of this portion of the curve.

The working point is a compromise and is chosen to provide a high value of flux density without running into heavy saturation, since this would call for a high level of field strength H and hence a large current in the primary winding to produce the required ampere-turns. In section B–C, the steel is approaching full saturation. When this occurs, the graph becomes a straight line and the ratio 'change of B/change of H' is the same as that of air or a non-magnetic solid.

Also shown in Figure C-5 is the magnetisation curve for a low carbon mild steel, curve (b). From these curves, the mild steel appears to compare reasonably well with the Silicon steel since its permeability (ratio of B to H) although generally lower is adequate over a good working range. However, as was shown when dealing with transformer losses, the total core loss for mild steel is greater than that for Silicon steel at the same flux density.

C.4 Practical C.1 – Theoretical Calculation for a Chosen Flux

From the magnetisation curve, we can derive the excitation MMF required to set up a given flux provided we know the dimensions of the transformer core. We know that:

$$\phi = B \times A$$

$$MMF = H \times \ell$$

and the excitation MMF = (H) x (mean length of magnetic path for each section of the core). Let us take a simple transformer with a given number of turns on the primary winding and work out the current required to produce a chosen flux in the core.

Figure C-6 shows a core which is the equivalent of that in a transformer but in a simplified form with constant cross-sectional area.

For these core dimensions and given that there are 270 turns on the primary, we will calculate the current required to produce a flux of 1.5 m Wb.

For any problem of this kind, we first draw the magnetic circuit and then find:

- the flux density B in each part of the path,
- the magnetomotive force in each part of the path using the magnetisation curve,
- the total magnetomotive force (MMF),
- the magnetising current required.

In this case, the magnetic circuit is simple since the same cross-sectional area and magnetic material is used in every part of the magnetic path, Figure C-6. The cross-sectional area is 0.00132 m^2.

$$\text{Flux density } B = \frac{\phi}{A} = \frac{0.0015}{0.00132} = 1.14 \text{ Wb/m}^2$$

From the magnetisation curve for Silicon steel, Figure B-5 curve (a), the value of H corresponding to this flux density is 340 ampere-turns per metre.

$$MMF = H \times \ell$$

where ℓ is the mean length of the flux path

$$MMF = 340 \times 0.266 = 91 \text{ ampere - turns}$$

The primary winding has 270 turns and the current will be:

$$I = \frac{MMF}{N} = \frac{91}{270} A$$

In a typical transformer, the core is made from laminations bonded together to form a solid. Each lamination has a total thickness of 0.55 mm of which 0.5 mm is steel and 0.05 mm is insulation. As a result, the true cross-sectional area of the steel is only 0.91 x the measured area.

C.4.1 Exercise C.1

Calculate the true cross-sectional area of the core material and use this to find a new value for the current required to produce the given flux.

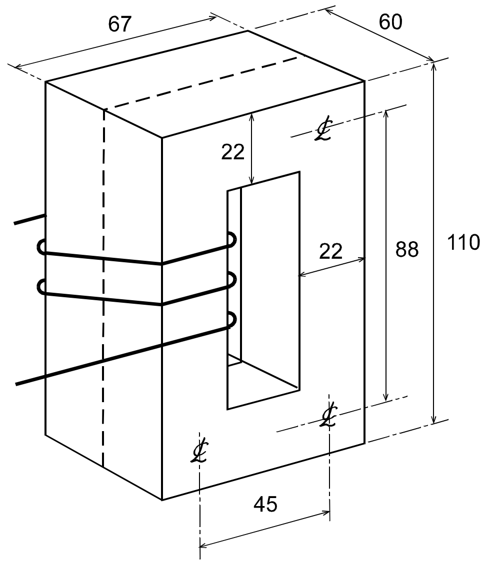


Figure C–6

C.4.2 Exercise B.2

From the cross-sectional area just calculated and the given path length, draw a graph of flux in Wb against magnetomotive force in AT. Use the B/H curve given in Figure C-5 curve (a) and calculate the ampere-turns required for flux levels of 0.5, 1.0, 1.3 and 1.6 milliweber.

If we measure the ratio MMF to ϕ at a number of points on the graph of the preceding exercise we can find the total reluctance of the circuit at those points.

$$R_m = \frac{\text{MMF (ampere turns)}}{\text{flux (weber)}}$$

This will show that as the flux increases the reluctance also increases but by a greater proportion, particularly in the saturation region.

