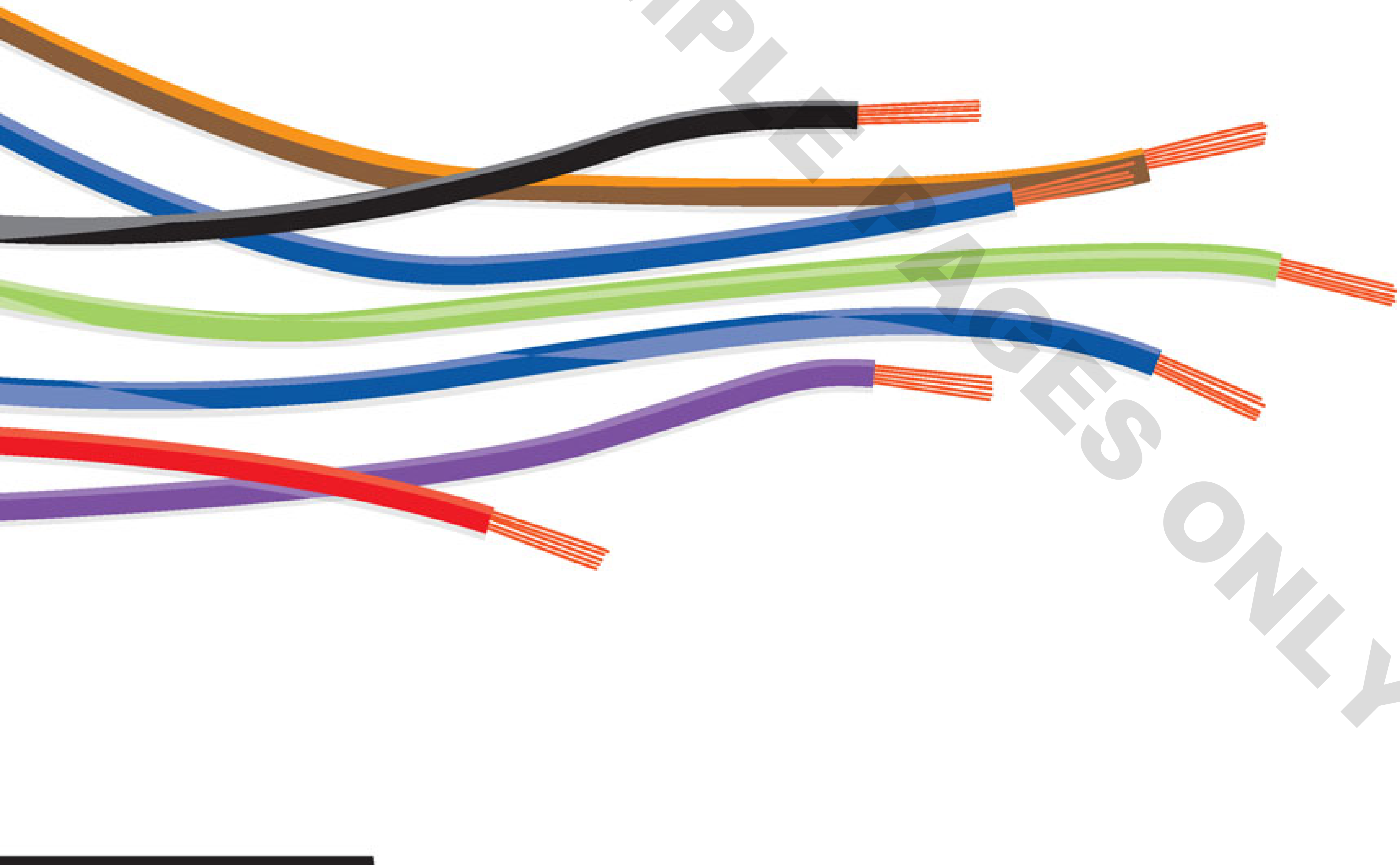
6TH EDITION

ELECTRICAL PRINCIPLES

FOR THE ELECTRICAL TRADES

VOLUME 2



Jim Jenneson
and Bob Harper

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worldskills Australia

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Contents

WorldSkills International Competition

CATEGORY: ELECTRICAL INSTALLATIONS

Australia's Silver Medallist

At just 23 years of age, John Rudge has achieved what many people only dream about—the honour of representing one's country.

After winning a Gold Medal in the Electrical Installations category at the WorldSkills Australia Macquarie Regional Competition in 2005, John progressed to the WorldSkills Australia National Competition in Melbourne 2006, where he won a Gold Medal and the accolade of Australia's Best.

At the 2007 WorldSkills International Competition in Shizuoka, Japan, John competed against the world's best electricians, returning home with a Silver Medal.

'It has been an amazing eye opener to compete at an international level. It has also given me the confidence to tackle any challenge.'

Following his success in Japan, John started a new job with OMYA Australia where his role is to maintain and update PLC software for their five plants throughout Australia and New Zealand. In 2008 John was named the Electrical Installations International Expert, mentoring and training the 2009 Electrical Installations *Skillaroo*, Gavin Press.

'WorldSkills Australia has made me a stronger person and my work is up to international standards, keeping the client, my boss and myself a lot happier.'

John Rudge: 2007 Skillaroo

WORLDSKILLS AUSTRALIA

WorldSkills is Australia's largest and most prestigious trade and skills competition, encouraging young people to rise to the challenge of stimulating competition. For the past 28 years this not-for-profit organisation has motivated over 70 000 young Australians to participate in WorldSkills Australia programs.

Its mission is to challenge young people, their teachers, trainers and employers to achieve world class standards in work skills and promote the status of vocational education and training across Australia. Through a program of competitions, aligned to the National Training Packages, WorldSkills Australia works to ensure that today's young people have the skills and abilities to compete within a rapidly changing global marketplace.

worldskills Australia

A portion of the profits from this book will go to WorldSkills Australia.

For further information about WorldSkills Australia competitions visit www.worldskills.org.au.

Text at a Glance

SETTING A CLEAR AGENDA

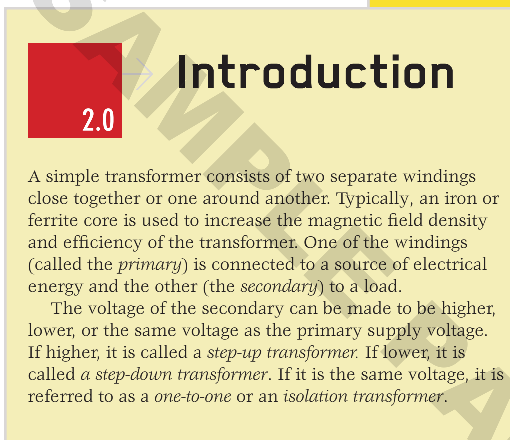
Each chapter begins with a brief introduction and a list of objectives that the reader can aim to achieve.

CHAPTER OBJECTIVES

- define the terms transformer, primary winding, secondary winding, magnetic core
- explain the operating principle of a two coil transformer
- define transformation ratio, turns ratio, voltage ratio, current ratio and impedance ratio
- sketch the phasor diagram of a transformer under no-load conditions
- sketch the phasor diagram of a transformer under on-load conditions
- define and calculate iron losses, copper losses, transformer losses, and transformer efficiency,
- describe and calculate transformer voltage regulation
- describe typical single phase transformer construction
- describe typical three phase transformer construction
- describe typical testing of transformers for commissioning, and parallel operation
- describe special use transformers such as potential transformers, current transformers, autotransformers, variacs, isolation and hi-reactance types

Transformers

CHAPTER 2



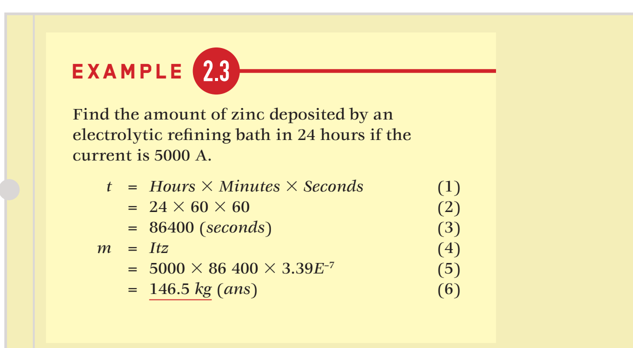
2.0 Introduction

A simple transformer consists of two separate windings close together or one around another. Typically, an iron or ferrite core is used to increase the magnetic field density and efficiency of the transformer. One of the windings (called the *primary*) is connected to a source of electrical energy and the other (the *secondary*) to a load.

The voltage of the secondary can be made to be higher, lower, or the same voltage as the primary supply voltage. If higher, it is called a *step-up transformer.* If lower, it is called *a step-down transformer*. If it is the same voltage, it is referred to as a *one-to-one* or an *isolation transformer*.

WORKED EXAMPLES

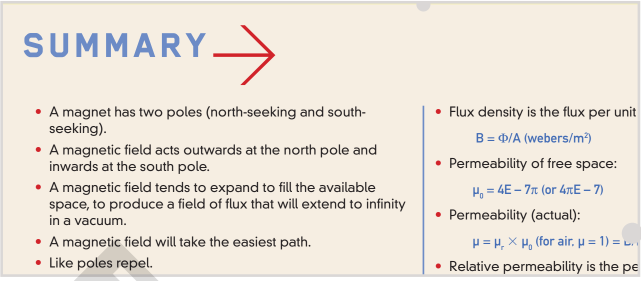
Each chapter supports the theoretical aspects by providing practical applications of the theory covered. The theory is illustrated by fully worked examples. These examples give students a template to use when completing similar exercises (e.g. page 39).



EXAMPLE 2.3

Find the amount of zinc deposited by an electrolytic refining bath in 24 hours if the current is 5000 A.

$$
\begin{aligned}
t &= Hours \times Minutes \times Seconds && (1)\\
&= 24 \times 60 \times 60 && (2)\\
&= 86400\ (seconds) && (3)\\
m &= Itz && (4)\\
&= 5000 \times 86\,400 \times 3.39E^{-7} && (5)\\
&= \underline{146.5\ kg}\ (ans) && (6)
\end{aligned}
$$



SUMMARY

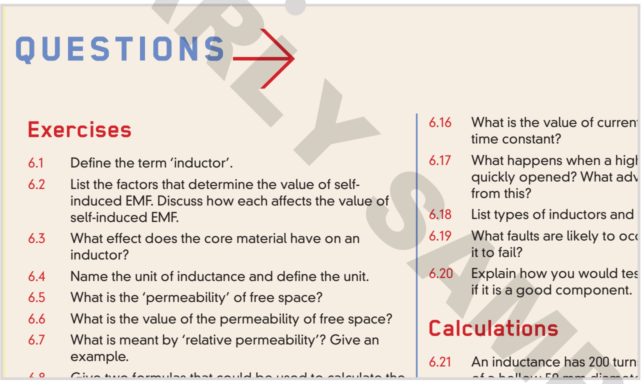
- A magnet has two poles (north-seeking and south-seeking).
- A magnetic field acts outwards at the north pole and inwards at the south pole.
- A magnetic field tends to expand to fill the available space, to produce a field of flux that will extend to infinity in a vacuum.
- A magnetic field will take the easiest path.
- Like poles repel.
- Flux density is the flux per unit
  B = Φ/A (webers/m²)
- Permeability of free space:
  μ_0 = 4E – 7π (or 4πE – 7)
- Permeability (actual):
  $\mu = \mu_r \times \mu_0$ (for air, μ = 1) =
- Relative permeability is the pe

SUMMARY

Each chapter ends with a comprehensive summary listing the core concepts covered, making it an excellent tool for revision and reference (e.g. page 59).

EXERCISES

Each chapter contains Questions to test a student's understanding of the chapter content (e.g. page 114).



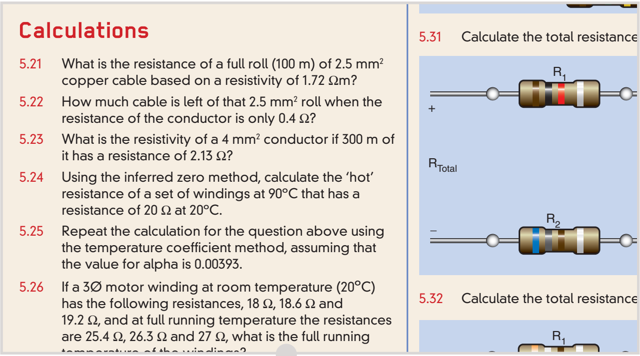
QUESTIONS

Exercises

6.1 Define the term 'inductor'.
6.2 List the factors that determine the value of self-induced EMF. Discuss how each affects the value of self-induced EMF.
6.3 What effect does the core material have on an inductor?
6.4 Name the unit of inductance and define the unit.
6.5 What is the 'permeability' of free space?
6.6 What is the value of the permeability of free space?
6.7 What is meant by 'relative permeability'? Give an example.
6.16 What is the value of curren time constant?
6.17 What happens when a higl quickly opened? What adv from this?
6.18 List types of inductors and
6.19 What faults are likely to occ it to fail?
6.20 Explain how you would tes if it is a good component.

Calculations

6.21 An inductance has 200 turn



Calculations

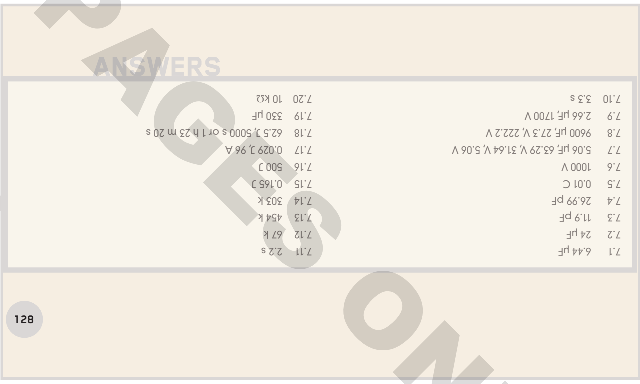
5.21 What is the resistance of a full roll (100 m) of 2.5 mm² copper cable based on a resistivity of 1.72 Ωm?
5.22 How much cable is left of that 2.5 mm² roll when the resistance of the conductor is only 0.4 Ω?
5.23 What is the resistivity of a 4 mm² conductor if 300 m of it has a resistance of 2.13 Ω?
5.24 Using the inferred zero method, calculate the 'hot' resistance of a set of windings at 90°C that has a resistance of 20 Ω at 20°C.
5.25 Repeat the calculation for the question above using the temperature coefficient method, assuming that the value for alpha is 0.00393.
5.26 If a 3Ø motor winding at room temperature (20°C) has the following resistances, 18 Ω, 18.6 Ω and 19.2 Ω, and at full running temperature the resistances are 25.4 Ω, 26.3 Ω and 27 Ω, what is the full running
5.31 Calculate the total resistance
5.32 Calculate the total resistance

CALCULATIONS

Calculations are mathematical exercises designed to give the student experience at solving typical problems found in the electrical trades (e.g. page 96).

They cover:

1. power and energy meters
2. Greek letters used in the text
3. list of the elements
4. standard SI quantities and units used in the text.



ANSWERS

128

ANSWERS TO SELF-TESTING PROBLEMS

Answers to calculations are placed at the end of each chapter to allow the student to check the answers (answers are inverted to ensure students think before taking the easy way out) (e.g. page 128).

AUXILIARY CHAPTER

An auxiliary chapter is included at the back of the book for ease of reference and revision of basic concepts, including:

- units and physical quantities
- SI base units
- SI derived units
- multiples and sub-multiples
- scientific notation
- engineering notation
- transposition
- work, power and energy
- scalar and vector quantities
- periodic table
- characteristics of materials
- formulae
- graphs
- Greek letters and applications.

Preface

This sixth edition of *Electrical Principles for the Electrical Trades (Machines)* is the second volume of a two-volume set, the first of which is *Electrical Principles for the Electrical Trades Volume 1*.

Many of the ideas and suggestions for this edition were forthcoming from an Australia-wide representation of teachers and instructors who have been associated with previous editions of this book.

The symbols used in this book should comply with the latest drawing standards given in SAA/SNZ HB3:1996, as updated. In some cases, more pictorial symbols have been used where doing so assists new students to understand the material. At times I had to make a teacher's decision in selecting which symbol to use, rather than a drafting decision. Colleges and individual teachers quite rightly have their own preferences and this puts me in the invidious position of knowing that I cannot please everyone. So it is!

