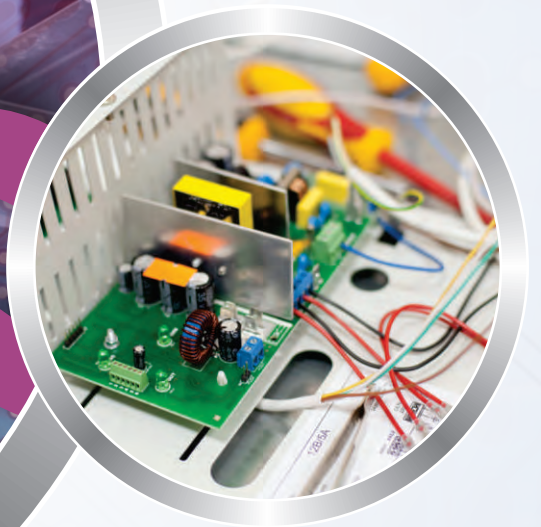


N5

Electrotechnics

Gateways to Engineering Studies



Gateways to Engineering Studies - John Dillon & Chris Brink



**HYBRID
LEARNING
SOLUTIONS**

Gateways to Engineering Studies

Electrotechnics
N5

John Dillon & Chris Brink

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Table of Contents

Module 1:

DC Machines	7
1.1 Introduction	7
1.2 DC motors	7
1.2.1 Brushed DC motors.....	7
1.2.2 Brushless DC motors.....	7
1.2.3 EMF generated.....	8
1.2.4 Speed developed by a DC motor.....	8
1.2.5 Torque and power for DC motors	8
1.3 Armature windings.....	9
1.3.1 Wave winding.....	9
1.3.2 Lap winding.....	9
1.3.3 Armature reaction	9
1.3.4 Effect of armature reaction	10
1.3.5 The adverse effects of armature reaction	10
1.3.6 To reduce armature reaction.....	11
1.3.7 Back EMF	12
1.4 Commutation.....	12
1.4.1 methods of improving commutation.....	12
1.4.2 Resistance method of improving commutation.....	13
1.4.3 EMF commutation	14
1.4.4 Brush shifting method.....	14
1.4.5 Inter-pole method	14
1.5 Starting conditions	15
1.5.1 Efficiency.....	15
1.5.2 starting torque	16
1.5.3 Starting of DC motor	16
1.5.4 Starting methods of a DC motor	17
1.5.5 Grading starting resistance.....	18
1.6 Wound stators	19
1.6.1 Series wound stators.....	19

1.6.2 Shunt wound stators.....	20
1.6.3 Compound wound stators.....	21
1.6.4 Methods of reversing the rotational direction of a DC motor.....	21
1.7 DC generators.....	23
1.7.1 Open circuit characteristic (OCC).....	25
1.7.2 Internal or total characteristic.....	26
1.7.3 External characteristic.....	26
1.7.4 Characteristics of DC shunt generator.....	27
1.7.5 Characteristics of DC series generator.....	28
1.7.6 Characteristics of DC compound generator.....	28
1.8 Welding machine.....	30
1.8.1 MMA.....	31
1.8.2 Polarity.....	31

Module 2:

AC Circuit Theory 41

2.1 Introduction.....	41
2.2 Single phase alternating current.....	41
2.2.1 Instantaneous values of current and power at different phase angles.....	41
2.2.2 Average and RMS values of current and power.....	43
2.2.3 Power factor.....	44
2.3 Phasors and complex numbers.....	50
2.3.1 Phasor addition.....	53
2.3.2 Phasor subtraction.....	54
2.3.3 Phasor diagram summary.....	55
2.4 Generating three-phase EMF.....	57
2.4.1 Three phase supply.....	57
2.4.2 Star / delta connections.....	59
2.4.3 Star connected system.....	60
2.4.4 Delta connected system.....	61
2.4.5 Power in a three-phase system.....	62

Module 3:

Transformers 71

3.1 Introduction.....	71
-----------------------	----

3.2 Construction of three-phase transformers	71
3.2.1 Uses of three-phase transformers	72
3.2.2 Construction of three-phase transformers	72
3.2.3 Operation of three-phase transformers.....	73
3.3 Welding machines	75
3.3.1 Power supply	75
3.3.2 Welding transformer leakage	75
3.3.3 Operation of three-phase welding machines.....	75
3.4 Useful flux and leakage	76
3.4.1 Inductive reactance.....	76
3.4.2 Resistance of a transformer	76
3.4.3 Leakage flux.....	77
3.4.4 Reducing inductive reactance	78
3.5 On load and off load.....	78
3.5.1 Transformer at no-load having no winding resistance and no leakage	78
3.5.2 Transformer at on-load having no winding resistance and no leakage	79
3.5.3 Transformer at on-load having winding resistance but no leakage.....	81
3.5.4 Transformer at on-load having winding resistance and leakage.....	82
3.5 Equivalent circuit of a transformer	83
3.5.1 Primary equivalent circuit.....	83
3.5.2 Approximate equivalent circuit.....	83
3.5.3 Equivalent circuit on secondary.....	84
3.6 Voltage regulation of a transformer	84
3.6.1 Voltage regulation of a transformer	85
3.6.2 Voltage regulation of a transformer for a lagging power factor	85
3.6.3 Voltage regulation of a transformer for a leading power factor	86
3.7 Transformers in parallel	86
3.7.1 Conditions of parallel operation	86
3.7.2 Load sharing.....	87
3.7.3 Tap changing	88
Module 4:	
AC Machines	99
4.1 Introduction	99

4.2 The alternator	99
4.2.1 Principle of operation	99
4.2.2 Synchronous speeds	101
4.2.3 Uses for the alternator	102
4.3 Alternators in parallel operation	103
4.4 Rotating field by a three-phase current	104
4.5 Reversal of rotating field	105
4.5.1 Hunting.....	106
4.5.2 Causes of hunting	107
4.5.3 Effects of hunting	107
4.5.4 Reduction of hunting.....	107
4.6 Synchronous motor	107
4.6.1 Introduction	107
4.6.2 Uses for synchronous motors.....	108
4.6.3 Construction	108
4.6.4 Starting up.....	110
4.7 Induction motor.....	110
4.7.1 Introduction	110
4.7.2 Construction	111
4.7.3 Construction of three-phase induction motor	111
4.7.4 Squirrel cage three phase induction motor.....	112
4.7.5 Slip ring or wound three phase induction motor	113
4.7.6 Slip	114
4.7.7 Starting up.....	115
Module 5:	
Generation and Supply of AC Power	126
5.1 Introduction	126
5.2 Losses in overhead lines	127
5.2.1 Resistance	127
5.2.2 Frequency effect	127
5.2.3 Temperature Effect	127
5.2.4 Current-Carrying Capacity	128
5.2.5 Inductance and Inductive Reactance.....	128

5.2.6 Bundle Conductor Effect.....	129
5.2.7 Inductance of a three-phase three-conductor line.....	130
5.2.8 Capacitance of a Three-Phase Line.....	130

Module 6:

Measuring Power in Balanced and Unbalanced Systems..... 138

6.1 Introduction	138
6.2 Measuring three-phase power by three Wattmeter method.....	138
6.3 Measuring three-phase power by two Wattmeter method.....	139
6.4 Measuring three-phase power by one Wattmeter method.....	140
6.5 Instrument transformers in a single-phase circuit	141

Module 7:

Switchgear and Protective Devices and Control..... 148

7.1 Introduction	148
7.2 Protective relays.....	148
7.2.1 Earth leakage relay.....	148
7.2.2 The attracted armature relay	149
7.2.3 The electromagnetic relay.....	150
7.2.4 Buchholz relay	150
7.3 High inductive circuits.....	152

Module 8:



















Installation and Care of Electrical Equipment 154

8.1 Introduction	154
8.2 Installation of a transformer.....	154
8.2.1 Site considerations.....	155
8.2.2 Final inspection and testing:.....	157
8.3 Care of equipment.....	158
8.3.1 Inspection of transformers	158
8.3.2 Maintenance of transformers.....	159
8.4 Materials used in electrical systems	160
8.4.1 Copper	160
8.4.2 Aluminium	161
8.4.3 Dielectric materials.....	162

Past Examination Papers..... 164

Icons used in this book

We use different icons to help you work with this book; these are shown in the table below.