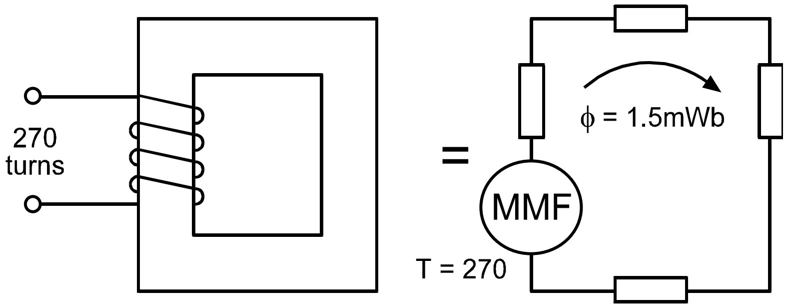


Figure C–7

Notes

D Current Transformer

D.1 Introduction

Current transformers are simply transformers designed and/or applied with an emphasis on the ratio of the currents in the primary and secondary windings, rather than on the voltage ratio. As mentioned in Appendix A General Information, applications are usually in the fields of measurement and protection, and therefore require the secondary current to be accurately related to the primary current in a known ratio. The ratio will usually be chosen to bring the secondary current to a convenient value for use in instruments and protective equipment.

Current transformers may be constructed in any of the forms, core, shell and toroid which are used for other transformers and described in Appendix A, differences in design being largely a matter of choosing the proportions to give a different distribution of losses between iron and copper, to suit the different applications. The current transformer with a bar primary, Figure D-1, is a common form, and an extreme example of this different distribution of losses.

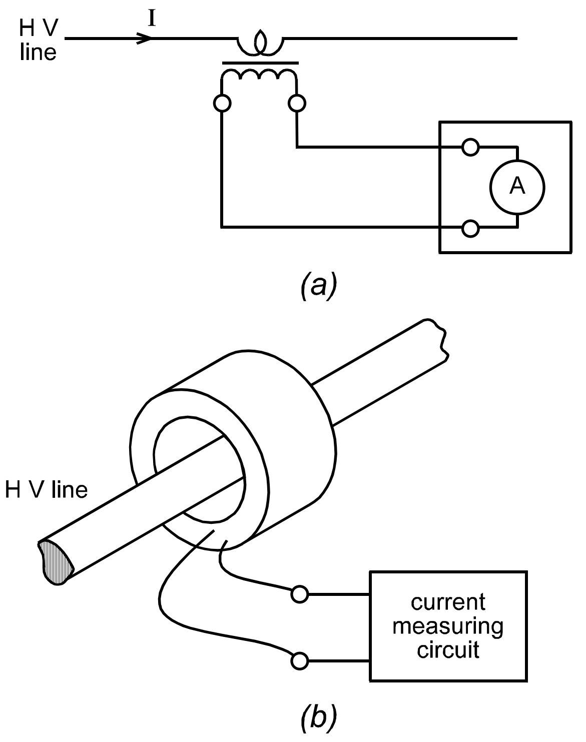


Figure D-1

The one-turn primary with its great length of conductor may have large voltage-drop and associated power losses in the conductors, but this is not relevant to its function as a current transformer.

D.2 Ratio of Current Transformer

As you have already discovered, the primary and secondary ampere-turns for an ideal transformer are equal;

$$I_1 T_1 = I_2 T_2$$

$$\frac{I_1}{I_2} = \frac{T_2}{T_1}$$

To see physically why this is so, consider Figure D-2, in which a current I_1 flowing in the primary of the current transformer is to be measured by the meter in the secondary circuit. Suppose that when I_1 is 50 A, the meter is to show its full scale deflection, requiring a secondary current of 5 A, and suppose also that a primary winding of two turns is chosen.

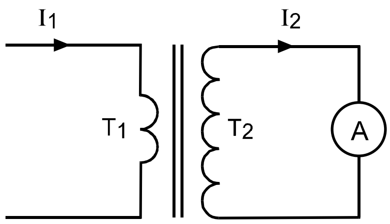


Figure D-2

Some (usually small) voltage is required to drive 5 A through the ammeter. If we assume that the secondary has 20 turns, this determines the amplitude of flux change required.

The primary current has to produce ampere-turns:

- to magnetise the core, say 10 ampere-turns in this case,
- to cancel the demagnetising ampere-turns produced by the secondary winding, i.e. 100 ampere-turns.

If the corresponding primary currents were in phase, the discrepancy in this assumed case would be only 10% between turns ratio and current ratio. If the core-magnetising current were (as it ideally should be) in quadrature, the error would be only 0.5%.

An exact expression for the current ratio in the presence of losses becomes very complicated. However, for the majority of cases, the current transformation ratio R defined as:

$$\frac{I_1}{I_2}$$

is very nearly approximated by:

$$R = \frac{N_2}{N_1} + \frac{I_O}{I_S} \sin(\alpha + \delta)$$

where:

- I_o is the exciting current; i.e. the resultant of the primary current necessary to magnetise the core and supply its losses,

- δ is the angle between the secondary current and secondary induced voltage, i.e. the phase angle of the secondary circuit load impedance including the secondary leakage reactance of the transformer,
- α is the angle between I_o and the working flux.