There have been modifications to the general text to meet other suggestions, but some of these suggestions, while meriting earnest consideration, became somewhat impracticable within the confines of this volume and current teaching practices. Some sections of the text have been deleted and other sections added. Diagrams have in most cases been modified, updated or simply coloured in! Some required corrections and some were simplified, while others were added, amended or deleted as required to match the text.

There were many requests for the book to be modified to fit exactly with the current training package. It is considered unacceptable to adopt this approach, since even a minor change in a competency would immediately make the book almost useless. The text is intended for a greater range of uses and hopefully as a long-term reference for tradespeople. Therefore a more logical approach, a more natural flow or pathway, has returned in this edition. The book was originally written to be used as both a guide for students and, hopefully, as a reference that tradespeople can use for many years.

A student's initial studies are usually undertaken with the assistance of an experienced instructor. As a consequence, even with the extensive material within the text, the book should not be expected to stand alone. Individual teachers should have the opportunity to expand the basic theories within this book with practical examples of real, local technology. There are, however, more than enough diagrams to make the text meaningful, while the instructor, as part of the teaching process, is encouraged to supply additional material of direct interest to the particular class.

Each chapter has a summary of its salient points and this is followed by both exercises and calculations. The student exercises and calculations from the previous edition have been updated and changed to reflect the move to 230/400V ac distribution. Many calculations are new, with more examples starting at a simpler level. In general, examples range from the simple, through the chapter material, to challenge questions which require the student to apply the theory to more practical applications. Hopefully teachers will agree that this helps students to learn to apply their newfound knowledge.

Teacher resources

Teachers may contact me via the McGraw-Hill website or via online feedback on the site for the latest range of resources that are available. Any corrections, omissions, updates or new information will be made available to teachers using this text. There is a solutions manual with full workings on each question from each chapter, in PDF form. More questions are expected to be generated for each chapter and a bank of exam questions is to be developed. Images and diagrams will be available, most likely in PDF format, and some SWF demonstrations are in preparation. Much has been learned in the eLearning field and eMedia materials are expected to become a big part of the average classroom in the future.

ACKNOWLEDGMENTS

The modifications incorporated in this sixth edition of *Electrical Principles for the Electrical Trades (Machines)* are the result of the work of many Australian TAFE instructors. This comprises a great deal of hard work undertaken in addition to their normal duties, in their own private time. Particular thanks go to Bob Moore, Kevin Dennis, Dave McKee, Ted Harwood, Drew O'Shea and Peter Waley, all from SkillsTech Australia, as well as many from other TAFE colleges and RTOs whose comments and suggestions were valued contributions to the revision process. Without their input, the book wouldn't be what it is.

The organisation, production and success of such a book is due to the hard work of not only the editors but many other staff members of McGraw-Hill Australia. Thank you all for your good work, advice and support; it is greatly appreciated.

Bob Harper, Beerwah

About the Authors

Jim Jenneson

Jim Jenneson is now happily retired after a long and distinguished career as a teacher of VET electrotechnology. The first edition of his text appeared in 1980 and quickly established itself as the bible in its field, a status which it continues to hold. The text reflects his approach to teaching, which must have been patient, thorough and focused on clarity.

Bob Harper

Bob Harper is a TAFE teacher working at SkillsTech Australia, an institute of Queensland TAFE. He joined the Department of Education in 1983 as an industrially experienced electrician to teach electronics. TAFE applied Bob to whatever class needed teaching at the time and so his experience widened. Bob accumulated several TAFE certificates, a Diploma of Teaching, a Diploma of Freelance Journalism, a Bachelor of Technology (Eng.) and is currently studying for a Bachelor of Science (Psychology). Bob likes teaching and working with people to help them study; he is currently teaching renewable energy and working in online education and eLearning.

Supplements for instructors

www.mhhe.com/au/jenneson6e

The following supplements are provided for instructors free of charge. These are available on the Online Learning Centre that accompanies *Electrical Principles for the Electrical Trades (Machines)*.

Instructor Resource Manual

The Instructor's Resource Manual provides the instructor with a chapter-by-chapter summary of the text, solutions to all end-of-chapter questions, and additional teaching resources to enhance students' learning.

Art Work Library

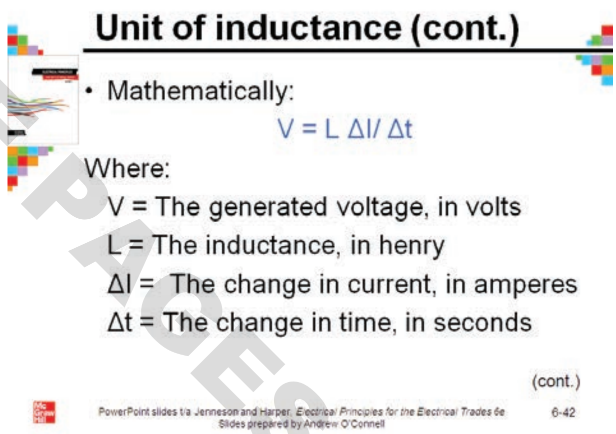
All images and illustrations within this book are also available individually in our online Art Work Library so that instructors have the flexibility to use them in the format that best suits their needs.

EZ Test online

EZ Test is a flexible and easy-to-use testing program. It generates tests that can be exported to other course management systems (such as Web CT and Blackboard) and can be used to create hardcopy tests. Many questions of varying degrees of complexity are available.

PowerPoint® slides

Available to all instructors on the Online Learning Centre are PowerPoint® presentations featuring a summary of key points in each chapter.



Test Bank

A Test Bank of questions is available to assist instructors to set examinations quickly and easily. This may be provided as a simple document file, or formatted for delivery in WebCT or EZ Test, McGraw-Hill's exclusive test generator.

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Transformers

CHAPTER 2

CHAPTER TOPICS

EARLY SAMPLE PAGES ONLY

2.0 Introduction

A simple transformer consists of two separate windings close together or one around another. Typically, an iron or ferrite core is used to increase the magnetic field density and efficiency of the transformer. One of the windings (called the *primary*) is connected to a source of electrical energy and the other (the *secondary*) to a load.

The voltage of the secondary can be made to be higher, lower, or the same voltage as the primary supply voltage. If higher, it is called a *step-up transformer.* If lower, it is called *a step-down transformer*. If it is the same voltage, it is referred to as a *one-to-one* or an *isolation transformer*.

Many transformers are fully reversible in operation, so the winding connected to the source of supply is always referred to as the primary winding.

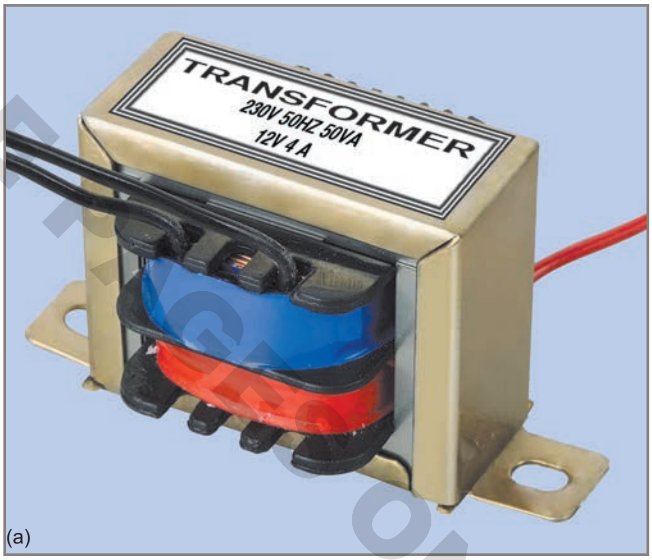
A transformer has no moving parts, so it needs minimal maintenance. Transformers range in size from a few volt-amperes to over 100 MVA with efficiencies over 99 per cent in the larger sizes. The level of efficiency is far higher than any other electrical apparatus or mechanical machine, yet, although there are no moving parts, the transformer is usually referred to as an electric machine.

2.1 Operating principle

The primary and secondary windings and the magnetic core of the transformer are all stationary with respect to each other. The primary winding is connected to an alternating supply causing an alternating magnetic flux to be produced in the magnetic core (i.e. the magnitude of the flux is changing with respect to time).

The three factors required to produce an induced voltage are present: conductors, flux and relative movement. Transformer operation is based on the principle of mutual induction. i.e. The changing current in the primary winding produces the changing flux in both windings causing a back EMF in the primary winding and an induced voltage in the secondary winding, which is in fact the same as the induced EMF.

A small transformer is shown in Figure 2.1(a) and the standard circuit symbol for a single-phase, iron-cored transformer is shown in Figure 2.1(b). Note the two windings are normally wound separately and placed side by side.



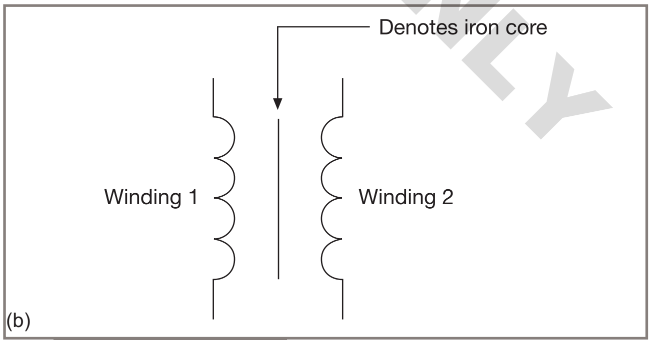


Figure 2.1 Transformer and drawing symbol

2.1.1 NO-LOAD CONDITIONS

Under no-load conditions, the supply voltage is applied to the highly inductive primary winding. DC would cause a larger current to flow probably burning out the transformer in a very short time. The ac current however produces a self-induced voltage V_1', only slightly less than the applied voltage and in opposition to the applied voltage.

The only losses are that required to produce the magnetic field and the current flowing through the resistance of the primary winding.

The no-load or excitation current is typically very small compared to the full load current. In many cases the

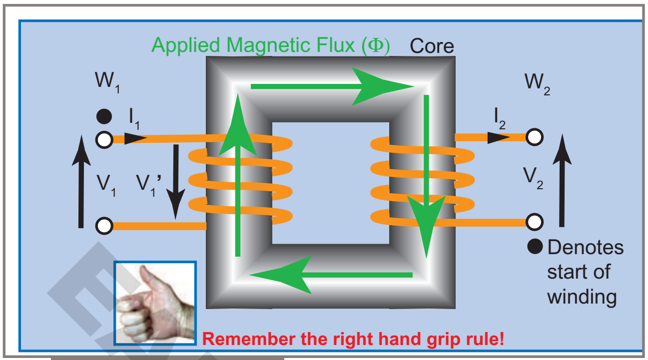


Figure 2.2 Non-loaded transformer

excitation current can be as low as 1 to 3 per cent of the full-load current.

The excitation current causes an alternating flux called the *mutual flux* to be set up in the core linking both primary and secondary windings. The mutual flux causes a voltage to be induced in the secondary winding—the secondary voltage V_2', but no current can flow until a load is connected. See Figure 2.2 and note the phasor diagram of a non-loaded transformer.

The excitation current can be resolved into two rectangular components called the *energy* and *magnetising components*. Parallel circuits use the voltage as the reference phasor, and series circuits use the current as in each case reference phasor is common to all of the components in the circuit. In transformers, the mutual flux produced by the magnetising component is common to both windings is used as the reference phasor when drawing phasor diagrams for transformers.

The phasor relationships are shown in Figure 2.3. The flux **Φ** is shown as the reference phasor, and the magnetising component of the excitation current is in phase with it. Both **Φ** and I_m represent the purely inductive part of the circuit and as such they will lag 90˚E behind the applied voltage V_1.

This means that with flux as the reference phasor, the voltage will be leading the flux by 90˚E. The energy component of current I_e that represents the losses in the iron circuit and the small copper losses is resistive and will be represented by a phasor in phase with the voltage.

A wattmeter connected in the primary circuit would show power being used to cover these losses. The phasor sum of I_m and I_e add up to the no-load current I_0. The large angle (perhaps approaching 90°) between V_1 and I_0 indicates a very poor power factor for a transformer on no load.

The self-induced voltage V_1' in the primary winding, since it opposes the applied voltage, is 180˚E out of phase with V_1.

2.1.2 ON-LOAD CONDITIONS

When a load is applied to the secondary terminals, a secondary current I_2 will flow and its magnitude and phase

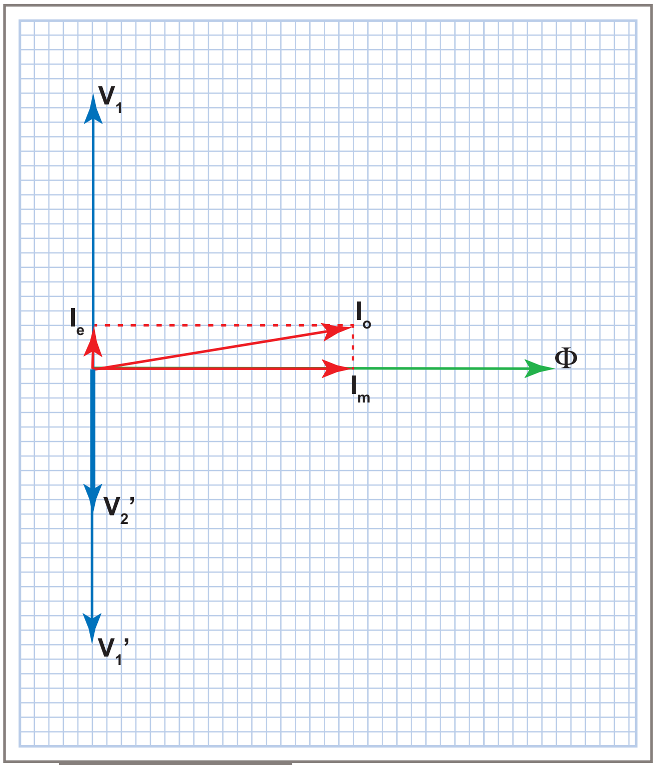


Figure 2.3 Phasor diagram for non-loaded transformer

relationship with the secondary terminal voltage V_2 is determined by the type of load.

Lenz's law tells us that the direction of this secondary current I_2 will always be such as to oppose any change in the flux **Φ**. In Figure 2.4, W_1 is the primary winding with the start of the winding marked by a solid dot '•'.

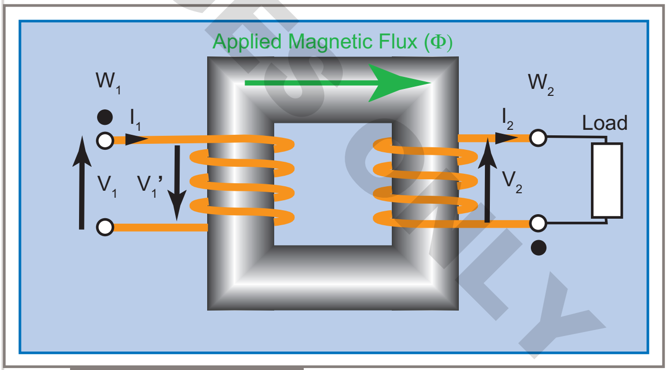


Figure 2.4 Loaded transformer

Assume that at a particular instant in time the primary current I_1 flows from the start to the end of the winding, establishing a flux with a magnetic polarity in a clockwise direction around the iron core as shown. This flux is mutual to both coils.

The mutual flux causes a reaction current in both coils, which has the effect of opposing the establishment of the mutual flux. This can be seen as an opposing reactive flux, but the total effect is reduce the mutual flux, thus reducing the self-induced voltage V_1' in the primary and thus allowing more current to flow in both the primary and secondary.

All of these events happen together. The application of a load draws a current in the secondary winding; causing a demagnetising flux; reducing the mutual flux. The self-induced voltage in the primary decreases; the primary current increases; the mutual flux rises to its original value. In practice, the mutual flux in the iron core of a transformer effectively stays at a constant value for all loads.

An increase in secondary load current therefore causes an increase in primary line current.

The phasor diagram in Figure 2.5 shows the general case for a transformer on load. Assume for the purposes of the diagram that the secondary voltage is equal to the primary voltage and the connected load is inductive, so that the secondary current I_2 lags behind the induced voltage V_2' by the phase angle ϕ_2.