Icon	Description	Icon	Description
	Assessment / Activity		Multimedia
	Checklist		Practical
	Demonstration/ observation		Presentation/ Lecture
	Did you know?		Read
	Example		Safety
	Experiment		Site visit
	Group work/ discussions, role-play, etc.		Take note of
	In the workplace		Theoretical – questions, reports, case studies, etc.
	Keywords		Think about it

Module 1

DC Machines

Learning Outcomes

On the completion of this module the student must be able to:

- Describe the uses of and characteristics of shunt, series and compound motors and generators and welding machines
- Describe speed control and grading of starting resistances
- Describe compensating windings and compound machines
- Calculate speed and starting torque back-EMF

1.1 Introduction



This module describes the characteristics of shunt, series and compound motors and generators and welding machines and gives examples of calculations involving their use.

1.2 DC motors

1.2.1 Brushed DC motors

The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary magnets, and rotating electrical magnets.

Advantages of a brushed DC motor include low initial cost, high reliability, and simple control of motor speed.

Disadvantages are high maintenance and low life-span for high intensity uses.



Note:

Maintenance involves regularly replacing the carbon brushes and springs which carry the electric current, as well as cleaning or replacing the commutator.

1.2.2 Brushless DC motors

Typical brushless DC motors use one or more permanent magnets in the rotor and electromagnets on the motor housing for the stator. A motor controller converts DC to AC.

Advantages of brushless motors include long life span, little or no maintenance, and high efficiency.

Disadvantages include high initial cost, and more complicated motor speed controllers.

1.2.3 EMF generated

Φ is the useful flux per pole

P is number of pole pairs

N is the speed

Z is the number of armature conductors

c is number of parallel paths between positive and negative brushes

$$\text{Number of conductors per path} = \frac{Z}{c}$$

$$\text{For a wave winding } c = 2$$

$$\text{For a lap winding } c = 2P$$

$$\text{Time taken to move past one pole pitch} = \frac{60}{2NP}$$

$$E = \frac{\Phi}{t}$$

$$\text{For one conductor } E = \frac{2NP\Phi}{60}$$

$$\text{Total } E = \frac{2ZNP\Phi}{60 \cdot c}$$

1.2.4 Speed developed by a DC motor

E is the voltage generated by the motor

EMF is the supply to the armature

R_a is the resistance of the armature circuit

$$\text{EMF generated by motor } E = EMF - (I \times R_a)$$

$$\text{For a lap connected armature } E = 2 \times \frac{\text{number conductors}}{c} \times \frac{Np}{60} \times \Phi_p$$

Where N is the speed in r/min

1.2.5 Torque and power for DC motors

Torque and power are calculated using:

$$\text{Mechanical power developed } P = \frac{2 \pi T N}{60} = EI_a$$

$$EI_a = 2 \frac{Z}{c} \times \frac{Np}{60} \times \phi \times I_a$$

For any motor, the number of poles, the number of conductors and p is fixed, so:

T is proportional to $I_a \times \phi$

1.3 Armature windings

Armature windings are mainly of two types – **lap winding** and wave winding. Here we are going to discuss about **lap winding**.


1.3.1 Wave winding

Wave winding is one type of armature winding. In this winding the end of one coil is connected to the starting of another coil of the same polarity as that of the first coil.

1.3.2 Lap winding

Lap winding is the winding in which successive coils overlap each other. It is named "Lap" winding because it doubles or laps back with its succeeding coils.

In this winding the finishing end of one coil is connected to one commutator segment and the starting end of the next coil situated under the same pole and connected with same commutator segment.

	<p>Definition: Lap winding</p> <p>Simplex lap winding A winding in which the number of parallel path between the brushes is equal to the number of poles is called simplex lap winding.</p> <p>Duplex lap winding is a winding in which the number of parallel path between the brushes is twice the number of poles is called duplex lap winding.</p>
---	---

1.3.3 Armature reaction

In a DC machine, two kinds of magnetic fluxes are present; 'armature flux' and 'main field flux'. The effect of armature flux on the main field flux is called as armature reaction.

EMF is induced in the armature conductors when they cut the magnetic field lines. But, there is an axis (or, you may say, a plane) along which armature conductors move parallel to the flux lines and, hence, they do not cut the flux lines at the moment.

MNA (Magnetic Neutral Axis) may be defined as the axis along which no EMF is generated in the armature conductors as they move parallel to the flux lines.

Brushes are always placed along MNA because reversal of current in the armature conductors takes place along this axis.



Definition: Geometrical Neutral Axis (GNA)

The axis which is perpendicular to the stator field axis.

1.3.4 Effect of armature reaction

Consider, no current is flowing in the armature conductors and only the field winding is energized (as shown in the first sketch **Figure 1.1**). In this case, magnetic flux lines due to the field poles are uniform and symmetrical to the polar axis. The 'Magnetic Neutral Axis' (MNA) coincides with the 'Geometric Neutral Axis' (GNA).

The second sketch in **Figure 1.1** shows armature flux lines due to the armature current.

Now, in case the machine is running, both the fluxes (flux due to the armature conductors and flux due to the field winding) will be present at a time. The armature flux superimposes with the main field flux and, hence, disturbs the main field flux (as shown in third sketch in **Figure 1.1**). This effect is called **armature reaction in DC machines**.

1.3.5 The adverse effects of armature reaction

Armature reaction weakens the main flux. In case of a DC generator, weakening of the main flux reduces the generated voltage.

Armature reaction distorts the main flux, hence the position of M.N.A. gets shifted (MNA is perpendicular to the flux lines of main field flux). Brushes should be placed on MNA, otherwise, it will lead to sparking at the surface of brushes. So, due to armature reaction, it is hard to determine the exact position of MNA.

For a loaded dc generator, MNA will be shifted in the direction of the rotation. On the other hand, for a loaded dc motor, MNA will be shifted in the direction opposite to that of the rotation.

The neutral axis will be turned to a new neutral axis because of this distortion of the magnetic flux. This angle that the axis turns is θ .

I is the total armature current

Z is the number of armature conductors

c is the number of parallel paths

p is the number of pairs of poles

$$\frac{\text{Current}}{\text{conductor}} = \frac{I}{c}$$


$$\frac{\text{Conductors}}{\text{poles}} = \frac{Z}{2p}$$

$$\text{Ampere} \times \text{conductors per pole} = \frac{I}{c} \times \frac{Z}{2p}$$

$$\text{Armature ampere turns per pole} = \frac{I}{2} \times \frac{I}{c} \times \frac{Z}{2p}$$

1.3.6 To reduce armature reaction

Usually, no special efforts are taken for small machines (up to few kilowatts) to reduce the armature reaction. But for large DC machines, compensating winding and inter-poles are used to get rid of the ill effects of armature reaction.



Note: Now we know that the armature reaction is due to the presence of armature flux. Armature flux is produced due to the current flowing in armature conductors.

Now, if we place another winding in close proximity of the armature winding and if it carries the same current but in the opposite direction as that of the armature current, then this will nullify the armature field.

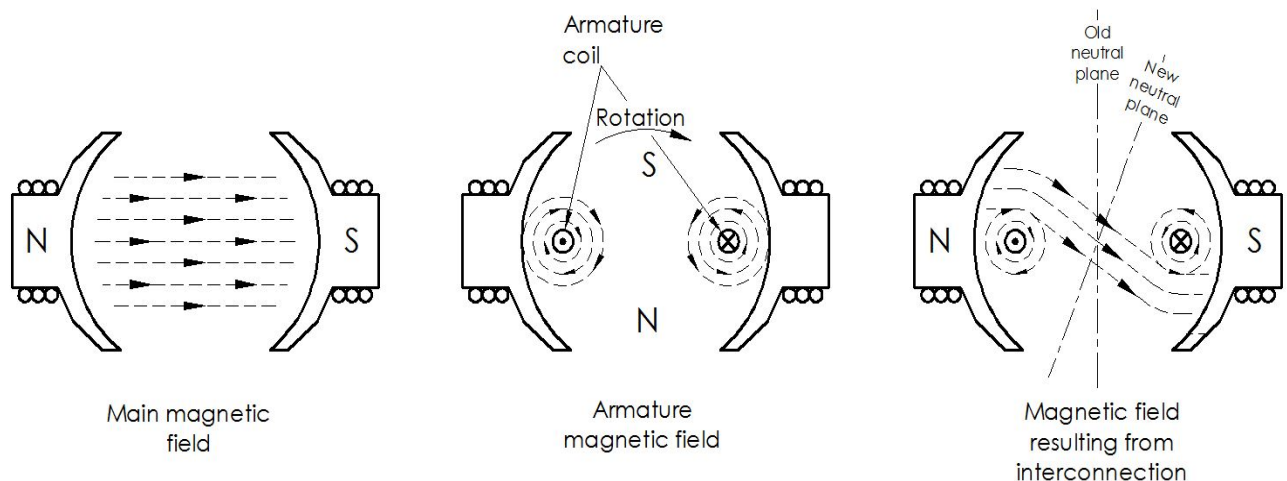


Figure 1.1 Armature reaction


Such an additional winding is called as **compensating winding** and it is placed on the pole faces. Compensating winding is connected in series with the armature winding in such a way that it carries the current in opposite direction.