The turns ratio and the current ratio can be seen to differ by an amount dependent on the exciting current. For the particular case of $\delta = 0$, a resistive burden,

$$R = \frac{N_2}{N_1} + \frac{I_O}{I_S} \sin\alpha = \frac{N_2}{N_1} + \frac{I_C}{I_S}$$

where I_C is the component of the exciting current which supplies the core losses. It is clearly important to keep these small.

D.3 Ratio of a Current Transformer

Suppose that you wish to use a 100 mA ac ammeter for measuring currents up to 5 A, using a transformer. The required current ratio R is 50:1, and none of the existing combinations of windings can supply this. If one of the secondary windings available is used, having 148 turns and losses in the transformer are neglected, the primary turns required are:

$$T_1 = \frac{T_2}{R} = \frac{148}{50} = 2.96 \approx 3$$

Using this information, a transformer's secondary current against primary current can be monitored and plotted on a graph for a transformer having a primary winding comprising 3 turns, and for one having only 1 turn.

A typical graph is shown in Figure D-3.

For each plot, the current ratio $R = \frac{I_1}{I_2}$, can be found and compared with the turns ratio $\frac{N_2}{N_1}$.

<u>3 turns primary winding</u>

$$\frac{I_1}{I_2} = \frac{0.5}{0.0102} = 49 \qquad \frac{N_2}{N_1} = \frac{148}{3} = 49.3$$

<u>1 turns primary winding</u>

$$\frac{I_1}{I_2} = \frac{0.5}{0.0034} = 147 \qquad \frac{N_2}{N_1} = \frac{148}{1} = 148$$

D.4 Conclusion

If the turns ratio of a current transformer is increased by a factor of 3, the current in the secondary winding decreases by a factor of 3.

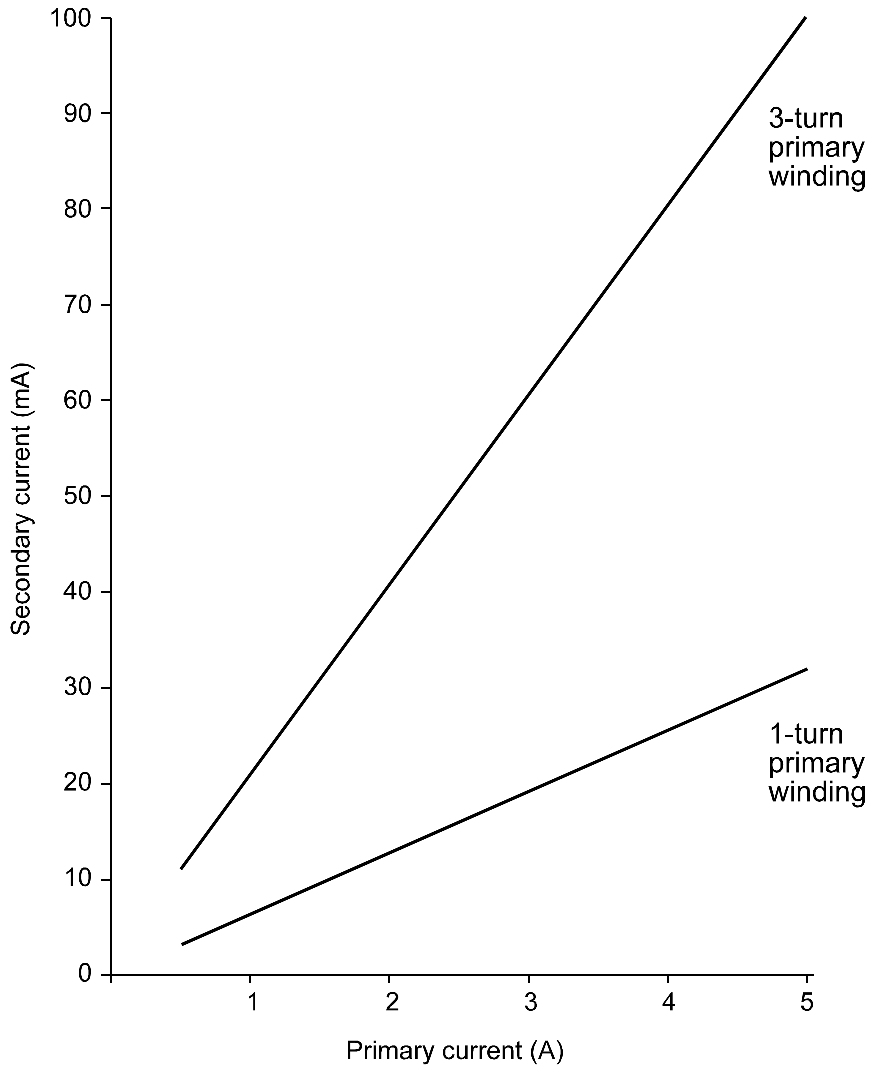

100
90
80
70
60
50
40
30
20
10
0
Secondary current (mA)
1
2
3
4
5
Primary current (A)
3-turn
primary
winding
1-turn
primary
winding