The equivalent current to supply this load will be the value I_1'. If the transformer were 100 per cent efficient, this value of primary current would be the actual current flowing into the transformer from the supply. Since the excitation current I_0 is already flowing in the primary windings to cover core losses, the total primary current will be the phasor sum of these two currents $(I_1' + I_0)$. The phasor sum of I_1' and I_0 gives the actual primary current of I_1 flowing at a lagging phase angle of ϕ_1. It should be noted that the excitation current has been enlarged for the sake of clarity and copper losses in the windings are considered negligible.

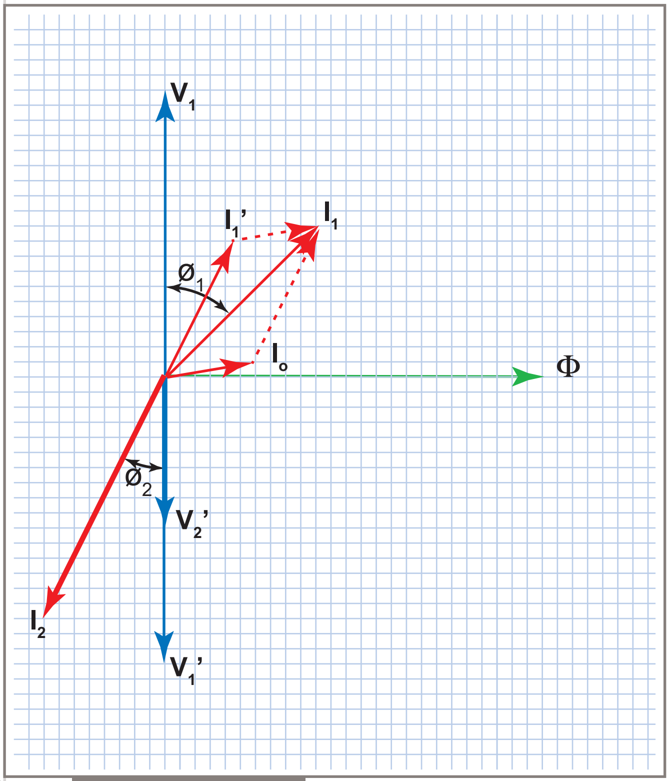


Figure 2.5 Phasor diagram for loaded transformer

2.1.3 VALUE OF INDUCED VOLTAGE

The value of an induced voltage in a transformer depends on three factors: frequency, number of turns, and the maximum instantaneous flux. Provided that the current waveform, and consequently the flux distribution, is sinusoidal, the equation for the r.m.s. value of induced voltage is given by:

$$V' = 4.44\,\Phi_{max}\,fN$$

where

$2\pi/\sqrt{2} = 4.44$ (adjustment for an RMS Sine Wave)

Φ_{max} = maximum instantaneous flux

f = frequency

N = number of turns

Since transformer cores are usually designed on the basis of permissible flux density, the above equation may be expressed as:

$$V' = 4.44\,B_{max}\,AfN$$

where B_{max} = maximum permissible flux density in Wb

A = cross-sectional area of core in square metres

Note: $\Phi = BA$

2.2 Transformation ratios

2.2.1 VOLTAGE RATIO

The mutual flux is common to each winding. Therefore, it must induce the same voltage per turn in each winding.

If V_1' is the total induced voltage in the primary winding having N_1 turns, then the induced voltage per turn is V_1'/N_1. Similarly, the induced voltage per turn in the secondary winding is V_2'/N_2.

On no load, the applied voltage V_1 and the self-induced voltage V_1' are almost equal and $V_2 = V_2'$, so the above ratios are transposed and usually expressed as:

$$V_1 / V_2 = N_1 / N_2$$

That is, on no load, the ratio of the voltages is equal to the ratio of the turns.

EXAMPLE 2.1

A transformer has 1000 turns on the primary winding and 200 on the secondary. If the applied voltage is 250 V, calculate the output voltage of the transformer.

$$V_1/V_2 = N_1/N_2$$
$$V_2 = V_1.N_2/N_1$$
$$= 250 \times 200/1000 = 50 \text{ V}$$

2.2.2 CURRENT RATIO

When the transformer is connected to a load, the secondary current I_2 produces a demagnetising flux proportional to the secondary ampere-turns I_2N_2. The primary current increases, providing an increase in the primary ampere-turns I_1N_1 to balance the effect of the secondary ampere-turns. Because the excitation current I_0 is so small compared with the total primary current on full load, it is usually neglected when comparing the current ratio of a transformer. Therefore the primary ampere-turns equal the secondary ampere-turns:

$$I_1N_1 = I_2N_2$$

By comparing the current and voltage ratios, it can be seen that the current transformation ratio is the inverse of the voltage transformation ratio:

$$I_1 / I_2 = N_2 / N_1$$

2.2.3 IMPEDANCE RATIO

Although a main concern of audio and radio technicians, impedance ratio is important to understand for electrical workers. The reason is that when the voltage goes down as a result of the turns ratio, the current will go up for the very same reason. The impedance, or resistance if it makes it easier to understand, is a result of both changes, therefore *the impedance ratio is the square of the turns ratio.*

A typical situation is when a TV antenna has been designed with an impedance of 300 Ohms but needs to be connected to the coaxial cable that has an impedance of 75 Ohms. A transformer is used with a turns ratio of 2:1, therefore the voltage ratio will also be 2:1 so the output voltage will be a half of the input voltage. Meanwhile the output current will be twice the input current. Therefore the output impedance $Z_2 = V_2/I_2 = 0.5V_1/2I_1 = 0.25Z_1$ or a quarter the input impedance. i.e. the ratio of Z_2/Z_1 is found from $(N_2/N_1)^2$.

2.3 Transformer losses

2.3.1 IRON LOSSES

Eddy currents

The magnetic core of a transformer consists of many laminations of a high-grade silicon steel of a definite thickness. The power absorbed by the core of a transformer is due to eddy currents and hysteresis and is called iron losses.

When the alternating flux cuts the steel core, an e.m.f. is induced in each lamination, causing a current (called an eddy current) to flow in the closed electrical circuit of the lamination. This eddy current flows through the resistance in each lamination causing heat to be generated in the laminations and therefore in the core as a whole. Although eddy-current losses are effectively reduced by using laminations for the core, they are never entirely eliminated.

Hysteresis

The alternating flux also causes changes in the alignment of the magnetic domains in the magnetic core with the magnetic polarity reversing 100 times a second. This change is energy consuming and heat is produced within the core. The energy loss is referred to as hysteresis loss, the degree of loss being dependent on the nature of the material used for the laminations.

Silicon steel has low hysteresis losses making it suitable for electrical laminations. Figure 2.6 shows a comparison of two hysteresis curves for different materials. It can be seen that the silicon steel curve has a smaller area, representing a lower energy loss and reduced heat production. References to these losses have been made in *Electrical Principles for the Electrical Trades Vol 1*.

The total iron losses represent the power absorbed by the iron core and so are proportional to I_e, the energy component of I_0 in Figure 2.3. The mutual flux **Φ** remains fairly constant from no load to full load, therefore, it follows that the excitation current I_0 producing that flux, and so I_e, will also be constant. The iron losses will be constant irrespective of the load applied to the transformer. These iron losses can be obtained by measuring the power

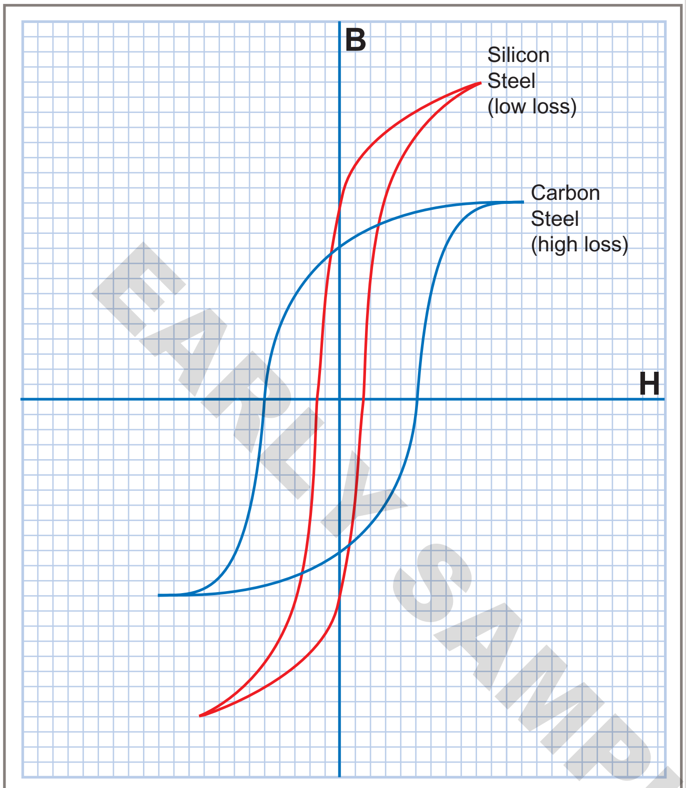


Figure 2.6 Hysteresis curves

consumed on no load in what is known as a ‘no-load or open circuit test’.

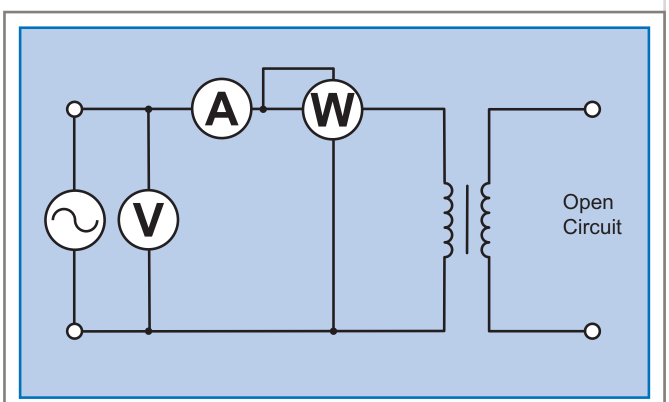


Figure 2.7 No-load or open-circuit test

The transformer is connected as in Figure 2.7 to a supply at the rated voltage and frequency. The primary current on no load is usually less than 3 per cent of the full-load current, so the primary I^2R loss on no load is negligible compared with the iron loss. The wattmeter reading can then be taken as being the total iron loss of the transformer.

2.3.2 COPPER LOSSES

Another form of loss that occurs in a transformer is copper loss, which is the energy lost in the windings when the transformer is loaded. The resistance of each winding is relatively low, but since the power dissipated in each winding is proportional to the square of the current flowing through that winding, it follows that the copper loss is significant when the load current is high.

The total copper loss is $P_{cu} = I_1^2R_1 + I_2^2R_2$, where R_1 and R_2 are the resistance values of the primary and secondary windings respectively. The copper losses are not constant, but change according to the square of the load current. The value of the losses can be obtained by performing the short-circuit test, as shown in Figure 2.8. The typically shaped curve of copper losses can be seen in Figure 2.9.

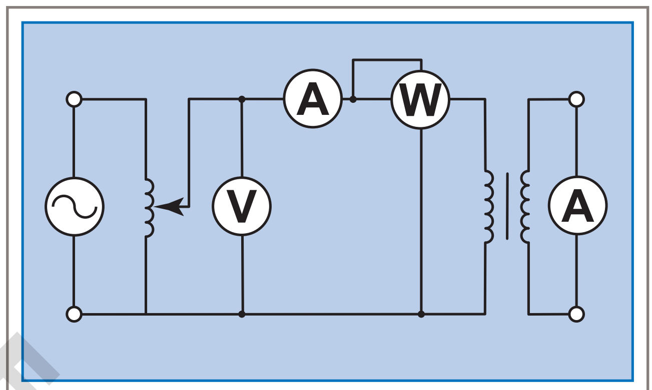


Figure 2.8 Transformer short circuit test

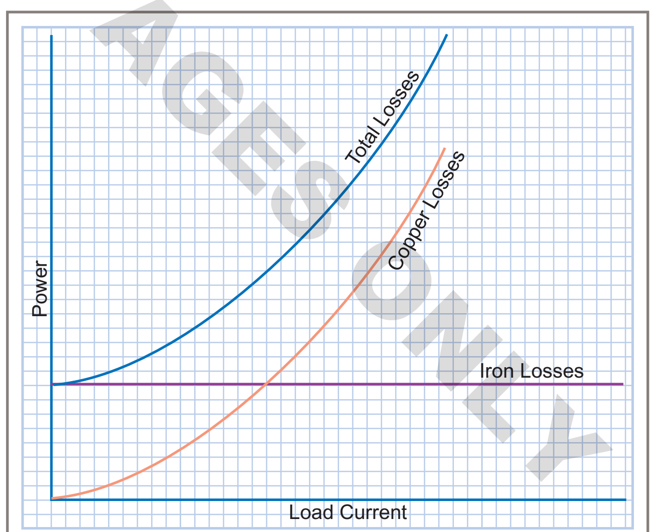


Figure 2.9 Transformer losses

As Figure 2.8 shows, the secondary winding of the transformer under test is shorted through the ammeter A_2. An adjustable autotransformer is used to provide a low-voltage supply to the primary winding of the transformer on test. The output of the autotransformer is increased until the full rated current flows in the primary and secondary circuits.

The supply voltage to the transformer is low, and the flux in the iron core is also low, and so the iron losses are negligible. The power registered on the wattmeter 'W' can be taken as the total copper losses in the transformer on full load. For details on autotransformers, see section 2.9.5.

2.3.3 TRANSFORMER EFFICIENCY

The efficiency of any machine is expressed as:

$$\eta = \text{output}/\text{input}$$

A transformer normally has a high efficiency, therefore the difference between the output and input readings is very small (typically 1–3%) and the efficiency is usually determined from the losses.

$$\eta = \text{output}/\text{input} = \text{output}/\text{output} + \text{losses}$$

that is, $V_2I_2\lambda_2/(V_2I_2\lambda_2 + P_{cu} + P_{fe})$

where

P_{cu} = copper losses
P_{fe} = iron losses

Assuming the output voltage V_2 remains constant, the only variables affecting the efficiency of a transformer are load current and power factor.

2.3.4 FLUX LEAKAGE

It has been assumed so far that all of the primary winding flux was magnetically linked with the secondary winding, thus creating a mutual flux that coupled both windings perfectly. In practice a small portion of the primary flux passes through the air gap and does not cut the secondary conductors. This flux is called the primary leakage flux and is shown as Φ_1 in Figure 2.10. The leakage flux helps in producing the self-induced voltage V_1' in the primary winding but, in bypassing the secondary winding, plays no part in producing the voltage V_2, which is accordingly reduced slightly below the theoretical value.

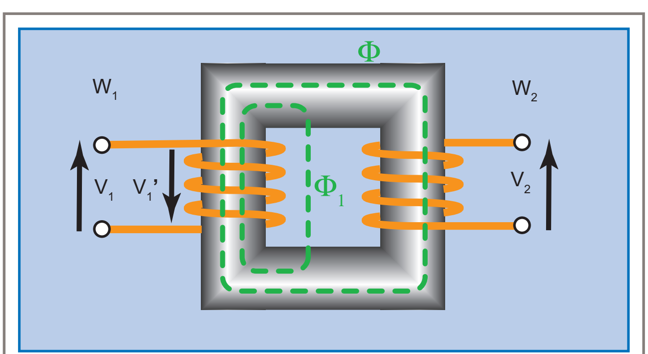


Figure 2.10 Primary leakage flux

When the transformer is on load, the secondary current I_2 sets up a demagnetising flux opposing the mutual flux (section 1.1.2). Some of this secondary flux also passes through the air gap and is called the secondary leakage flux (indicated as Φ_2 in Figure 2.11).

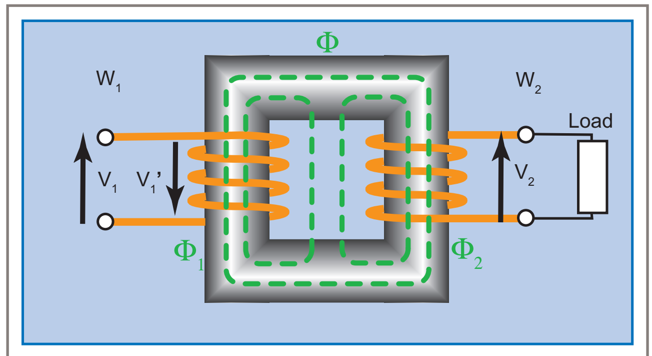


Figure 2.11 Secondary leakage flux

The primary and secondary leakage fluxes both induce voltages in their respective windings and cause inductive reactance to be set up. As the load current increases, the leakage flux—and so the inductive reactance—increases. This inductive reactance and the winding resistance cause voltage drops on load, as shown in Figure 2.12.