Inter-poles are the small auxiliary poles placed between the main field poles. Winding on the inter-poles is connected in series with the armature. Each inter-pole is wound in such a way that its magnetic polarity is same as that of the main pole ahead of it. Inter-poles nullify the quadrature axis armature flux.

1.3.7 Back EMF

Since the armature windings of a direct-current or universal motor are moving through a magnetic field, they have a voltage induced in them. This voltage tends to oppose the motor supply voltage and so is called back EMF.

The voltage is proportional to the running speed of the motor. The back EMF of the motor, plus the voltage drop across the winding internal resistance and brushes, must equal the voltage at the brushes. This provides the fundamental mechanism of speed regulation in a DC motor.


	<p>Note: If the mechanical load increases, the motor slows down; a lower back-EMF results, and more current is drawn from the supply. This increased current provides the additional torque to balance the new load.</p>
---	---

L is the inductance induced

$$\text{Back EMF } e_L = L \frac{\Delta i}{\Delta t}$$

1.4 Commutation

The voltage generated in the armature, placed in a rotating magnetic field, of a DC generator is alternating in nature.

	<p>Note: The commutation in DC machine or more specifically commutation in DC generator is the process in which generated alternating current in the armature winding of a DC machine is converted into direct current after going through the commutator and the stationary brushes.</p>
---	--

1.4.1 methods of improving commutation

To make the commutation satisfactory we have to make sure that the current flowing through the coil completely reversed during the commutation period attains its full value.

There are two main **methods of improving commutation**.

These are:

- Resistance commutation
- EMF commutation

1.4.2 Resistance method of improving commutation

In this method of commutation, we use high electrical resistance brushes for getting spark less commutation. This can be obtained by replacing low resistance copper brushes with high resistance carbon brushes.

We can clearly see from **Figure 1.2** that the current I_C from the coil C may reach the brush in two ways in the commutation period. One path is direct through the commutator segment b and to the brush and the 2nd path is first through the short-circuit coil B and then through the commutator segment a and to the brush.

When the brush resistance is low, then the current I_C from coil C will follow the shortest path, i.e. the 1st path as its electrical resistance is comparatively low because it is shorter than the 2nd path.

When high resistance brushes are used, then as the brush moves towards the commutator segments, the contact area of the brush and the segment b decreases and contact area with the segment a increases.

Now, as the electrical resistance is inversely proportional to the contact area of then resistance R_b will increase and R_a will decrease as the brush moves. Then the current will prefer the 2nd path to reach to the brush.

Thus by this method of improving commutation, the quick reversal of current will occur in the desired direction.

$$\text{Resistance : } R = \rho \frac{l}{A}$$

ρ is the resistivity of the conductor. l is the length of the conductor. A is the cross-section of the conductor (here is this description it is used as contact area).

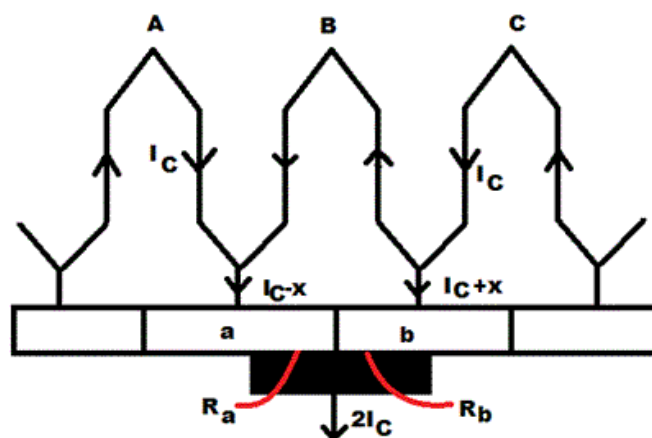


Figure 1.2 Commutation and the path to the brushes

1.4.3 EMF commutation

The main reason of the delay of the current reversing time in the short circuit coil during commutation period is the inductive property of the coil. In this type of commutation, the reactance voltage produced by the coil due to its inductive property, is neutralized by producing a reversing EMF in the short circuit coil during commutation period.


Reactance voltage:

The voltage rise in the short circuit coil due to inductive property of the coil, which opposes the current reversal in it during the commutation period, is called the reactance voltage. We can produce reversing EMF in two ways 1. By brush shifting. 2. By using inter-poles or commutating poles.

1.4.4 Brush shifting method

In this method of improving commutation the brushes are shifted forward direction for the DC generator and in backward direction for the motor for producing the sufficient reversing EMF for eliminating the reactance voltage.

When the brushes are given the forward or backward lead then it brings the short circuit coil under the influence of the next pole which is of the opposite polarity. Then the sides of the coil will cut the necessary flux from the main poles of opposite polarity for producing the sufficient reversing EMF.

	<p>Note: This method is rarely used because for best result, with every variation of load, the brushes have to be shifted.</p>
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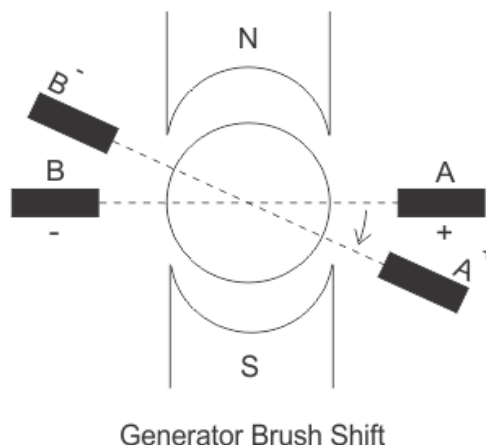


Figure 1.3 Generator brush shift

1.4.5 Inter-pole method

In this method of commutation some small poles are fixed to the yoke and placed between the main poles. These poles are called inter-poles. Their polarity is the same as the main poles situated next to it for the generator and for the motor the polarity is same as the main pole situated before it. The inter-

poles induce an EMF in the short circuit coil during the commutation period which opposes reactance voltage and give spark-less commutation.

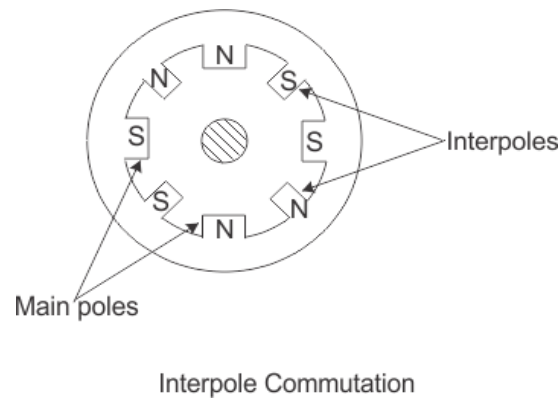


Figure 1.4



Worked Example 1.1

The current in a coil grows linearly from 0 to 10 A in 0.25 seconds. If the coil has an inductance of 0.75 H, find the induced back-EMF

Solution:

$$\text{Back EMF } e_L = L \frac{\Delta i}{\Delta t}$$

$$e_L = 0.75 \left(\frac{10 - 0}{0.25} \right) = 30 \text{ V}$$

1.5 Starting conditions

1.5.1 Efficiency

Motor losses are mainly due to resistive losses in windings, core losses and mechanical losses in bearings, and aerodynamic losses, particularly where cooling fans are present, also occur.

Losses also occur in commutation, mechanical commutators spark, and electronic commutators and also dissipate heat.

To calculate a motor's efficiency, the mechanical output power is divided by the electrical input power:

$$\eta = \frac{P_m}{P_e},$$

where η is energy conversion efficiency, P_e is electrical input power, and P_m is mechanical output power:

$$P_e = IV$$

$$P_m = T\omega$$

where V is input voltage, I is input current, T is output torque, and ω is output angular velocity. It is possible to derive analytically the point of maximum efficiency. It is typically at less than 1/2 the stall torque.

1.5.2 starting torque

It is obvious that a motor requires more torque to get it up to speed. So in order to accelerate from 0 r/sec to the required running speed an additional torque is required.