Figure D-3

D.5 Practical Aspects

Applications of current transformers include all kinds of situations in which a measurement or implied measurement of an alternating current is required, where the current in question is of an inconvenient value, or is at an inconvenient potential, or must be added to or subtracted from some other alternating current. The latter case may provide occasion for the use of more than one primary winding on a single current transformer, or alternatively separate current transformers may have their secondaries interconnected to combine the secondary currents in the required way. The measurement may be direct and give rise to an indication or it may take various indirect forms. Control systems for motors and the like often require signals that are proportional to current for torque control, or for stabilising the feedback.

Protective equipment may, through the current transformer, monitor the current in the main circuit and open the circuit if that current becomes excessive. Wattmeters, phase meters, watt-hour meters, reactive-VA meters and others may take the measure of primary current represented by the secondary current and combine it with other signals to form composite outputs which are recorded or indicated or otherwise processed as required.

For a resistive burden, it is mostly the core losses which must be kept low to maintain a current ratio which must be kept low to maintain a current ratio close to the turns ratio. However, it may be shown that the phase angle is (for a resistive burden) most affected by the magnetising component of the exciting current. Since the phase of the current is important in power measurements, it follows that a current transformer is widely useful only if both components of the exciting ampere turns are small.

Current transformers are often required to process robustness far exceeding that required for a power transformer of similar rating. If the current is being measured in a high voltage line, the current transformer must be insulated to withstand the highest voltage on that line, notwithstanding that neither primary nor secondary windings may develop more than a few millivolts. Also current transformers in power systems and elsewhere must withstand any fault currents which could occur in the system. The requirement may be merely to survive, or it may be to continue working (perhaps with reduced accuracy) while passing currents perhaps fifty times the normal maximum for brief periods.

Another situation in which a fault can be potentially dangerous is a break in the secondary circuit of a current transformer. In this case, the primary current will not change significantly (unlike the situation in a power transformer).

Instead the secondary winding develops a very large voltage, which may break it down, or present a hazard to personnel working in the neighbourhood of the (normally low-voltage) instrument wiring. A spark gap or other voltage limiting device is sometimes placed directly across the secondary terminals of a current transformer to limit the excess voltage in these cases.

An interesting application of the current transformer principle is the clip-on current transformer. This device shown in principle in Figure D-5 is a current transformer secondary with a core which can be opened on a hinge, and then closed around a conductor in which it is required to measure the current. This conductor forms the primary winding. The secondary is connected to a suitable meter. The advantage is that the instrument can be used for taking measurements at several different places in the circuit in turn without the necessity for breaking the circuit or making any electrical connections.

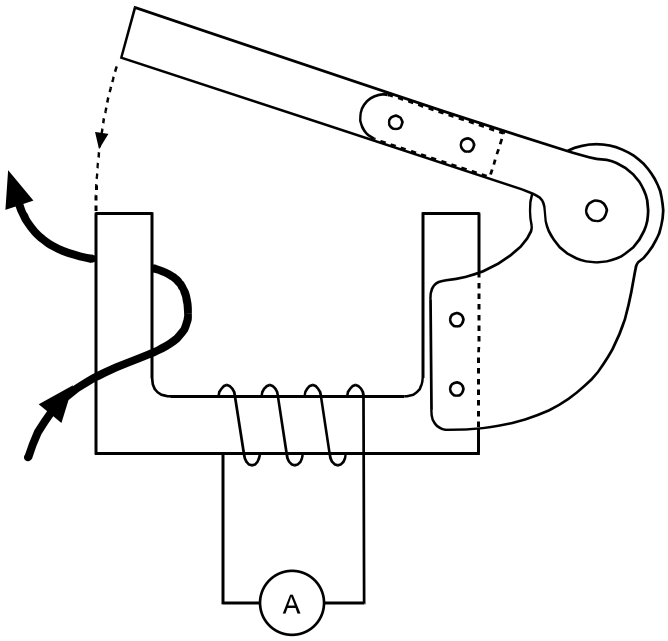


Figure D-5