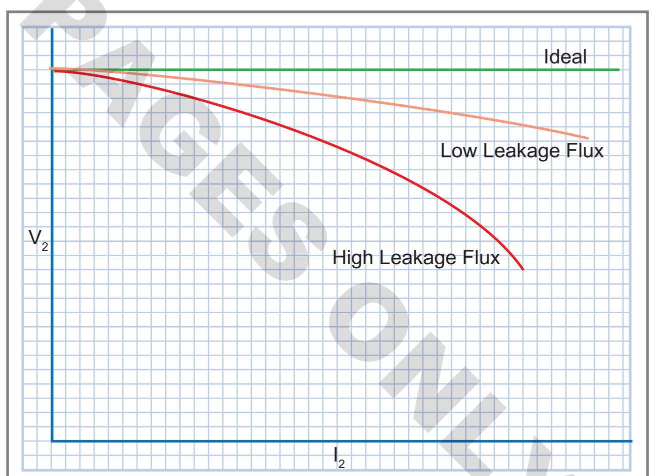


Figure 2.12 On-load voltage drop

In most transformer applications, leakage flux is a disadvantage and various methods are used to reduce it to a minimum. An arrangement such as in Figure 2.11, with the primary and secondary windings on separate limbs, is a poor design and is rarely used in practice. To minimise leakage flux, transformers are designed with the shortest possible magnetic core path, a low flux density in the core, and a high reluctance path for the leakage flux. This is achieved by using a combination of winding arrangements and special core shapes, which are discussed in section 2.4.

2.3.5 VOLTAGE REGULATION

A transformer is expected to deliver a predetermined voltage at full load. The two major losses discussed in the previous section were:

1. magnetic losses, which include leakage flux and other magnetic core losses
2. copper losses due to winding resistance.

Because of these losses the full-load voltage will tend to be less than the no-load voltage.

To obtain a regulation value, the primary input voltage should be maintained at its rated value and the power factor of the load must be known—the regulation value obtained is relevant only at this value of power factor for a particular transformer. The formula given is really only accurate for single-phase transformers. Voltage regulation of a transformer can be expressed as a percentage of its full-load voltage:

$$\text{voltage regulation} = [V_{NL} - V_{FL}/V_{FL} \times 100]\%$$

Note that the voltages used are all secondary values. Where a formula differs from the above, it should be checked to see whether equivalent or reflected values are to be used.

Care must be exercised when using a regulation value as a basis for comparison with another transformer. Comparisons with transformers of a different load, power factor, or voltage ratio are not valid.

2.4 Transformer construction

2.4.1 SINGLE-PHASE TRANSFORMER CORES

A transformer consists of a common magnetic circuit linking the primary and secondary windings. The form of construction is determined by the arrangement of the laminations and the way they are stacked together. Figure 2.13 shows two methods for making up the stack for a transformer core. Figure 2.13(a) shows U-I shaped laminations, which are stacked in alternate directions to make a core-type magnetic circuit. Figure 2.13(b) shows E-I shaped laminations, which are also stacked in alternate directions to make a shell-type magnetic circuit. Either type can be stacked from simple rectangles of lamination sheet that is the preferred method for larger transformers. Although there are several variations of these types of construction, transformers may in general be classified as one of these two types–U-I or E-I.

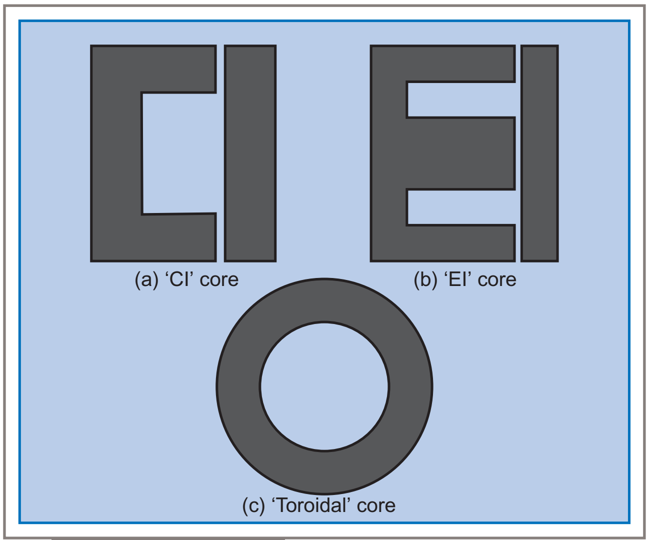


Figure 2.13 Core, shell and toroid

Transformers are also separated into groups known as Core, Shell and Toroidal.

Core type

With the core-type transformer, the windings surround the laminated core, as shown in Figure 2.14(a). To provide a uniform flux density throughout the magnetic core, the cross-sectional area of the core is uniform.

Shell type

The shell-type construction has the magnetic core surrounding the windings, as shown in Figure 2.14(b). Because the core provides a parallel magnetic path for the flux, the centre limb is twice the cross-sectional area of the outer limbs, maintaining uniform flux density throughout the iron core.

By comparison, the core-type construction has a lighter core of smaller cross-sectional area, but a greater length of magnetic circuit. It also has a relatively greater number of turns, but these have shorter mean length. The core type, with its larger window space, is more suitable for higher voltages, requiring many turns and a larger space for insulation. The shell type is particularly suited for moderate voltages requiring fewer turns, less insulation,

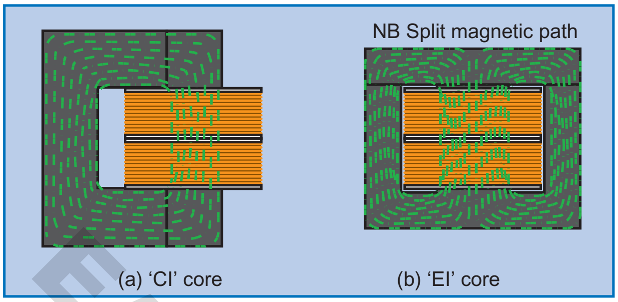


Figure 2.14 Windings, core and shell type

larger currents, and lower frequencies, with corresponding flux densities.

Toroidal type

The toroidal core is made from a continuous ribbon of thin metal tape made from a special alloy. It is wound tightly around a former and consolidated under pressure into a solid mass. Toroidal cores must be wound by a special machine that passes the coil wire through the center of the toroid many times. One advantage of the toroidal type is the windings are spaced around the whole core resulting in a shorter, constant cross section magnetic path, with very low leakage flux.

A toroid core may alternatively be sliced into two C-shaped pieces—the finished article is sometimes referred to as a C-core. The cut faces are ground to ensure good surface contact between the two halves. Two of these halves are placed around the transformer windings and clamped with a metallic band under moderate pressure to counter the effect of an air gap.

For core-type construction using C-cores, one pair of cores is used, while for shell-type construction, two pairs or C-cores are used. Figure 2.15 shows this method. It is usual to place a third clamp around the pair of cores after assembly to prevent noise and chafing by vibration.

For three phase transformers, three sets of C-cores are used so each coil has two C-cores through the coil set. This is shown in section 2.4.3 - Three phase transformers.

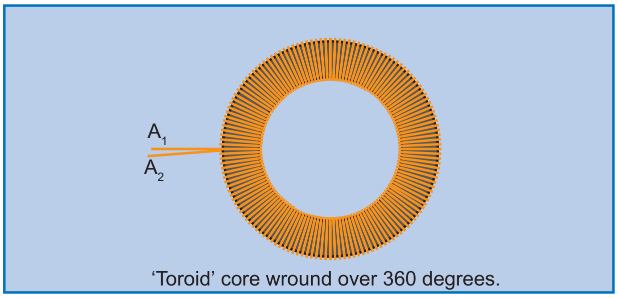


Figure 2.15 Toroidal winding

2.4.2 SINGLE-PHASE TRANSFORMER WINDING ARRANGEMENTS

The actual placement of the windings on the transformer core depends on the type of core and the intended use of the transformer. Other factors that influence this arrangement are the operating frequency and the size or power rating of the transformer. Some typical winding layouts are shown in Figure 2.16. While the core-type transformer construction is shown in the diagrams, the winding arrangement applies equally to the shell-type construction.

With the concentric method, one winding is wound on the top of the other (primary or secondary) and suitable insulation is installed between the two. A sandwich or pancake-type winding is used where closely coupled windings are required, so that the magnetic leakage can be reduced to a minimum. The sandwich method is also used in large distribution transformers for ease of winding and handling, and also in smaller transformers operating at higher audio frequencies.

The type of winding arrangement that is now becoming more common for power transformers is shown in Figure 2.16(c). This is due in part to Standards Australia recommendations for insulation requirements between primary and secondary windings.

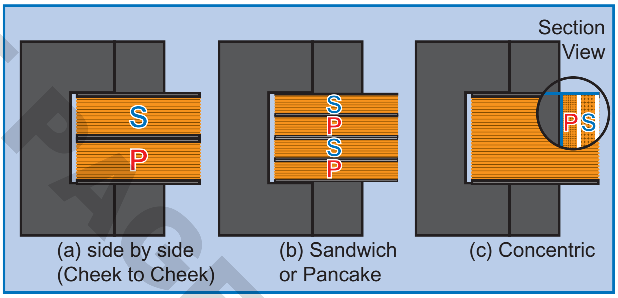


Figure 2.16 Winding arrangements

Note that Australian Standards commonly require a thermal fuse in the windings of transformers used in many household appliances and in items such as plug-pack power supplies.

2.4.3 THREE-PHASE CORES

The same variations in single-phase cores apply to three-phase cores. For single-phase, the majority of transformer cores use the shell-type construction, while for three-phase, the majority are of a core-type construction.

A three-phase transformer can be obtained by using three identical single-phase transformers, but usually a common three-phase magnetic core is used, with three identical sets of primary and secondary windings mounted on it.

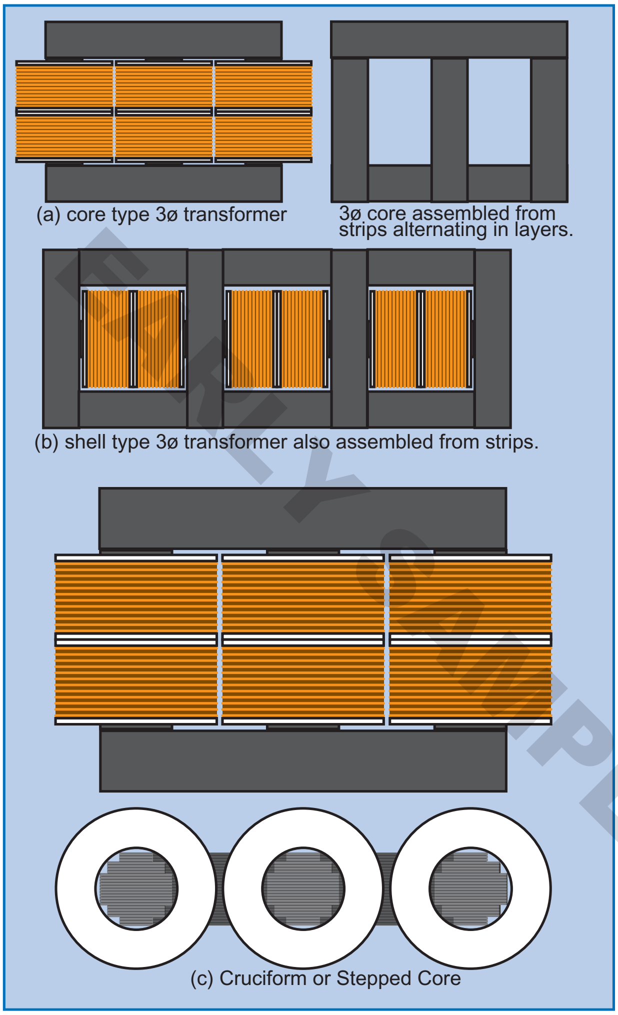


Figure 2.17 Three-phase core types

Three-phase core type

The shape shown in Figure 2.17(a) is usually employed in smaller distribution-type transformers. The core-type construction has a shorter length per turn of winding than the shell type but has a longer magnetic path. While similar in appearance to the single-phase shell type, each leg of the core has an equal cross-sectional area.

Three-phase shell type

This shape of core overcomes the tendency of the core type to have unequal flux densities and is shown in Figure 2.17(b).

Three-phase cruciform or stepped core

With conductors of large cross-sectional area, it becomes difficult to construct windings that have 90° bends in the conductors. With this shape of core the windings are wound on circular formers and the core is stepped (in cross-sectional area) to fill up the inside of the coil as far as possible with transformer laminations. The core is shown in cross-section in Figure 2.17(c) and it can be seen that a great number of different-size laminations are required. This form of construction is expensive and is generally used only on large transformers.

Three-phase toroidal

This type of construction has been mentioned in section 2.4.1 and in general, toroidal cores can be obtained in most shapes for three-phase transformers. See Figure 2.18.

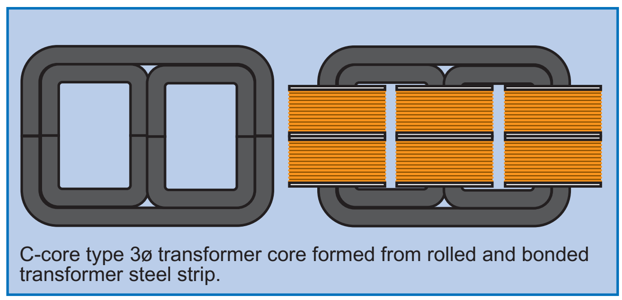


Figure 2.18 Three-phase 'C' core

2.4.4 THREE-PHASE TRANSFORMER WINDING ARRANGEMENTS

The same factors affecting windings and cores for single-phase transformers apply equally to three-phase transformers, although the majority of distribution transformers are wound in the sandwich or pancake style. The method lends itself to ease of construction and repair.

The degree to which the primary and secondary windings are magnetically coupled depends on the intended purpose of the transformer. A transformer is said to be close coupled when all the primary flux passes through the secondary turns. If a large proportion bypasses the secondary windings, the transformer is said to be loosely coupled. There are of course intermediate degrees of coupling. For example, a distribution transformer is less than close-coupled as a form of current limitation, to allow for the case of damage to overhead lines connected to its secondary. However, the degree of coupling for a high-tension transformer for an illuminated sign is far less than that for a distribution transformer. In this case it is required that the on-load voltage be considerably less than the open-circuit voltage.

2.5 Transformer ratings

Engineers design transformers for a specified voltage ratio and current (power) capacity; but, once a transformer is placed in service, the load placed on it is beyond the immediate control of both the designer and the power supply authority. The actual load depends on the loading of the total number of connected circuits. Transformer design may assume that the individual circuits will not all reach maximum load at the same time, therefore the transformer rating will be less than the total potential load.

The loads circuits may have a power factor different to the design expectations and therefore cause a higher current than a unity power factor. Therefore transformers are not rated by power but by voltage and current, which is expressed in terms of apparent power, VA.

For example, a single-phase transformer capable of delivering 100 A at 500 V would be rated at 500 × 100 = 50 000 VA, or 50 kVA. If the power factor of any given load is 0.5, then the maximum safe power output would be 25 kW. Similarly, at a power factor of 0.8 the safe power output would be 40 kW. In both cases the full-load current would be 100 A.

The current rating of the conductors in the windings is dependent on the rate at which the total heat generated in the transformer can be dissipated. The rating limitation of the transformer is a factor of the temperature rise of the unit on load and the ambient temperature. High ambient temperatures result in a lower rating and a low ambient temperature allows a high rating.

2.6 Transformer cooling

As with any device, a transformer on load generates heat. Transformers generate heat in both the core and the windings. For smaller units the surface area is great enough to remove the generated heat by convection and radiation. As transformer size increases, the surface area becomes proportionately smaller than the volume, and eventually the heat being generated cannot be dissipated quickly enough. As a result, the temperature of the transformer begins to rise and additional cooling methods must be used.