Note:

The way of supplying the armature circuit with reduced voltage that will create this increase in torque at start-up is to connect in series.

1.5.3 Starting of DC motor

A DC motor, unlike other types of motor has a very high starting current that has the potential of damaging the internal circuit of the armature winding of DC motor if not restricted to some limited value.



Note:

This limitation to the starting current of DC motor is brought about by means of the starter.

Thus the distinguishing fact about the starting methods of DC motor is that it is facilitated by means of a device containing a variable resistance connected in series to the armature winding so as to limit the starting current of DC motor to a desired optimum value taking into consideration the safety aspect of the motor.

Now the immediate question in why the DC motor has such high starting current ? To give an explanation to the above mentioned question let us take into consideration the basic operational voltage equation of the DC motor given by,

$$E = E_b + I_a R_a$$

Where E is the supply voltage, I_a is the armature current, R_a is the armature resistance. And the back-EMF is given by E_b . Now the back-EMF, in case of a DC motor, is very similar to the generated EMF of a DC generator as it's

produced by the rotational motion of the current carrying armature conductor in presence of the field. This back-EMF of a DC motor is given by:

$$E_b = \frac{P \cdot \phi \cdot Z \cdot N}{60A}$$

and has a major role to play in case of the starting of DC motor. From this equation we can see that E_b is directly proportional to the speed N of the motor. Now since at starting $N = 0$, E_b is also zero, and under this circumstance the voltage equation is modified to:

$$E = 0 + E_b R_a$$

$$\text{Therefore, } I_a = \frac{E}{R_a}$$

For all practical practices to obtain optimum operation of the motor the armature resistance is kept very small usually of the order of 0.5Ω and the bare minimum supply voltage being 220 volts.



Note:

Even under these circumstance the starting current, I_a is as high as $220/0.5 \text{ amp} = 440 \text{ amp}$.

Such high starting current of dc motor creates two major problems.

- Current of the order of 400 A has the potential of damaging the internal circuit of the armature winding of dc motor at the very onset.
- Since the torque equation of dc motor is given by

$$\text{Therefore, } I_a = \frac{E}{R_a}$$

Very high electromagnetic starting torque of DC motor is produced by virtue of the high starting current, which has the potential of producing huge centrifugal force capable of flying off the rotor winding from the slots.

1.5.4 Starting methods of a DC motor

As a direct consequence of the two above mentioned facts i.e high starting current and high starting torque of DC motor, the entire motoring system can undergo a total disarray and lead towards into an engineering massacre and non-functionality.

To prevent such an incidence from occurring several starting methods of dc motor has been adopted. The main principal of this being the addition of external electrical resistance R_{ext} to the armature winding, so as to increase the effective resistance to $R_a + R_{ext}$, thus limiting the armature current to the rated

value. The new value of starting armature current is desirably low and is given by.

$$\textit{Therefore, } I_a = \frac{E}{R_a + R_{ext}}$$

Now as the motor continues to run and gather speed, the back-EMF successively develops and increases, countering the supply voltage, resulting in the decrease of the networking voltage. Thus now,

$$\textit{Therefore, } I_a = \frac{E - E_b}{R_a + R_{ext}}$$

At this moment to maintain the armature current to its rated value, R_{ext} is progressively decreased unless its made zero, when the back EMF produced is at its maximum. This regulation of the external electrical resistance in case of the starting of dc motor is facilitated by means of the starter.

Starters can be of several types and requires a great deal of explanation and some intricate level understanding. But on a brief over-view the main types of starters used in the industry today can be illustrated as:

- 3-point starter
- 4-point starter



Note:

Used for the starting of shunt wound DC motor and compound wound DC motor.

All of these play a very significant role in limiting starting current of DC motor for proper starting and running of the DC motor, and are described vividly under their respective sub-headings.

All of these play a very significant role in limiting starting current of DC motor for proper starting and running of the DC motor, and are described vividly under their respective sub-headings.

1.5.5 Grading starting resistance

Figure 1.5 shows the current-time curves that grading the resistance is based on. Notching-up occurs when the current is at a minimum value I_2 and the maximum current on each notch is I_1 .

For a shunt circuit starter:

$$k = \sqrt[n]{\frac{R_1}{r_m}}$$

$$R_1 = \frac{\text{motor voltage}}{\text{max. current at starting}} = \frac{E_m}{I_s}$$

Armature resistance + interpole windings = r_m

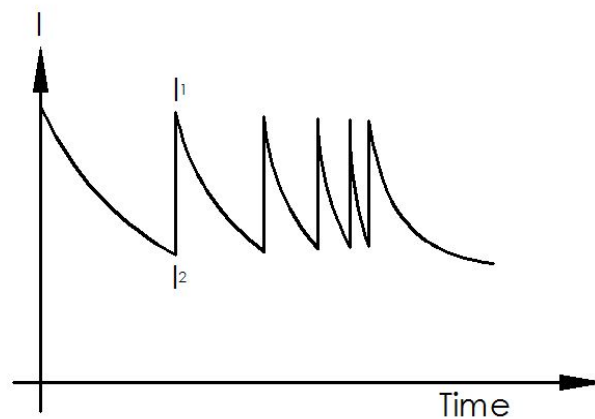


Figure 1.5 Current-time diagram

1.6 Wound stators

There are three types of electrical connections between the stator and rotor possible for DC electric motors: series, shunt/parallel and compound (various blends of series and shunt/parallel) and each has unique speed/torque characteristics appropriate for different loading torque profiles/signatures.

1.6.1 Series wound stators

A series DC motor connects the armature and field windings in series with a common DC power source.

The motor speed varies as a non-linear function of load torque and armature current. Current is common to both the stator and rotor yielding current squared behaviour.



Did you know?

A series motor has very high starting torque and is commonly used for starting high inertia loads, such as trains, elevators or hoists. This speed/torque characteristic is useful in applications such as dragline excavators, where the digging tool moves rapidly when unloaded but slowly when carrying a heavy load.

A series motor should never be started at no load. With no mechanical load on the series motor, the current is low, the counter-EMF produced by the field winding is weak, and so the armature must turn faster to produce sufficient

counter-EMF to balance the supply voltage. The motor can be damaged by over-speed. This is called a runaway condition.

Figure 1.6 shows a **series wound motor** in which the flux varies in proportion to the current and inversely proportional to the speed. Also shown are methods of reversing. See the speed characteristic curve **Figure 1.10 (a)**.

Series motors are used where the load does not deviate much. This is because if the load does fall, the speed may become dangerously high.

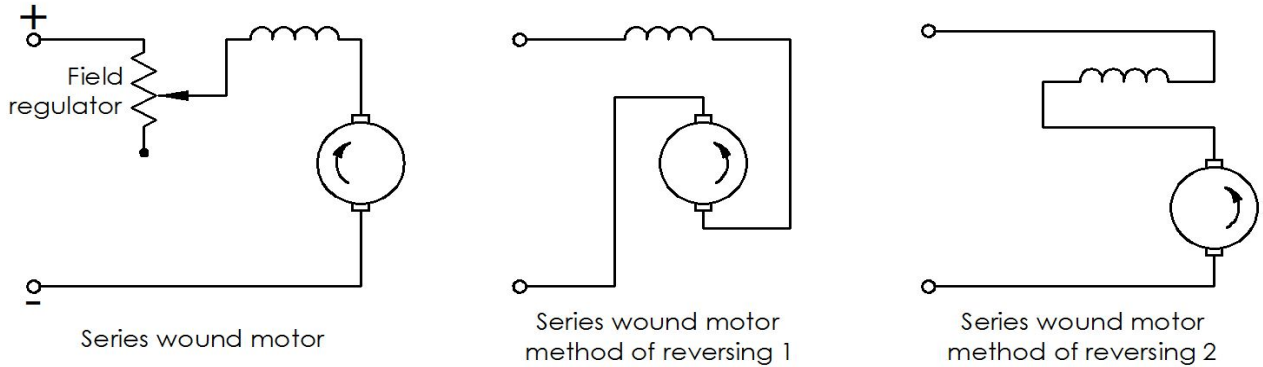


Figure 1.6 Series wound motor

1.6.2 Shunt wound stators

A shunt DC motor connects the armature and field windings in parallel or shunt with a common D.C. power source.

This type of motor has good speed regulation even as the load varies, but does not have the starting torque of a series DC motor. It is typically used for industrial, adjustable speed applications, such as machine tools, winding/unwinding machines and tensioners.

Figure 1.7 shows a **shunt wound motor** in which the flux is marginally affected by the armature current. Also shown are methods of reversing. See the speed characteristic curve in **Figure 1.10 (b)**.

Shunt motors are used where the speed must remain constant over a wide range of load deviation.

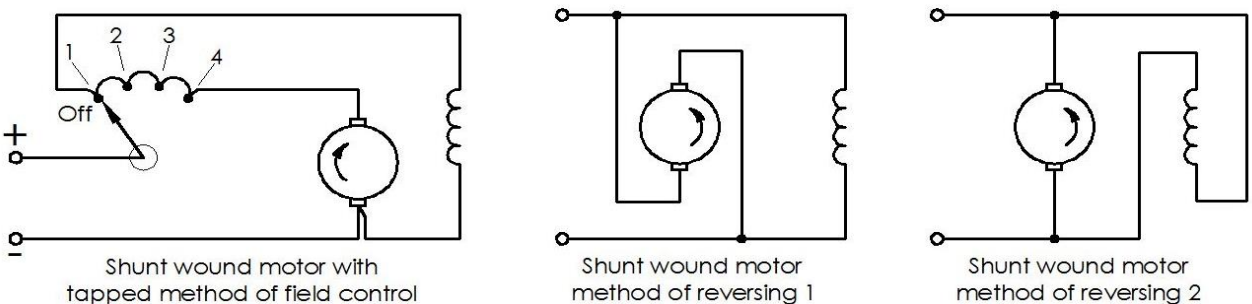


Figure 1.7 Shunt wound motor

1.6.3 Compound wound stators

A compound DC motor connects the armature and fields windings in a shunt and a series combination to give it characteristics of both a shunt and a series DC motor.



Note:

This motor is used when both a high starting torque and good speed regulation is needed.

Figure 1.8 shows a **compound wound motor** which has a combination of the series and shunt wound motors. See the speed characteristic curve in **Figure 1.10 (c)**.

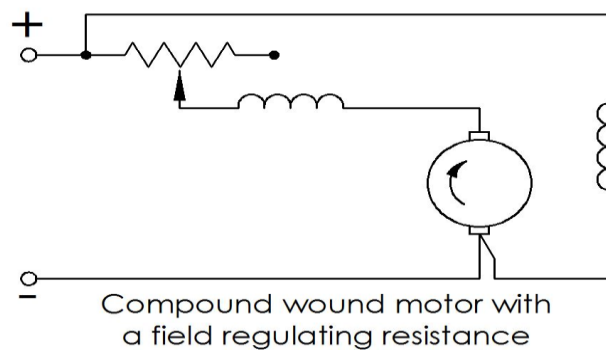


Figure 1.8

Figure 1.9 shows a **compound wound motor** with methods of reversing.

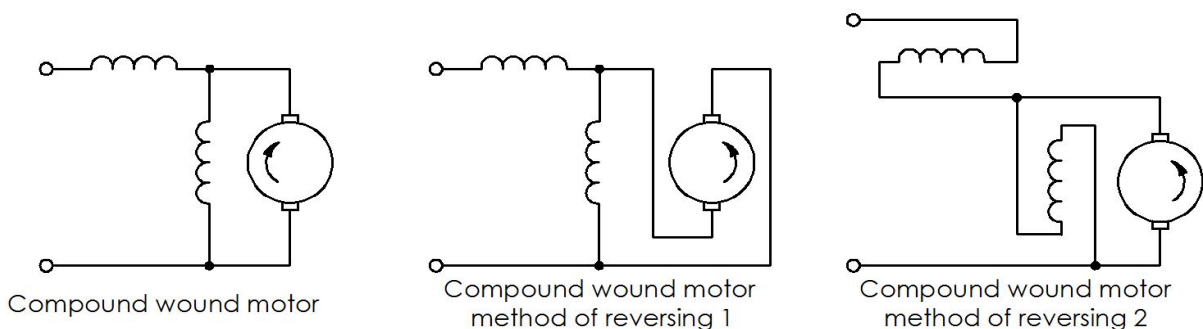


Figure 1.9

1.6.4 Methods of reversing the rotational direction of a DC motor

The need for inverting the rotational direction of a DC motor may become clear in the following practical example:

When using a DC motor to drive a lift or escalator, it is necessary to invert the rotational direction of operation in order to ensure that the lift may operate in both directions, ie up and down.

The following methods may be used to invert the rotational direction of a DC motor:

- interchanging field winding connections
- reversing the armature connection

Figure 1.6, Figure 1.7 and **Figure 1.9** shows these two methods of reversing rotation.

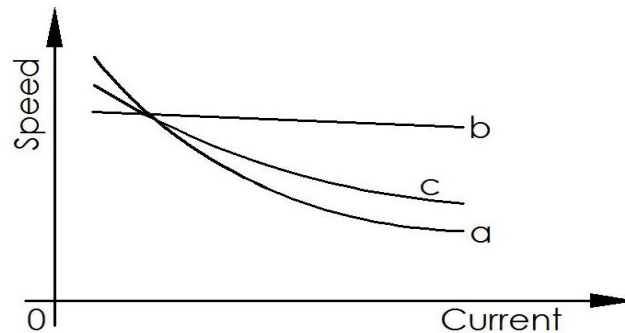


Figure 1.10 Speed characteristic curves

Figure 1.11 shows the curve of the torque against the armature current for A=Series wound and B=shunt wound motors

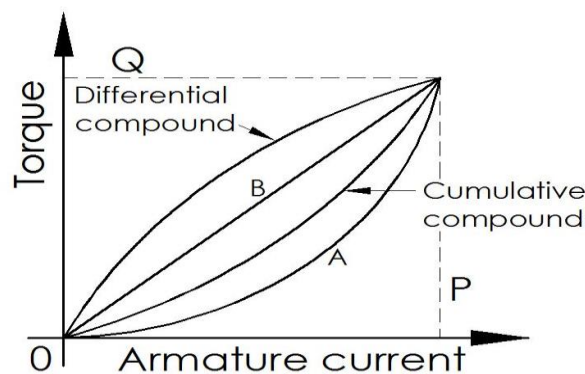


Figure 1.11 Torque characteristic curves



Worked Example 1.2

A series wound motor runs at a speed of 500 r/sec when using 100 A with a 220 V supply. The armature resistance is 0.18 ohms and the resistance of the series winding is 0.028 ohms.

Find the speed when the current has fallen to 50 A.

The useful flux per pole for 100 A is assumed to be 0.028 Wb and at 50 A, 0.018 Wb.

Solution:

$$\text{The total resistance} = 0.18 + 0.028 = 0.208 \text{ ohms}$$

$$\text{The EMF generated at } 100 \text{ A} = 220 - (100 \times 0.208) = 199.2 \text{ V}$$

$$\text{At } 100 \text{ A EMF} = 199.2 = k \times 500 \times 0.028$$

$$\therefore k = 14.23$$

$$\text{At } 50 \text{ A EMF} = 220 - (50 \times 0.208) = 209.6 \text{ V}$$

$$209.6 = 14.23 \times N \times 0.018$$

$$\therefore N = 818.3 \text{ r/min}$$

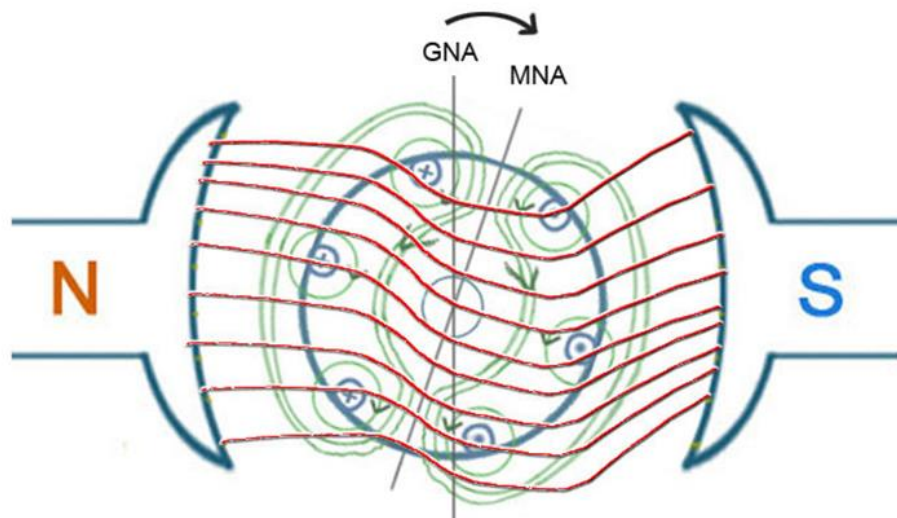
1.7 DC generators

Figure 1.12 Distortion of main field flux due to armature flux - Armature reaction

The armature reaction:

- demagnetizes the main field, and
- cross magnetizes the main field.