In general terms, there are two commonly used media for transformer cooling—air and oil. The methods and combinations for these two cooling materials, however, are many and varied.

2.6.1 AIR COOLING

For air cooling, the transformer must be provided with ducts between the coils, and between the core and the housing, so that air can be blown through them to remove the heat. The air must be filtered so that dust cannot build up in the ducts as dust can become wet and lead to faults occurring. Air-blast cooling is seldom used in very large transformers, or for voltages above 20 kV. The air-blast type of cooling is used on transformers where economy of space and weight is required, or where oil cooling may be a fire hazard.

2.6.2 OIL COOLING

One common method used for cooling is to immerse the transformer in a tank of special transformer oil, providing as large a cooling surface area of the tank as possible by using external tubes, as shown in Figure 2.19.

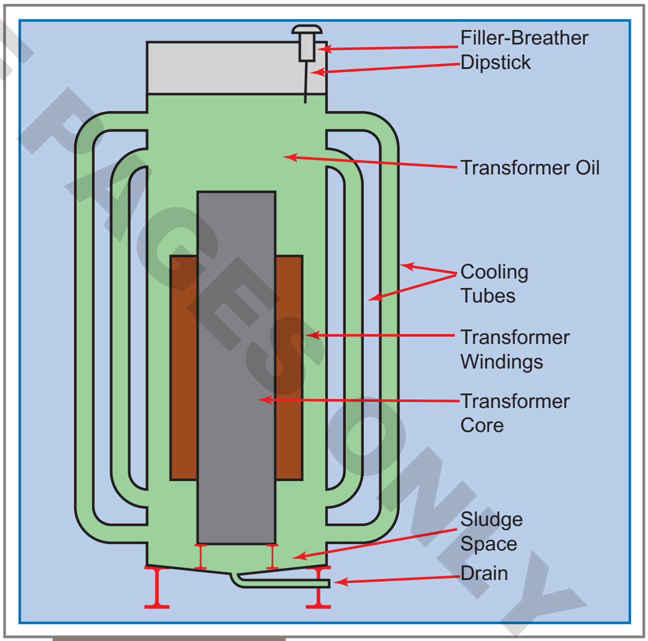


Figure 2.19 Transformer cooling

The oil serves the dual purpose of cooling and insulating. The oil conducts the heat from the core and the windings to the surface of the tank and the external

Figure 2.20 Transformer heat exchanger

tubes. The heat is then dissipated into the surrounding air, cooling the oil that circulates through the tank by means of natural convection.

For very large transformers, convection within the oil does not remove the heat quickly enough, so forced circulation methods are needed. The oil is drawn off at the top of the tank, pumped through a water-cooled heat exchanger and then returned to the bottom of the transformer tank. Figure 2.20 shows such a transformer.

2.6.3 TANK COLOURS

Polished metallic surfaces inhibit the removal of heat from transformer oil and casings. It has been found that colours such as low-sheen variations of black, green, or grey enable the oil to run at lower temperatures than would otherwise be the case. However, highly polished surfaces reflect the heat of the sun more than do the above colours so reflective shields are sometimes used to shade the transformer.

2.7 Winding polarities

It is sometimes necessary to operate two or more transformers in parallel and, to do so, not only must the output voltages be equal, but the instantaneous polarities must be the same.

2.7.1 SINGLE-PHASE TRANSFORMERS

Equal voltages

When two unequal voltage sources are connected in parallel, the phasor difference between the voltages causes a circulating current to be set up. The current flow is limited only by the impedances of the windings and will flow despite all other conditions for parallel operation being met.

Large quantities of heat are generated and the circulating current effectively renders both sources of power useless for any practical purposes.

Instantaneous polarities

The two transformers shown in Figure 2.21 have their primary windings wound in the same direction around the iron core. When the instantaneous polarity of line A is positive (indicated by the dot), the mutual flux Φ in each transformer acts in the same direction.

The secondary windings in Figure 2.21 are shown wound in opposite directions to each other. The induced voltage

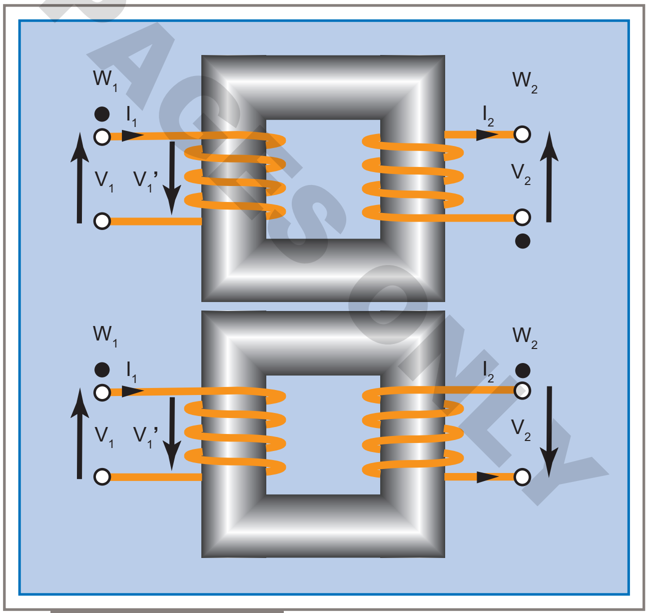


Figure 2.21 Winding polarity

V_2 acts in an upward direction in (a), while in (b) V_2 acts downward. In both cases the secondary flux Φ_2 must oppose the mutual flux (Lenz's law). This condition is met by the induced voltage acting downward in (b) and producing an instantaneous current flow as indicated by the arrows in both figures. That is, when an instantaneously positive voltage is applied to the primary terminals indicated by the dots, there will be an instantaneously positive voltage produced at the secondary terminals indicated by dots. In general terms the positioning of dots on winding ends is used to indicate the similar instantaneous polarities. For single-phase transformers to operate in parallel, their voltages must be equal and their instantaneous polarities must also be identical. The correct connections for two transformers in parallel are shown in Figure 2.22.

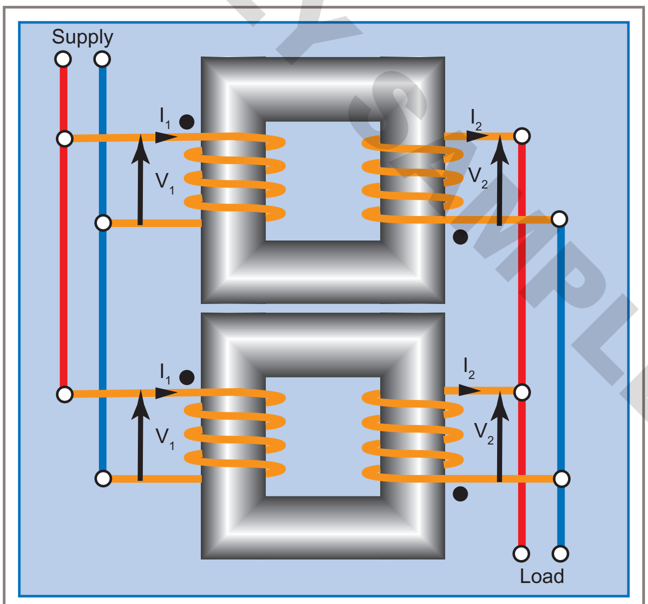


Figure 2.22 Correctly paralleled windings

If terminals of the wrong polarity are connected together, a high circulating current is set up in both primary and secondary windings. Effectively the two secondary windings are connected in series and then short-circuited. The path for the circulating current is shown in Figure 2.23 as a thicker line.

2.7.2 TERMINAL POLARITY IDENTIFICATION—SINGLE PHASE

When drawing sketches of transformers, the dot or a similar system of identification for winding ends is satisfactory. In practice it is more usual to be confronted with a transformer and a row of terminals, making some general system of identification necessary. Australian Standard AS 2374 sets out such a system for power transformers. In brief, all terminals are given an

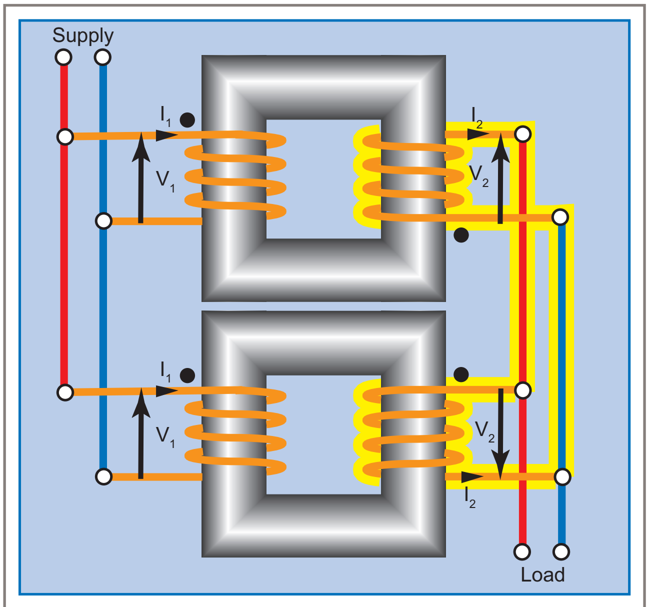


Figure 2.23 Circulating current fault

identifying letter and a subscript number—for the higher voltage winding, capital letters are used, and for the lower voltage winding, lower-case letters are used. Where more than one end of a winding is brought out to a terminal, the higher number is the line terminal unless a specific phase shift is required.

An example for a single-phase transformer is shown in Figure 2.24. The standard specifies that the identification be permanently marked on, or adjacent to, the terminals. Invariably this means stamping the identification into the metal of the terminal or the case adjacent to the terminal. In addition to this marking, supply authorities might require further markings on the transformer to assist them in installation or to match their phase sequence.

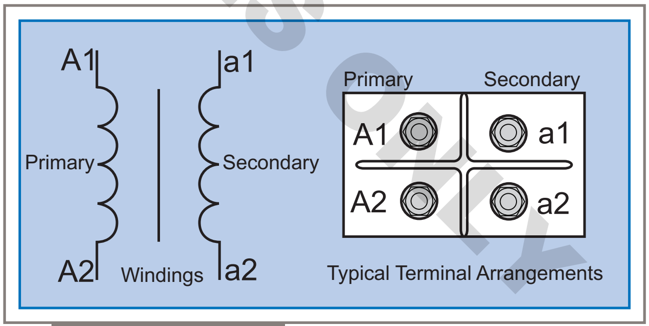


Figure 2.24 Typical terminal arrangements

2.7.3 THREE-PHASE TRANSFORMERS

A transformer can be used on a three-phase supply by using a three-legged core with primary and secondary

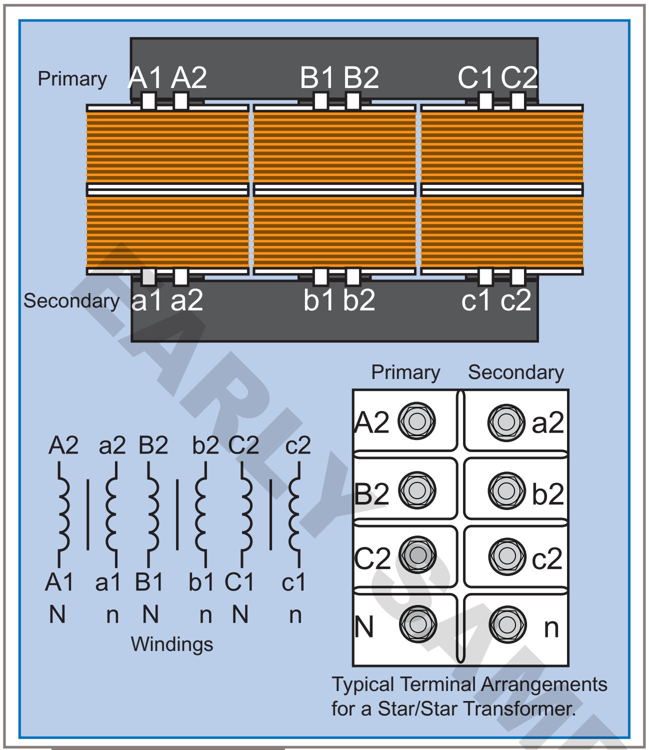


Figure 2.25 Three-phase Australian Standard 2374 markings

windings on each leg, as shown in Figure 2.25. The fluxes established in the windings are 120°E apart and their instantaneous sum will always be zero. Two of the fluxes will flow back through the third leg, in the same manner as the resultant current in any two lines of a three-phase system will flow back through the third line. Because the three windings are on a common core, the three-phase transformer is smaller and lighter than three separate transformers for the same VA rating.

2.7.4 TERMINAL POLARITY IDENTIFICATION–THREE PHASE

Standard AS/NZS 2374 sets out the same terminal arrangement and identification for both single- and three-phase transformers. There is now a greater variety of alternative connections available, so the system is necessarily more complicated than that for single-phase transformers. Capital letters with numerical subscripts are used for the higher voltage winding, with lower case for the lower voltage winding. The standard terminal arrangement is also shown for the transformer.

AS/NZS 2374 states that the terminal arrangement shall be in the order A, B, C from left to right when looking from the high-voltage side. When a neutral is fitted, its terminal shall be on the extreme left-hand side. It should be noted that supply authorities do not necessarily follow this standard. One supply authority uses the sequence b_2, n, c_2, a_2 in one situation and the sequence a_2, n, b_2, c_2 in another. There are valid reasons for persisting with a non-standard order and these vary from one authority to another.

2.7.5 THREE-PHASE TRANSFORMER CONNECTIONS

The four most common methods of connecting the primary and secondary windings are star–star, delta– delta, delta–star, and star–delta. A fifth connection sometimes used is called the zig-zag connection. It can be used in power transmission work although it may also be used for phase shifting or producing additional phases in industrial applications.

Figure 2.26 Delta connected transformer windings
Source: http://www.orinno-power.com/index.asp

The first four connections are shown in simple form in Figure 2.27. What cannot be readily shown in diagrams of this type is the phase shift introduced to the secondary voltages even when the primary voltages are in phase. The paralleling factors for different combinations of transformer connections are discussed in section 2.8.

The four main connections have the following phase shifts:

- star–star (YY)—no phase shift between primary and secondary
- delta–delta (ΔΔ)—no phase shift between primary and secondary
- delta–star (ΔY)—phase shift between line voltages. V_2 lags V_1 by 30°
- star–delta (YΔ)—phase shift between line voltages. V_2 leads V_1 by 30°.

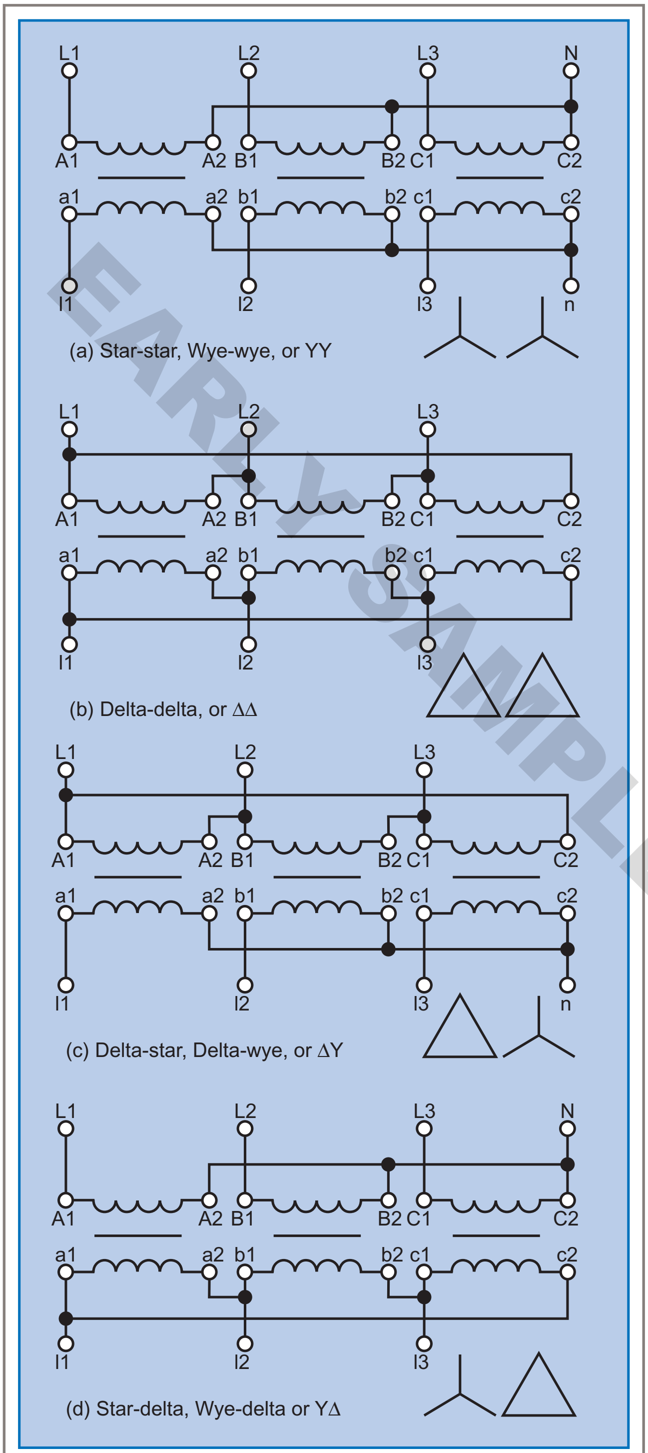


Figure 2.27 Most common transformer connections

Any of these connections can be used to suit applications and circumstances, but for distribution purposes the star–delta and delta–delta connection is used for step-up transformers and is best suited to moderate voltages. The star–delta connection has the added advantage of providing a grounding point on the primary for stability of the system and also for not introducing third harmonics.