The demagnetizing effect can be overcome by adding extra ampere turns on the main field winding. The cross magnetizing effect can be reduced by having common poles.

**Definition: Armature reaction drop**

The effect of a magnetic field on the distribution of the flux under main poles of a generator.

Since an armature is wound with coils of wire, a magnetic field is set up in the armature whenever a current flows in the coils. This field is at right angles to the generator field, and is called cross magnetization of the armature.

**Note:**

The effect of the armature field is to distort the generator field and shift the neutral plane.

The neutral plane is the position where the armature windings are moving parallel to the magnetic flux lines, that is why an axis lying in this plane is called as magnetic neutral axis (MNA). This effect is known as armature reaction and is proportional to the current flowing in the armature coils.

The brushes of a generator must be set in the neutral plane; that is, they must contact segments of the commutator that are connected to armature coils having no induced EMF. If the brushes were contacting commutator segments outside the neutral plane, they would short-circuit "live" coils and cause arcing and loss of power.

**Note:**

Without armature reaction, the magnetic neutral axis (MNA) would coincide with geometrical neutral axis (GNA).

Armature reaction causes the neutral plane to shift in the direction of rotation, and if the brushes are in the neutral plane at no load, that is, when no armature current is flowing, they will not be in the neutral plane when armature current is flowing. For this reason it is desirable to incorporate a corrective system into the generator design.

These are two principal methods by which the effect of armature reaction is overcome. The first method is to shift the position of the brushes so that they are in the neutral plane when the generator is producing its normal load current. In the other method, special field poles, called inter-poles, are installed in the generator to counteract the effect of armature reaction.

The brush-setting method is satisfactory in installations in which the generator operates under a fairly constant load. If the load varies to a marked degree, the neutral plane will shift proportionately, and the brushes will not be the correct position at all times.

**Note:**

The brush-setting method is the most common means of correcting for armature reaction in small generators (those producing approximately 1000 W or less). Larger generators require the use of inter-poles.

1.7.1 Open circuit characteristic (OCC)

Open circuit characteristic is also known as magnetic characteristic or no-load saturation characteristic.



Note:

This characteristic shows the relation between generated EMF at no load (E_0) and the field current (I_f) at a given fixed speed.

The OCC curve is just the magnetization curve and it is practically similar for all type of generators. The data for OCC curve is obtained by operating the generator at no load and keeping a constant speed. Field current is gradually increased and the corresponding terminal voltage is recorded.

The connection arrangement to obtain OCC curve is as shown in **Figure 1.13** below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.

Now, from the EMF equation of DC generators, we know that $E_g = k\phi$. Hence, the generated EMF should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of EMF is generated (represented by OA in **Figure 1.13**).

This initially induced EMF is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial EMF is induced in the armature. This initially induced EMF aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced EMF.

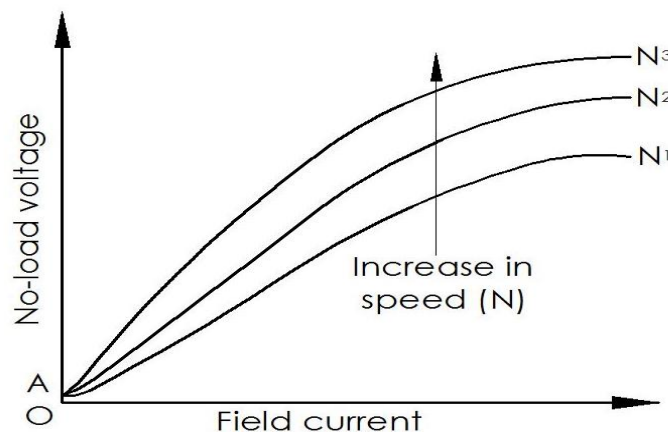


Figure 1.13 Open circuit characteristics (OCC)

Thus, OCC follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we

increase the I_f further, ϕ remains constant and hence, E_g also remains constant. Hence, the OCC curve looks like the B-H characteristic.

The above **Figure 1.13** shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

1.7.2 Internal or total characteristic

An internal characteristic curve shows the relation between the on-load generated EMF (E_g) and the armature current (I_a). The on-load generated EMF E_g is always less than E_0 due to the armature reaction.

E_g can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E_0 . Therefore, internal characteristic curve lies below the OCC curve.

1.7.3 External characteristic

An external characteristic curve shows the relation between terminal voltage (V) and the load current (I_L). Terminal voltage V is less than the generated EMF E_g due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve.

External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as performance characteristic or load characteristic.

Internal and external characteristic curves are shown below for each type of generator.

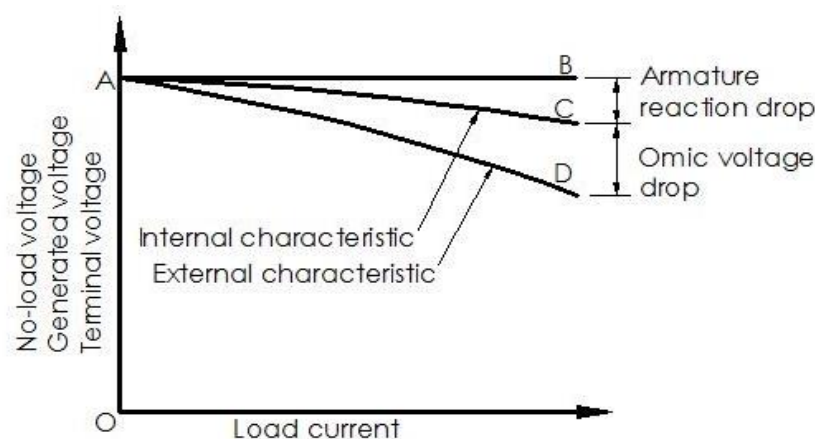


Figure 1.14 Characteristics of separately excited DC generator

If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight line AB in above figure represents the no-load voltage vs. load current I_L . Due to the demagnetizing

effect of armature reaction, the on-load generated EMF is less than the no-load voltage.

The curve AC represents the on-load generated EMF E_g vs. load current I_L ie internal characteristic (as $I_a = I_L$ for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current ie external characteristic.

1.7.4 Characteristics of DC shunt generator

To determine the internal and external load characteristics of a DC shunt generator the machine is allowed to build up its voltage before applying any external load. To build up voltage of a shunt generator, the generator is driven at the rated speed by a prime mover.



Note:

Initial voltage is induced due to residual magnetism in the field poles.

The generator builds up its voltage as explained by the OCC curve. When the generator has built up the voltage, it is gradually loaded with resistive load and readings are taken at suitable intervals.

Unlike, separately excited DC generator, here, $I_L \neq I_a$. For a shunt generator, $I_a = I_L + I_f$. Hence, the internal characteristic can be easily transmitted to E_g vs. I_L by subtracting the correct value of I_f from I_a .

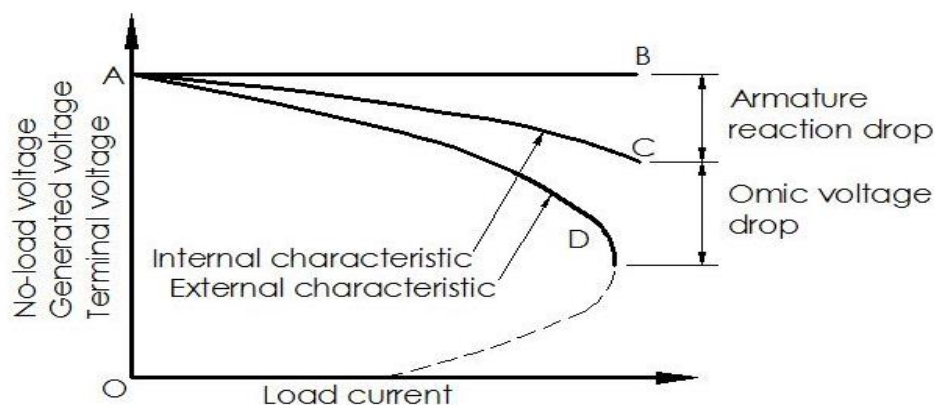


Figure 1.15 Characteristics of DC shunt generator

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls.

So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I^2R losses.

Hence, beyond this limit any further decrease in load resistance results in decreasing load current. Consequently, the external characteristic curve turns back as shown by dotted line in the **Figure 1.15**.

1.7.5 Characteristics of DC series generator

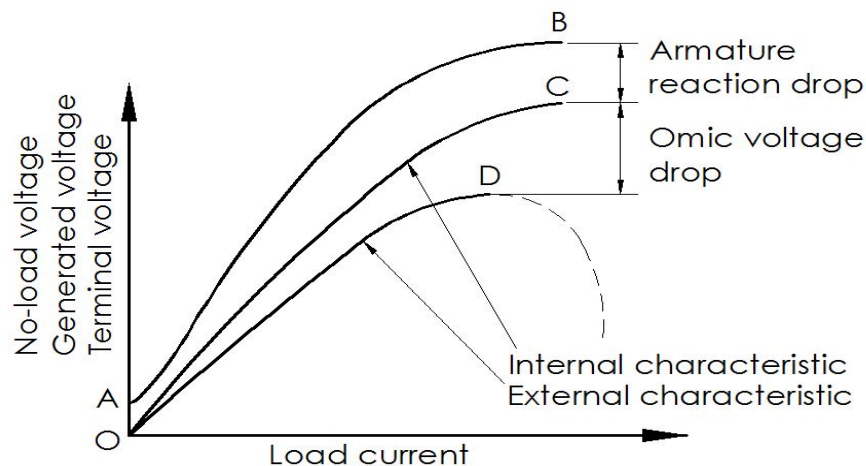


Figure 1.16 Characteristics of DC series generator

The curve AB in **Figure 1.16** is identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. **Figure 1.16**.

Hence, here load current is similar to field current (i.e. $I_L = I_f$). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current.

This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

1.7.6 Characteristics of DC compound generator

Figure 1.17 shows winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded.

The external characteristic for over compounded generator is shown by the curve AB in **Figure 1.17**.

If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a flat compounded generator is shown by the curve AC.

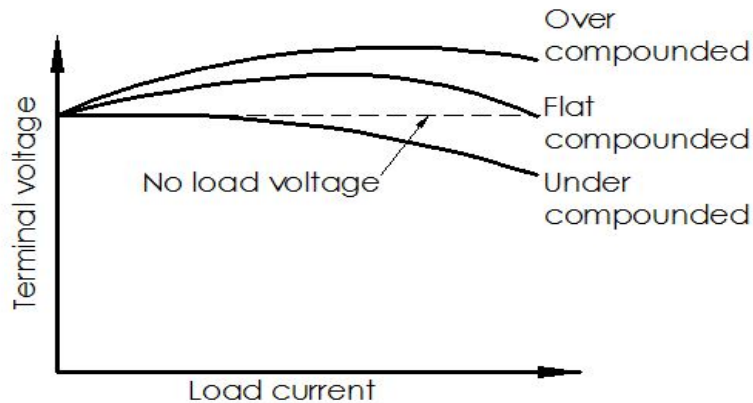


Figure 1.17 External characteristic of DC compound generator

If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.



Worked Example 1.3

Calculate the speed of a four-pole series generator having a wave-wound armature with 315 conductors and resistance of 0,6 ohm supplying a load of 50 kW at 1 000 V. The resistance of the field-winding brush contact resistance is 0,4 ohm. The field sets up a flux per pole of 0,1 Wb.

Solution:

$$\text{Flux} = 0,1 \text{ Wb} \quad P = 2 \quad C = 2 \quad Z = 315$$

$$I_a = I_L = P/V = \frac{50 \times 10^3}{1000} = 50 \text{ A}$$

$$E = V + I_a(R_a + R_{sc}) \quad E = \left(\frac{2Z}{C}\right) \left(\frac{NP}{60}\right) \times \Phi_m$$

$$= 1\,000 + 50(0,6 + 0,4) \quad 1050 = \left(2 \times \frac{315}{2}\right) \left(\frac{N2}{60}\right) \times 0,1$$

$$= 1\,050 \text{ V} \quad N = 0,105 N$$

$$= 1\,000 \text{ RPM}$$



Worked Example 1.4

A pole, 316 V shunt motor has its armature lap wound with 150 conductors. The armature draws a current of 80 A when the motor rotates at 1 200 r/min.

Calculate the useful flux per pole in Wb if the resistance of the armature is 0,2 ohm.

Solution:

$$\text{Flux} = \times Wb \qquad P = 2 \qquad C = 2p = 2 \times 2 = 4 \qquad Z = 315$$

$$E = V - IR \qquad E \times C \times \frac{60}{2} ZNP = \Phi_m$$

$$= 316 - (80 \times 0,2)$$

$$\phi_m = 300 \times 4 \times \frac{60}{2} \times 150 \times 1200 \times 2$$

$$= 300 V$$

$$= 0,1 Wb$$

1.8 Welding machine



Note:

The welding process uses a welding power supply to create and maintain an electric arc between an electrode and the base material to melt metals at the welding point.

They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas, known as a shielding gas, and filler material is sometimes used as well.

To supply the electrical power necessary for arc welding processes, a variety of different power supplies can be used. The most common welding power supplies are constant current power supplies and constant voltage power supplies.


In arc welding, the length of the arc is directly related to the voltage, and the amount of heat input is related to the current.



Note:

Constant current power supplies are most often used for manual welding processes such as gas tungsten arc welding and shielded metal arc welding, because they maintain a relatively constant current even as the voltage varies.

This is important because in manual welding, it can be difficult to hold the electrode perfectly steady, and as a result, the arc length and thus voltage tend to fluctuate.

	<p>Note: Constant voltage power supplies hold the voltage constant and vary the current, and as a result, are most often used for automated welding processes such as gas metal arc welding, flux cored arc welding, and submerged arc welding.</p>
---	--

In these processes, arc length is kept constant, since any fluctuation in the distance between the wire and the base material is quickly rectified by a large change in current. For example, if the wire and the base material get too close, the current will rapidly increase, which in turn causes the heat to increase and the tip of the wire to melt, returning it to its original separation distance.

1.8.1 MMA

One of the most common types of arc welding is shielded metal arc welding (SMAW); it is also known as manual metal arc welding (MMA) or stick welding.

Electric current is used to strike an arc between the base material and consumable electrode rod, which is made of filler material (typically steel) and is covered with a flux that protects the weld area from oxidation and contamination by producing carbon dioxide (CO₂) gas during the welding process. The electrode core itself acts as filler material, making a separate filler unnecessary.

Arc welders use both AC and DC current. In order to make the best welds a welder must understand what alternating current (AC) and direct current (DC) signify on the welder as well as on electrodes. AC and DC are terms that refer to the polarity of the electrical current that is created by the welder and runs through the electrode.

1.8.2 Polarity

Every electrical circuit has a negative and positive pole. Direct current flows in a single direction resulting in a constant polarity. Alternating current or AC current flows in one direction half of the time and in the opposite direction the other half. AC current changes its polarity 120 times per second with a 60 hertz current.

Electrode positive or reversed polarity (AC current) results in deeper penetration while electrode negative (DC) or straight current provides faster deposition rates because there is quicker melt-off of the electrode.

There are different types of electrodes and electrode shielding that can alter these basic conditions. Some kinds of shielded electrodes function using either polarity while others only operate on one polarity.

Welding with DC is best used for:

- Hard facing
- Single carbon brazing
- Build-up of heavy deposits
- Stainless steel TIG welding
- Cutting tap

DC reverse polarity:

In DC reverse polarity the electrode is positive and the current flows from the workpiece to the electrode. Welding with reverse DC polarity is ideal for:

- Overhead welding
- Vertical welding
- Cast iron welding
- Heavy aluminium
- Rivet welding
- Sheet metal
- Low hydrogen welding

Advantages of DC welding:

When it comes to stick welding applications DC welding offers certain advantages over AC:

- Starts are easier
- there are fewer arc outages and sticking
- there is less spatter
- welds have a better appearance
- welding vertically or overhead is much easier and DC current is the best ways for beginners to learn “how to weld”
- DC welding also provides a smoother arc and
- DC straight polarity welds a lot of thinner metals better than AC.