Delta–delta connected transformers are not the best connection for very high-voltage transmission systems. The combination of delta–star step-up and star–delta step-down is undoubtedly the best for long-distance, very high-voltage systems. Grounded neutrals also help to make a stable system.

In general terms the voltages across the primary and secondary windings are in proportion to the turns ratios of the phase windings. The line voltages will be a function of the phase connections and will not always be equal to the phase voltages. For example, star-connected secondaries could have phase voltages of 100 V each and the line voltages would be 173 V. With a 2:1 turns ratio, the primary phase voltage would be 200 V and the supply source would be 200 V to a delta-connected primary or 346 V to a star-connected primary.

EXAMPLE 2.2

If a 400 V three-phase transformer has 200 turns per phase on the primary windings and 40 turns on the secondaries, find the output line voltage for each of the four main types of connection.

(a) *Star–star*

$$(\text{star}_1)\ V_L = 400\ \text{V}$$
$$\therefore V_P = 400/\sqrt{3} = 230\ \text{V}\ (= V_1)$$
$$\text{V}_1/\text{V}_2 = \text{N}_1/\text{N}_2 = 200/40$$
$$V_2 = \text{V}_1\text{N}_2/\text{N}_1 = 230 \times 40/200$$
$$= 46\ \text{V}\ (= V_P)$$
$$(\text{star}_2)\ V_L = \sqrt{3}V_P$$
$$= \sqrt{3} \times 46 = 80\ \text{V}$$

(b) *Delta–delta*

$$(\text{delta}_1)\ V_L = V_P = 400\ \text{V}\ (= V_1)$$
$$\text{V}_1/\text{V}_2 = \text{N}_1/\text{N}_2 = 200/40$$
$$V_2 = \text{V}_1\text{N}_2/\text{N}_1 = 400 \times 40/200$$
$$= 80\ \text{V}\ (= V_P)$$
$$(\text{delta}_2)\ V_L = V_P$$
$$= 80\ \text{V}$$

(c) *Delta–star*

$$(\text{delta}_1)\ V_L = V_P = 400\ \text{V}\ (= V_1)$$
$$V_2 = \text{V}_1\text{N}_2/\text{N}_1 = 400 \times 40/200$$
$$= 80\ \text{V}\ (= V_P)$$
$$(\text{star}_2)\ V_L = \sqrt{3}V_P$$
$$= \sqrt{3} \times 80 = 139\ \text{V}$$

(d) *Star–delta*

$$(\text{star}_1)\ V_L = 400\ \text{V}$$
$$\therefore V_P = 400/\sqrt{3} = 230\ \text{V}\ (= V_1)$$
$$V_2 = \text{V}_1\text{N}_2/\text{N}_1 = 230 \times 40/200$$
$$= 46\ \text{V}\ (= V_P)$$
$$(\text{delta}_2)\ V_L = V_P = 46\ \text{V}$$

2.7.6 THREE-PHASE TERTIARY WINDINGS

For reasons best understood by engineers, a transformer supplied with a sinusoidal waveform voltage will take a magnetising current having a proportion of third-harmonic current due to non-linearity of the magnetising characteristics of the iron core. Unless steps are taken to minimise or neutralise this component, there will be a portion of induced voltage and current flowing at a frequency three times that of the fundamental. Where there is a path from the transmission system neutral back to the alternator, the effect is minimised or even cancelled.

In the absence of a primary neutral path, the flux wave in the transformer becomes distorted and the third-harmonic effect is transmitted through to the secondary and then to the transmission line. With standard 50 Hz line frequencies there is a proportion of 150 Hz current circulating as well as 50 Hz. This leads to electrical interference and poor voltage regulation.

With delta-connected primary windings, the third harmonics are less of a problem in transmission transformers because the delta connection tends to suppress them.

Therefore the third-harmonic currents can be suppressed by introducing a third (tertiary) winding to each phase of the transformer connected in a delta configuration. Tertiary windings have no connected load, their only purpose being the suppression of the third harmonics.

2.7.7 CHANGING TRANSFORMER RATIOS

With long-distance transmission lines the characteristics of the line affect the voltage at the delivery end of the line. The conductors have an inherent capacitance between them and there is an inductive effect due to the length of the parallel conductors. Each conductor also has a fixed value of resistance.

At light loads with little or no current flow, resistance and inductance are not a problem; the capacitance effect between lines is the dominant characteristic. The result is a leading power factor on the line and a delivery voltage that might be higher than the source voltage.

With heavily loaded lines, the voltage drop due to the line resistance and inductance increases in proportion to the current. While the line capacitance effect still remains constant, there is now a magnetic coupling effect due to the magnetic field surrounding the conductors. The inductive effect increases and so does the voltage drop. These effects result in a reduced voltage at the load end of the line and at a lagging power factor.

Synchronous capacitors can be used to correct the power factor and so correct the line voltage, but the more usual and cheaper way is to vary the line voltage with transformer tap changers at the source of the supply.

Tap changers are installed in situations where they can compensate for variations in voltage. A rising or falling voltage at the load end of the line can be corrected by the action of a tap changer at the supply end. There are two possible ways of doing this—off load and on load.

Off-load tap changing

The off-load tap-changing method merely involves disconnecting the transformer from the supply, adjusting the turns ratio, and then reconnecting the transformer to the supply. The tap changing can be done only after disconnecting the transformer from the supply. To facilitate the changeover, there are usually built-in switches and the task only involves turning a handle or operating a lever. It always causes an interruption to the supply, unless there is a second transformer available, which must be connected to the supply before the first one is removed.

On-load tap changing

When it is necessary that a transformer provide a constant voltage into a supply system, a means must be found to alter the transformer ratio while the transformer is still on line, so ensuring that there is no interruption to the supply.

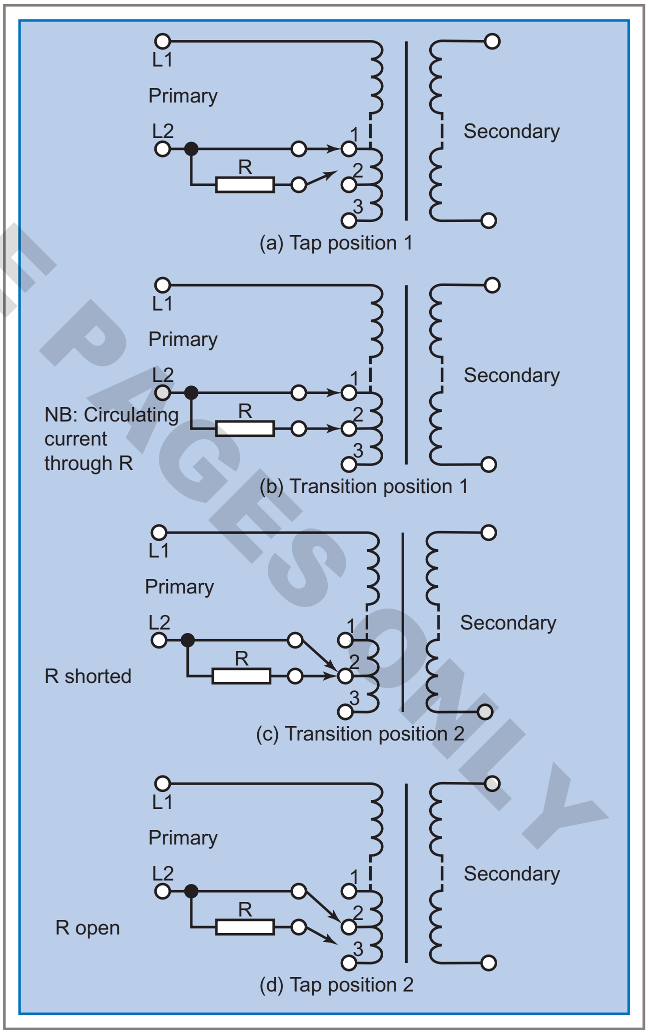


Figure 2.28 On-load tap changing

On-load tap changing is more convenient to consumers and suppliers alike and the procedure lends itself to automatic operation so that line voltages can be regulated without manual intervention.

On-load tap changing is illustrated in Figure 2.28 for only one phase. In a three-phase system there must obviously be three such systems, all operating simultaneously.

For clarity, the primary winding is shown in two sections. Three taps only are shown at the other end of the primary winding and the selected transformer tap is connected to the other line through a dual switching mechanism.

In Figure 2.28(a), one of the supply lines is connected to tap 1. The other part of the switching mechanism is open circuit.

In Figure 2.28(b), tap changing has been initiated. The second part of the switch has connected the low value resistor R to tap 2. The potential difference between taps 1 and 2 causes a circulating current to flow through the resistor.

In Figure 2.28(c), the switching mechanism has been connected to tap 2. Resistor R has been shorted out.

In Figure 2.28(d), the resistor R has again been isolated by the switching mechanism. The supply to the transmission lines has not been interrupted, yet the input to the transformer has been shifted to another tap.

Resistor tap changers are lighter, cheaper and more compact than the previously used centre-tapped inductor changeover mechanisms. The transition process takes only a few cycles and is commenced by releasing the energy stored in a spring under tension.

2.8 Parallel connection of transformers

2.8.1 TRANSFORMER COMPATIBILITY

When connecting three-phase transformers in parallel, the two transformers should have the same transformation ratio, phase sequence, and internal phase shifts. The two transformers are assumed to have their primary windings connected to the same supply.

Care must be taken to ensure that the transformers have compatible internal impedances or their load sharing will change over the load range and one may 'hog' the load causing it to overheat even though their combined load capacity has not been exceeded.

2.8.2 PHASE SHIFTS

In a transformer connected in delta primary and star secondary (delta–star), the secondary voltage is induced such that it lags the applied voltage by 30°E. In the case of star–delta the induced secondary voltage leads the applied voltage by 30°E. Because of the phase shifts, these two transformers must not be connected in parallel since the secondary voltages are out of phase with each other by a total of 60°E. Only transformers with the same phase shift should be paralleled.

2.8.3 PARALLELING REQUIREMENTS

Equal voltages

If two unequal voltage sources are connected in parallel, a circulating current is set up between the two sources. One transformer becomes a burden on the other and they are unable to supply full power to an external load. Essentially for the same style of connection, the turns ratios must be the same.

Same phase sequence

If different phase sequences are connected in parallel, the least that can occur is a short-circuit between the lines. Heavy circulating currents flow and damage will almost certainly occur to both transformers and perhaps the installation.

Phase angle shift

The change in phase angle from primary to secondary on both transformers must be identical, or once again dangerous circulating currents will be generated.

Satisfactory parallel operation can occur only when the two transformers belong to the same group and have the same phase shift.

Compatible internal impedance

The two transformers must have a compatible range of internal impedance to allow effective load sharing across the load range. Parallel operation involves two or more transformers connected to a common source of supply, and their secondaries connected to a common load. Only when the two transformers match in all important characteristics can they be expected to share the load evenly, or according to design.

2.8.4 PHASING TRANSFORMER WINDINGS

Single-phase transformers

To determine the polarities of transformer windings, one terminal of each winding are connected together, as shown in Figure 2.29. If the voltmeter reading across the other

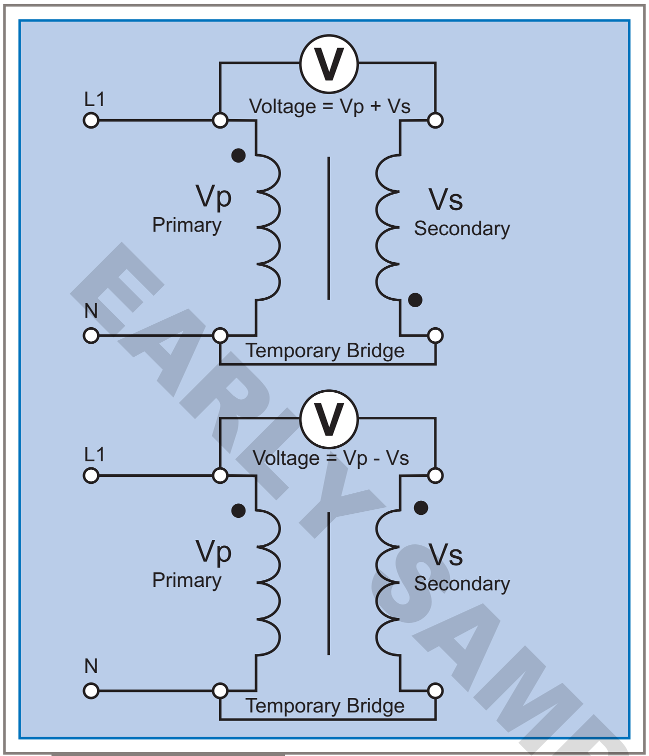


Figure 2.29 Determining phasing

two connections is greater than the supply voltage, the two voltages are aiding each other and the transformer is said to have dissimilar ends joined. Therefore the 'open end' of the primary is marked as the 'start' of the primary, and the joined end of the secondary is also marked as a 'start' end.

If the voltmeter reads less than the supply voltage, then the voltages are opposing each other and the windings have similar ends bridged in which case both 'open ends' should be marked as 'starts' signified by a 'dot' (•).

Three-phase transformers

The same method can be applied to the windings of a three-phase motor or transformer. It must be remembered however, that these windings are 120˚E apart and that the induced voltages must be at the same 120˚E in the same sequential order.

As the transformer has three legs, each with a separate primary and secondary winding, and perhaps several secondaries, great care must be taken to ensure that only the cores of each phase are tested against one another.

2.8.5 TESTING FINAL CONNECTIONS

Transformer connections should always be checked before loading. Serious damage can be caused by an improperly connected transformer and operators risk injury or electric shock.

Star

Transformer secondaries connected in star configuration have three line connections and a fourth for the neutral. All voltages should be tested without load applied. Each phase voltage should be tested between line and neutral. A-N, B-N, & C-N. All voltages should be equal and meet the nameplate specifications.

The three line voltages should also be tested: A-B, B-C and C-A. These should all be identical and 1.73 times greater than the phase voltages. A reversed phase winding will be indicated if two of the line voltages being equal to the phase voltages.

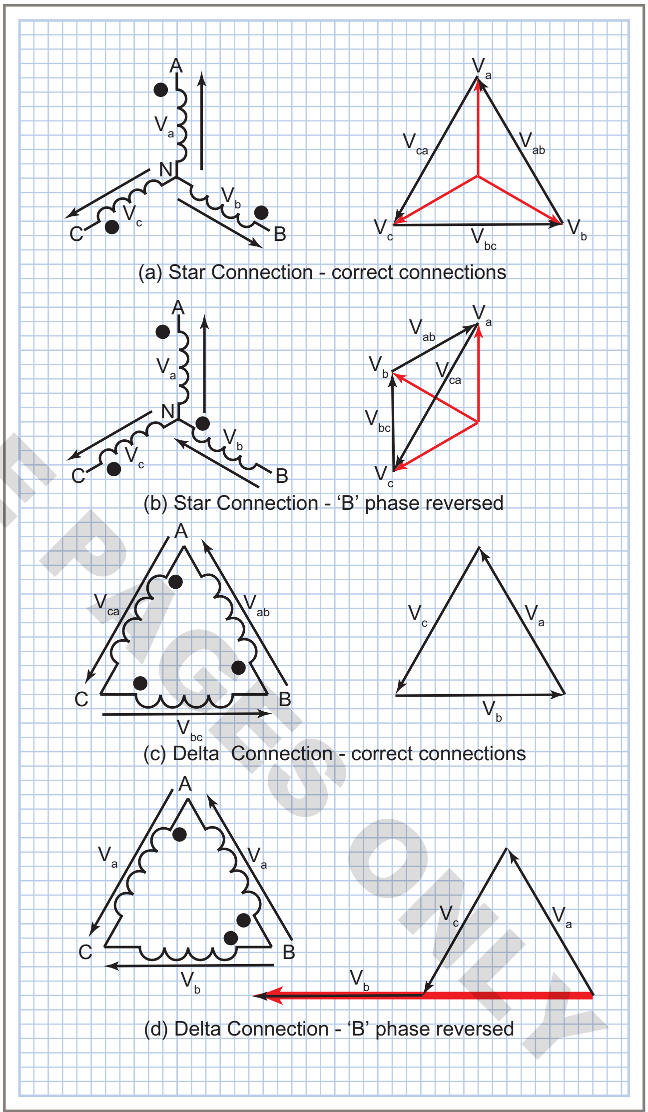


Figure 2.30 Testing secondary connections

Delta

Delta connected transformer secondaries should be tested by leaving one of the three bridges open and connecting a voltmeter in place of the bridge. If the connections are correct, the voltmeter will indicate zero voltage (or very small voltage).

If the voltmeter reads about double the expected line voltage, one of the windings has been reversed, requiring all connections to be rechecked. If the Delta was complete in such a condition, a high current would circulate.

2.8.6 OPEN-DELTA CONNECTION

The open delta is an asymmetrical connection for three phases. It is seldom used other than for small loads, or in an emergency when one phase winding of a three-phase transformer has failed. The connections are shown in Figure 2.31. It is a method for providing a three-phase supply from two transformers. It can also be used to provide two single-phase supplies for small consumers. Due to the unbalanced and out-of-phase currents, a transformer is reduced to 58 per cent of its normal capacity when working in open-delta connection and therefore the connection is only suitable for small loads or emergencies, or sometimes for short duration tasks such as for autotransformer starting of three-phase motors. The transformer can be overloaded just for the starting period of the motor.

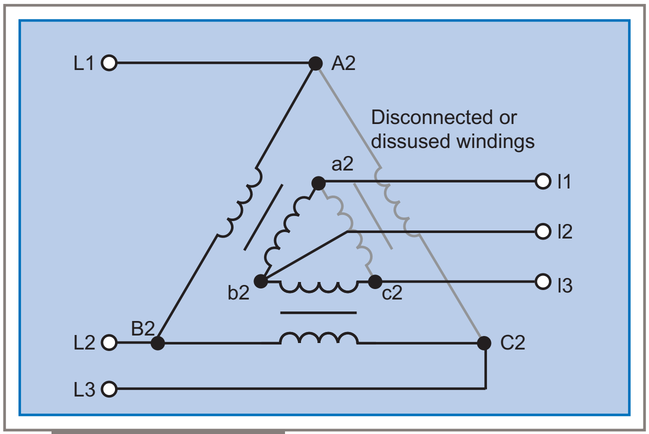


Figure 2.31 Open delta connection

2.9 Special transformers

2.9.1 INSTRUMENT TRANSFORMERS

It is unsafe to connect instruments and allied equipment to high voltage and current circuits, so instrument transformers are used to reduce these voltages and currents to safer, more convenient values. The two types of instrument transformers used are potential and current transformers.

Potential transformers (PT or VT)

The potential or voltage transformer operates on the same principle as the power transformer, where the ratio of the primary and secondary voltages is proportional to the turns ratio of the primary and secondary windings (i.e. $V_2 \propto V_1$). Potential transformers are designed to have a standard output voltage when the full rated voltage is applied to the primary windings. For single-phase work, AS/NZS 1243 specifies a secondary voltage of 110 V; where transformers are used in the star connection for control work in substations, the standard output voltage for each transformer is 63.5 V, giving a line-to-line voltage of 110 V.

The secondary voltage is connected to the appropriate loads such as voltmeters, wattmeters and protection relays. The VA ratings of potential transformers are quite small as instruments require little energy to operate. One terminal of the secondary winding is often earthed as an added safety measure in the event of a breakdown in the insulation between primary and secondary windings. The Standard symbol for a PT is shown in Figure 2.32 and a typical PT transformer is shown in Figure 2.33.

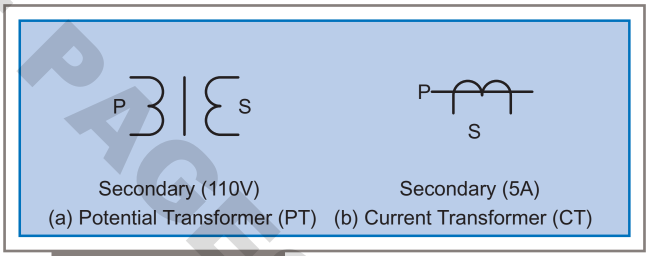


Figure 2.32 Potential and current transformer symbols

The physical features are similar to those of a power transformer except that the primary has to be insulated for a much higher voltage and is often immersed in oil for extra protection.

The important factor with potential transformers is the accuracy of the voltage ratio and the elimination of phase-angle errors. The energy levels being measured are generally large and therefore losses in the transformer are inconsequential compared to the power levels. A phase angle of 0°E is desirable, and or 180°E is acceptable also, particularly where a PT has to supply such instruments as wattmeters, which have more than one operating coil.

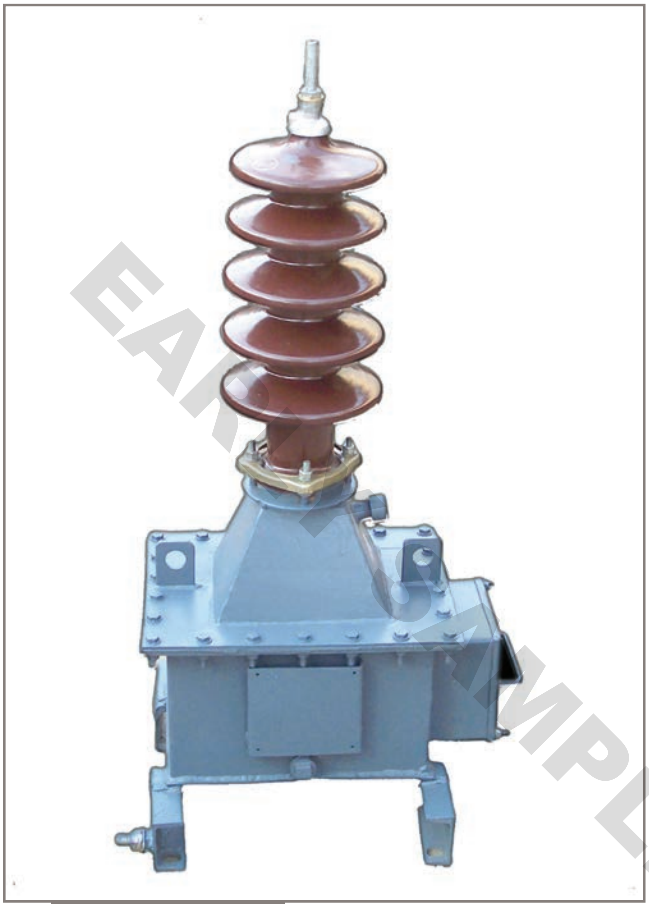


Figure 2.33 Potential transformer
Source: Transdelta Transformers Pvt. Ltd., India

As a general guide, a potential transformer usually operates at low flux densities in iron cores of relatively large cross-sectional areas. The copper conductors have few turns and are large in cross-section for the small current taken.

The Standard symbol for a PT is shown in Figure 2.32 and its connections in a test circuit are shown in Figure 2.33. The four terminals of a PT are designated, and care must be taken to see they are correctly connected and the two voltage systems appropriately isolated.

Potential Transformer Burden

A PT is also assigned a load or burden rating. This gives an indication of the available full-load secondary current and also the load placed on the supply source. For example, a 200 VA potential transformer at 110 V would make available approximately 1.8 A of secondary current for meters and relays:

$$110 \text{ V} \times 1.8 \text{ A} = 200 \text{ VA}$$

Current transformers (CT)

In a power transformer, the flux density in the core is high, the primary current depends largely on the secondary current, and the voltage ratio is the main consideration. However, for the current transformer the core flux density is very low, the secondary current is connected across a low impedance load and therefore depends directly on the primary current, and the current ratio is the main consideration.

The primary winding of a current transformer is connected in series with the load and consists of one or a few turns of a heavy gauge conductor, often a copper busbar. The impedance of the primary winding is therefore so low that the primary current I_1 is not affected by the secondary load, but depends on the external load connected in the primary circuit.

The secondary circuit consists of the current coils of ammeters, wattmeters, and protective relays that are all low impedance loads. The secondary circuit is always closed, so the secondary current produces a flux, which opposes the primary flux, greatly limiting the flux density of the core and therefore any load on the primary. The current ratio is equal to the inverse of the turns ratio and so there are more turns on the secondary winding.

If the secondary becomes open-circuited, there will be no secondary flux to oppose the primary flux, and so the core flux density increases. Owing to the large ratio of secondary to primary turns, and the excessive core flux, the induced voltage at the secondary terminals increases greatly, producing a safety hazard and the possibility of insulation breakdown.

The greater core flux might also cause excessive heat losses and saturation in the core. Consequently the secondary of a current transformer must never be open-circuited under any circumstances and a suitable short-circuiting link is normally provided for connection across the secondary terminals when the instruments are disconnected.

Note: The secondary of a current transformer must never be open-circuited under any circumstances.

Current transformers are made in a number of forms, depending on requirements and current ratios. Some types have primary windings that have more than one turn, while others are variations of the one-turn primary stage. One variation of the single-turn primary type has a short straight conductor passing through a hole in the iron core that forms part of the transformer's construction. Another type has an opening in the iron core and the transformer is slipped over the busbar or cable. Some current transformers have a secondary winding wound on a circular iron core, which is also slipped over the busbar adjacent to a circuit breaker or power transformer.

The standard for current transformers (AS/NZS 1675) specifies two values or current range—1 A and 5 A. The higher value is still used in many instances, but increasing use is being made of the lower value, especially in substation work where the instrumentation and control relays are some distance away from the transformers. At the lower value of current, the resistance and impedance of the cable is of relatively less importance.

Figure 2.34 Current transformer
Source: ABB Australia

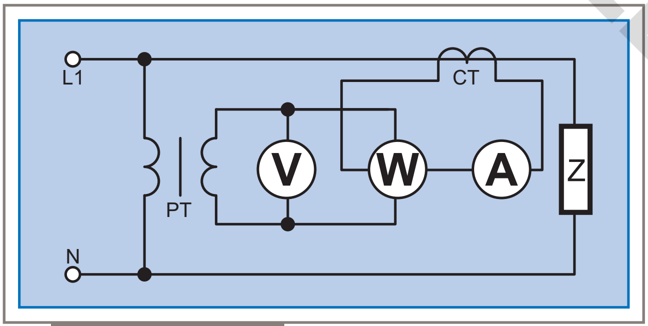


Figure 2.35 PT/CT power measurement

Current Transformer Burden

Current transformers are designed to measure line currents without affecting the load in any way. Consequently, while a CT might be able to handle high or low currents, the burden it imposes must be as low as possible (e.g. 5 VA). The CT must have a load on the secondary at all times, therefore the burden will exist at all times, causing a small voltage drop in the primary conductor at the point of the CT placement.

2.9.2 SAFE-WORKING PROCEDURES

Potential transformers

Potential transformers are designed to restrict the high voltage to a designated area and conduct a safe lower voltage to a monitoring point where it can be connected to instruments or relays. The secondary voltage should always be proportional to the primary voltage.

One of the secondary terminals is usually earthed and care must be taken in the choice of instruments and their handling to ensure that an additional earth is not introduced at some other point within the circuit. In some cases a non-magnetic, electrostatic shield is installed between the primary and secondary windings during manufacture. This is shield is earthed as a means of protection for the operator as well as removing electrostatic interference and noise. When connecting meters to a PT, a short-circuit across the terminals must be avoided as with any high-impedance device.

Current transformers

Current transformers are used to handle high currents while providing a proportional current to normal instruments on a.c. The CT isolates the supply voltage from the operator, and at the same time smaller conductors can be taken from the CT to the measuring location.

The secondary of a CT must never be open-circuited as to do so would allow high voltages at the terminals. With most CTs and associated instruments a shorting link is provided. Any connecting or disconnecting in CT circuits must follow a standard operating procedure that ensures the CT is not open-circuited at any stage.

An additional factor that should be taken into account is that an open circuit, apart from the high secondary voltage problem, can also lead to magnetic saturation occurring within the core that can affect the accuracy of the CT for future use.

Current transformers must have all the windings held firmly in place to withstand the magnetic forces created during overloads, current surges, and fault conditions. The secondaries often have one side of the winding earthed for protection and in some cases a non-magnetic screen between the windings.

2.9.3 TRANSFORMERS WITH MULTIPLE SECONDARIES

There are instances where more than one secondary voltage is desired. The choice is then one of having two or more transformers to obtain the voltages, or having one transformer with one primary winding and more than one secondary.

On occasion it could be mandatory from a safety point of view to have separate transformers, but it is common and cheaper to have one transformer with a slightly larger core and have as many secondaries as required. This is illustrated in Figure 2.36 where a transformer is shown with three secondary windings, each having different voltages. These extra windings may be called 'Tertiary' windings.

The current and voltage ratios as discussed in section 2.2 still hold true for the individual windings, but it should be

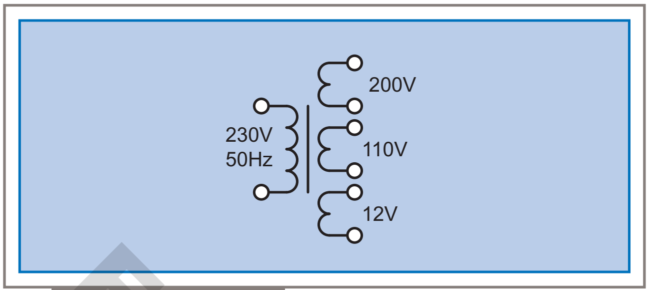


Figure 2.36 Tertiary winding transformer

kept in mind that the volt-ampere rating of the transformer will be the sum of the individual ratings of each winding. For example, to use the windings at ratings of 50 VA, 55 VA and 40 VA, the transformer as a whole would have to be rated at the sum of these figures, or 145 VA.

If due regard is given to phasing the windings, it is only one further step to connect all three windings in series and have a total voltage of 322 V. This procedure then produces a winding with taps brought out at various voltages.

2.9.4 TAPPED WINDINGS

Particularly for smaller transformers, it is common to see primary and secondary windings with tappings brought out to give a range of voltages from a common point. This method of obtaining various voltages is shown in Figure 2.37. It is also a variation of the autotransformer method that is discussed in section 2.9.5.

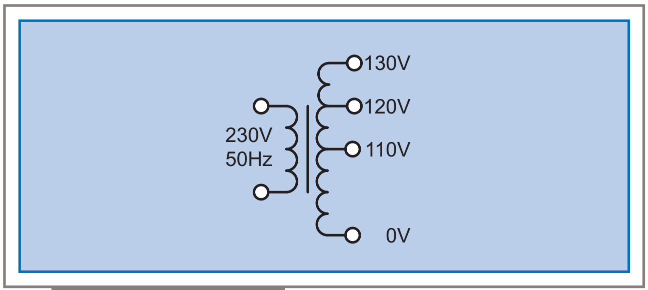


Figure 2.37 Tapped windings

While the taps are shown here on the secondary windings, it must be appreciated that the method is not restricted to secondary windings. It also quite common to have tapped primary windings, sometimes reflecting a range of acceptable primary supply voltages such as 220/230/240 volts.

Once the 'turns per volt' ratio of a transformer is established it is a straightforward matter of calculating the required number of turns to determine the location of a voltage tap on the winding.

A 'rule of thumb' commonly used in winding rooms during my apprenticeship stated 7 turns per volt per square inch of iron, referring to the cross-sectional area of the laminations in the window in the coil. Using that rule of thumb, winding rooms could convert an existing transformer to a new voltage secondary. Note that the Rule of Thumb related to common laminations of the day and modern materials will probably allow lower numbers of turns.

Remember the volt-ampere rating of the transformer has to be observed so converting a 24 volt transformer to a 12 volt transformer will allow for twice the current output assuming the winding conductor is an appropriate CSA.

2.9.5 AUTOTRANSFORMERS

An autotransformer has a part of the winding common to both the primary and the secondary circuits, as shown in Figure 2.38.

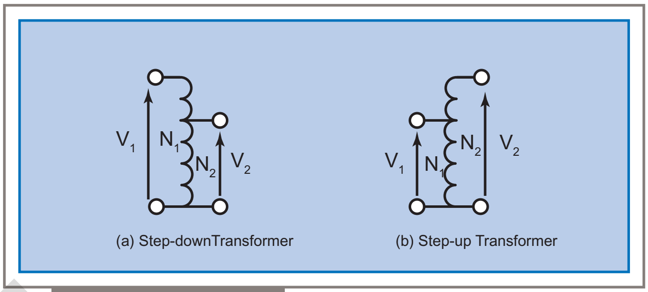


Figure 2.38 Autotransformers

The voltage across any number of turns is proportional to the turns per volt established into the primary winding. Therefore, for simplicity, assume a certain transformer has one volt per turn, and is connected across a 230 volt supply. It would require 230 turns. If however it was intended to also provide the correct output voltage at either 220 volts or 240 volts, there might be a tapping at 220 turns and another at 240 turns.

Autotransformers, like other transformers, may be a step-up or step-down type meaning the secondary may be a higher, or lower voltage than the primary voltage.

If a voltmeter were placed between the common (neutral) terminal and each of the tappings in turn, the meter would read 220 volts, 230 volts and 240 volts respectively. A load connected to one of the terminals would be provided with that voltage and a current allowed by the VA rating of the transformer. In this way a device designed to operate on 240 volts could be supplied from a 230 volts supply (or 220 V, or 240 V) simply by selecting the appropriate tapping of the primary winding. Autotransformers are usually considered not to have a secondary winding but the output may be referred to as secondary, and indeed there may be a secondary or even tertiary winding included.

Standard AS/NZS 3000 indicates the limitations placed on the use of autotransformers for general use. In general, the rules stipulate that except in special circumstances the secondary voltage should not vary by more than ±25 per cent of the primary voltage.

2.9.6 VARIAC TRANSFORMERS

Extending from the concept of an autotransformer, a transformer could have a tapping on every turn, making the range of output voltage almost continuous. A ‘Variac’ is a common trade name for a transformer which is an autotransformer having a toroidal winding with an exposed side, cleaned of insulation so a moving ‘wiper’ can be adjusted along the winding, thus making an apparently continuously variable voltage. In fact the voltage would only vary in steps according to the volts per turn if the wiper didn’t cover more than one turn.

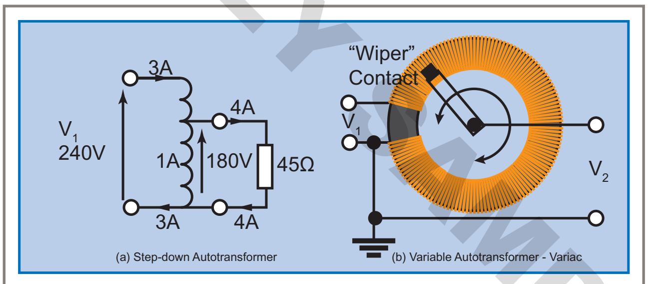


Figure 2.39 Variable voltage autotransformers

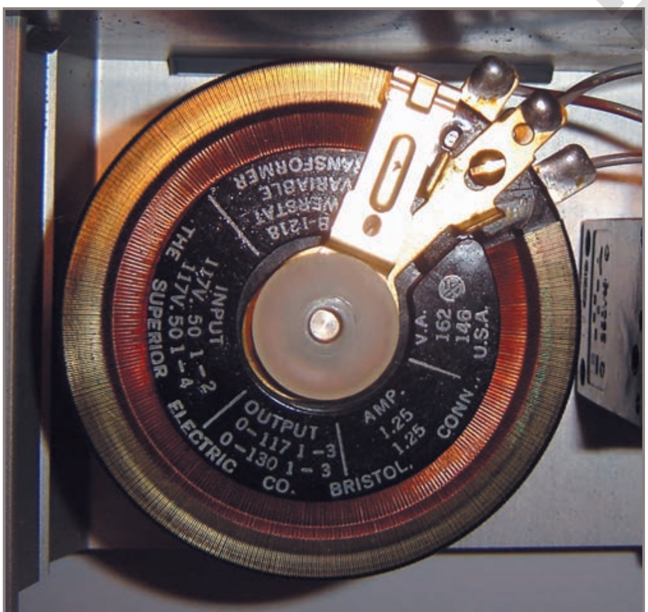


Figure 2.40 Variac style transformer

2.9.7 ISOLATION TRANSFORMERS

An Isolation Transformer is a type of transformer that has an equal number of turns on the primary and secondary windings. That means of course that the output voltage is equal to the supply voltage. Isolation transformers have two basic uses, one in providing isolation from the supply voltage so a machine that has a potential earth fault can be tested without dropping out the RCDs. Of course care must be taken when working in such environments.

Another purpose is in testing circuits with a reduced risk of fault current as the current is limited by the impedance and VA of the transformer.

Isolation transformers were once commonly used on worksites to operate power tools with a reduced risk of earth faults, and are still used in testing RCDs for compliance to the standards.

The theory of using isolation transformers is that the output is unrelated to earth and therefore an operator would need to make contact with both sides of the transformer to cause a shock situation.

2.9.8 HIGH-REACTANCE OR FLUX LEAKAGE TRANSFORMERS

When designing transformers, the highest possible efficiency is usually desired, and design features are incorporated to reduce the leakage flux. In some applications, however, transformers with poor efficiency may be deliberately designed to meet particular requirements. One such transformer, called a high-reactance or leakage transformer, produce a very high no-load voltage and a comparatively small short-circuit current.

The design is such as to permit a low flux leakage on no-load, but a high flux leakage on increasing load. This is achieved by spacing the primary and secondary windings some distance apart on the core, and by using either fixed or variable magnetic shunts (see Figure 2.41).

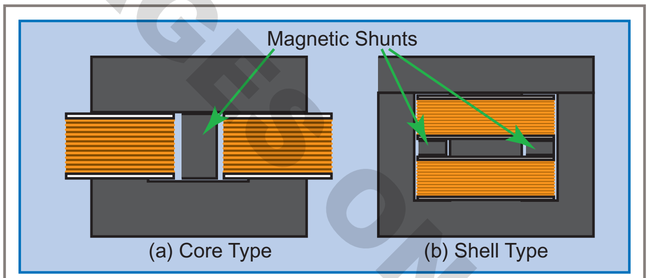


Figure 2.41 Flux leakage transformer

On no load, the primary winding produces a flux in the core which cuts the secondary winding, inducing a voltage in it. The leakage flux is reasonably low because the air gaps in the magnetic shunt circuits produce a reasonably high reluctance in the shunt circuits. The secondary voltage can be calculated using the usual transformation ratio.

When the transformer is loaded however, the secondary current produces a flux that opposes the primary flux, causing some of the primary flux to be diverted through the magnetic shunts, thus reducing the value of flux cutting the secondary turns. This reduces the value of secondary voltage at an increasing rate.

Figure 2.42 shows the secondary voltage decreasing as the load current increases. Transformers using this principle are found in such applications as furnace ignition, gaseous discharge lighting and welding machines.

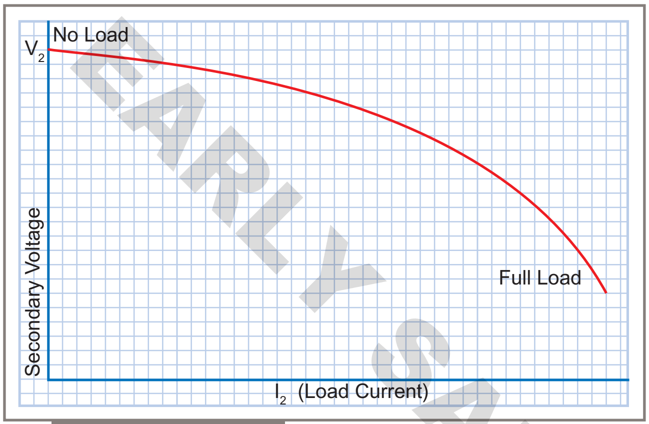


Figure 2.42 Flux leakage transformer load curves

Long narrow cores can achieve the same result as magnetic shunts, the length of the core governing the degree of leakage. Distribution transformers have a small leakage factor built into them as protection against excessive currents in the event of transmission line failures.

2.9.9 WELDING TRANSFORMERS

Welding transformers (that are not electronically controlled) generally used flux leakage or shunted flux techniques to control the amount of current delivered to the welding rod. Most cheap home welders and even many high power welders still use this basic technique.

Figure 2.43 shows the transformer of a typical home welder including the flux shunt which is adjustable for varying the welding current.

Figure 2.43 Flux shunt welding transformer

SUMMARY

- Transformers operate on the principle of mutual induction. Alternating current creates an alternating magnetic flux that cuts both windings and generates a self-induced voltage in the first or primary winding and a mutually-induced voltage in the second winding.
- The secondary voltage can be greater or less than the applied voltage, depending on the number of turns on the two windings.
- The Transformation ratios are:

  $V_1/V_2 = N_1/N_2 = I_2/I_1$
- Transformer losses are due to copper and iron losses and affect the above ratios in practical situations.
- Transformer efficiency = output / output + losses
- Voltage regulation = $V_{NL} - V_{FL} / V_{FL} \times 100\%$.
- Transformer cores can be shell type or core type for both single-phase and three-phase transformers.
- Cores are usually laminated with special grades of steel to reduce iron losses. Some smaller transformer cores may be made from powdered iron cores set in a medium to hold their shape.
- There is a growing trend to C-cores that are preformed from special grade steel and stress-relieved before use.
- Toroidal cores are a very efficient alternative to C-cores.

- Coil winding arrangements depend on the use to which the transformer is put. Windings may be tightly or loosely coupled.
- Transformer cooling is essential on larger transformers. It may be air or oil cooling. There are many variations and combinations of cooling methods. Even the colour of the tank holding the transformer has an effect on cooling.
- Winding polarity knowledge is necessary in order to connect transformer windings for paralleling purposes.
- Three-phase transformer connections can cause phase shifts in secondary voltages.
- Factors affecting parallel operation of transformers are: voltages, frequencies, instantaneous polarities, and phase relationships affected by connections.
- Commercial transformers have to conform to Australian and New Zealand standards as regards terminal-plate layouts.
- Transmission transformers may have a tertiary winding to suppress third harmonics in the system.
- In long-distance transmission lines it might become necessary to change transformer ratios while on line to maintain voltage levels.
- Two methods for changing ratios are off-line and on-line tap changing.
- Special purpose transformers comprise:
  - potential and current transformers
  - multiple secondaries
  - tapped secondaries
  - autotransformers
  - variable autotransformers
  - isolation transformers
  - high-reactance transformers.

QUESTIONS

Exercises

2.1 What is meant by the terms *primary* and *secondary* windings?

2.2 Explain the relationship between the voltages and number of turns of the two windings of a transformer.

2.3 Explain how a transformer regulates the amount of primary current required to supply a given secondary load.

2.4 What is meant by the term *leakage flux*, and how is it kept to a minimum?

2.5 What are the major losses in a transformer and how are they affected by the load?

2.6 Explain why the polarities of transformers must be known when the transformers are to be connected in parallel.

2.7 What are the four types of connection for three-phase transformers?

2.8 Using a diagram, show the method of connecting the instruments required to measure voltage, current and power in a high-voltage, high current a.c. circuit.

2.9 Describe the construction of a current transformer.

2.10 Compare the operation of a current transformer with that of a potential transformer.

2.11 Why is it necessary for the secondary of a current transformer to be kept closed?

2.12 What is an autotransformer? List the advantages and disadvantages of autotransformers.

2.13 Explain an application where an autotransformer might be used.

2.14 Australian Standards give a maximum percentage of over/under voltage for Autotransformers. State that percentage and explain why it is considered necessary.

2.15 What is a Variac? Explain an application where it might be used.

2.16 What is an Isolation transformer? Explain an application where it might be used.

2.17 What type of transformer is suitable for a gaseous lamp ballast? Explain why it is used.

2.18 Explain what a flux shunt is and how it effects the operation of a transformer.

2.19 How does a welding transformer restrict current flow after the arc is struck?

2.20 A 500 VA transformer supplied with a 32 V output is to be rewound to deliver 12 V.

(a) Will it be necessary to rewind the primary winding?

(b) How will the secondary need to be altered for the new voltage?

(c) What effect will the rewinding have on the iron losses of the transformer assuming the core is correctly disassembled and reassembled?

(d) What effect will the rewinding have on the copper losses of the transformer?

Calculations

2.1 The primary winding of a 400/24 V transformer has 400 turns. How many turns are there on the secondary winding?

2.2 A 100 kVA 11000 V/230 V transformer operates at 6 V per turn. Find the number of turns and current rating of each winding.

2.3 The 230/110 V transformer is connected to a 22 Ω resistive circuit. Calculate the primary current.

2.4 230 V is applied to the primary winding of a transformer having 100 turns. If the secondary has 900 turns, calculate the secondary voltage.

2.5 Three single-phase transformers with a transformation ratio of 20:1 are connected to an 11000 V three-phase supply as step-down transformers. Calculate the secondary line voltage and phase difference if the transformers are connected in:

(a) star–star

(b) star–delta

(c) delta–delta

(d) delta–star.

2.6 Tests on a transformer rated at 19 kV to 480 V at 50 Hz establish:

(a) open-circuit test—iron losses = 586 W

(b) short-circuit test—copper losses = 600 W

If the transformer supplies a resistive load of 9.6 Ω, calculate the efficiency of the transformer.

2.7 An autotransformer is used to boost the voltage on a 7700 V feeder to 8000 V. If the load on the secondary is 72 kW at unity power factor, find:

(a) the secondary or output current

(b) the primary or input current

(c) the current in the common section of the winding.

Neglect all losses.

2.8 A 240/115 V single-phase transformer has 960 turns on its primary winding. Calculate the number of turns required on the secondary winding.

2.9 The load on the secondary of a 240/32 V single-phase transformer is 3 A. Calculate the primary current if the transformer efficiency is 75 per cent.

2.10 A 240 V 50 Hz single-phase transformer has a core area of 25 cm^2. If it is to work at a maximum flux density of 1.1 T, find the number of turns required for the primary winding.

2.11 The maximum flux of a 50 Hz transformer is 0.001 Wb. If the primary is wound with 1080 turns, find the applied primary voltage and then calculate the number of turns required for a 15 V secondary.

2.12 A voltmeter, ammeter and wattmeter are connected to a single-phase circuit, by means of the appropriate instrument transformers, and the following results are obtained:

- CT ratio 100:5
- PT ratio 11000:110
- voltmeter reading 10 800 V
- ammeter reading 95 A
- wattmeter reading 872 kW.

Calculate the actual voltage, current, volt-amperes and power in the secondary circuit.

2.13 An 11 kV star–delta distribution transformer has 326 turns on each of its primary windings. Calculate the number of turns required on each secondary winding if the delta-connected secondary output is 6.6 kV.

2.14 An 11 kV step-up distribution transformer is connected in delta–star configuration. The delta-connected primary windings have 566 turns each. Ignoring losses, calculate the number of turns required on the star-connected secondary windings if its line output is 33 kV. Given an output current of 150 A at a power factor of 0.95 leading, calculate:

(a) primary line current

(b) primary phase current

(c) output power being delivered

(d) output rating in kVA.

ANSWERS

Each chapter will contain answers to the chapter questions.