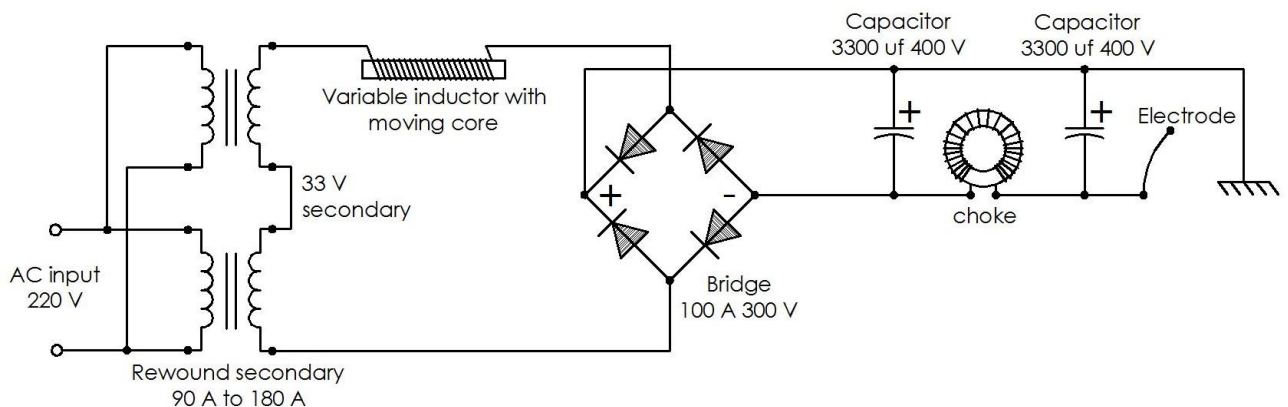


Figure 1.18 DC welding machine diagram

Figure 1.18 shows a welding machine diagram. A transformer changes the voltage into a useful range for the welding process. The variable inductor offers a range of current settings. The current is converted to DC as shown.



Worked Example 1.5

An eight pole DC motor has a wave connected armature with 800 conductors. The brushes are displaced through five angular degrees from the geometrical axis. The armature current is 270 A.

Calculate the following:

1. The demagnetising and cross-magnetising ampere turns per pole.
2. The additional field current required neutralising this demagnetisation if the field winding has 1 600 turns/pole.

Solution:

$$1. \quad p = 4c = 2Z = 800 \text{ mech deg} = 5^\circ \text{ and Elect deg } p \times 5 = 20^\circ \text{ Ia} = 270$$

$$\text{Field winding} = 1600 \text{ t/p}$$

$$\text{Demag At/p} = 0,5 \times \text{Ia/c} \times Z/2p \times (40/360)$$

$$= 0,5 \times 270/2 \times 800/8 \times (4 \times 20/360) = 1500 \text{ At/p}$$

$$\text{Cross - mag At/p} = 0,5 \times 270/2 \times 800/8 \times [1 - (4 \times 20/360)]$$

$$= 5250 \text{ At}$$

$$2. \quad \text{MMF} = N I$$

$$I = 1500/1600$$

$$= 0,94 \text{ A}$$



Worked Example 1.6

A 535 V shunt motor draws an armature current of 40 A while running at 550 r/min. The armature circuit has a resistance of 0,5 Ω . If the magnetic flux is decreased by 30% and the torque developed by the armature increases by 40%.

Calculate the following:

1. The armature current
2. The speed

Solution:

$$1. \quad V = 535 \text{ V} \quad I_a = 40 \text{ A} \quad N_1 = 550 \text{ rpm} \quad R_a = 0,5 \Omega \quad \Phi_1 = 100\% \quad (1)$$

$$\Phi_2 = 70\% \quad (0,7) \quad T_1 = 100\% \quad (1) \quad T_2 = 140\% \quad (1,4)$$

$$T \propto I_a \Phi$$

$$T_1/T_2 = I_{a_1} \Phi_1 / I_{a_2} \Phi_2$$

$$I_{a_2} = T_2 I_{a_1} \Phi_1 / T_1 \Phi_2$$

$$= 1,4 \times 40 \times 1 / 1 \times 0,7$$

$$= 80 \text{ A}$$

$$2. \quad E_1 = V - I_a R_a$$

$$= 535 - (40 \times 0,5)$$

$$= 515 \text{ V}$$

$$E_2 = V - I_{a_2} R_a$$

$$= 535 - (80 \times 0,5)$$

$$= 495 \text{ V}$$

$$3. \quad E_1/E_2 = N_1 \Phi_1 / N_2 \Phi_2$$

$$N_2 = E_2 N_1 \Phi_1 / E_1 \Phi_2$$

$$= 495 \times 550 \times 1 / 515 \times 0,7$$

$$= 755,2 \text{ r/pm}$$

**Worked Example 1.7**

A 40 kW, 475 V, 1 000 r/min DC shunt motor has a full-load efficiency of 90%. The armature circuit has a resistance of 0,24 Ω and a total voltage drop of 3 V at the brushes. The field current is 1,6 A.

Calculate:

1. The full-load line current.
2. The full-load shaft torque in Nm.
3. The total resistance of the motor starter to limit the armature starting current to 1,3 times of the full load current.

Solution:

$$1. \quad V = 475 \text{ V} \quad P = 40 \text{ kW} \quad N = 1000 \text{ rpm} \quad \eta = 90\% = 0,9$$

$$R_a = 0,24 \quad I_f = 1,6 \text{ A} \quad I_a R_b = 3 \text{ V}$$

$$\text{Input} = \text{Output} = 40 / 0,9 = 44,444 \text{ kW}$$

$$I_L = P/V = 44444 / 475$$

$$= 93,57 \text{ A}$$

$$2. \quad \text{Output} = \frac{2 \pi N T}{60}$$

$$4000 = \frac{2 \pi 1000 T}{60}$$

$$T = \frac{40\,000 \times 60}{2 \pi 1000}$$

$$= 381,97 \text{ Nm}$$

$$3. \quad \text{Starting current} = 1,3 \text{ (full Load)} = 1,3 \times 93,57 = 121,64 \text{ A}$$

$$I_a = I - I_f = 121,64 - 1,6 = 120,04 \text{ A}$$

$$V = E + V_b + V_a \text{ (at start)} \quad E = 0 \quad V_a = I_a (R_a + x)$$

$$475 = 0 + 3 + 120,04(0,24 + x)$$

$$x = \frac{475 - 31,81}{120,04}$$

$$= 3,69 \, \Omega$$



Worked Example 1.8

A DC motor draws an armature current of 180 A at 550 V.

The resistance of the armature circuit is 0,4 Ω .

The motor has a 6 poles and the armature is lap-connected with 1 800 conductors.

The flux per pole is 0,05 Wb.

Calculate:

1. The speed.
2. The gross torque developed by the armature.

Solution:

$$1. \quad I_a = 180 \text{ A} \quad V = 550$$

$$R_a = 0,4 \text{ ohms}$$

$$\text{Lap - connected - } c = 6$$

$$Z = 1\,800 \text{ Flux/pole} = 0,05 \text{ Wb}$$

$$E = V - (I_a \times R_a)$$

$$= 550 - (180 \times 0,4)$$

$$= 550 - 72$$

$$= 478 \text{ V}$$

$$\frac{2 \pi N T}{60} - E I_a = 2 \frac{Z}{c} \times \frac{N p}{60} \times \phi \times I_a$$

$$478 = 2 \times \frac{1800}{6} \times \frac{N \times 3}{60} \times 0,05$$

$$478 = 1,5 N$$

$$N = 318,67 \text{ r/min} (5,31 \text{ rps})$$

$$\begin{aligned}
 2. \quad P &= E I_a \\
 &= 478 \times 180 \\
 &= 86040 \text{ W} \\
 \frac{2 \pi NT}{60} &= 86040 \\
 T &= \frac{60 \times 86040}{2 \pi \times 318,67} \\
 &= 2578,28 \text{ Nm}
 \end{aligned}$$



Worked Example 1.9

- Calculate the number of series turns per pole, required on a compound generator, for it to maintain a constant voltage at 630 V, between no-load and full-load of 450 kW. With no series winding, it was found that the shunt current has to be 6 A on no-load and 7,5 A on full-load, to maintain the voltage constant at 630 V. Number of turns per pole on the shunt winding is 2 400.
- If the series coils were wound with 8 turns/pol and had a total resistance of 0,06 Ω :

Calculate the value of the diverter resistance required to give level-compounding.

Solution:

$$\begin{aligned}
 1. \quad \text{Ampere turns required on no load} &= 6 \times 2400 = 14400 \\
 \text{Ampere turns required on full load} &= 7,5 \times 2400 = 18000 \\
 \text{Ampere turns required on series field on full load} &= 18000 - 14400 \\
 &= 3600 \\
 \text{Full load line current} &IL = P/V \\
 &= \frac{450 \times 10^3}{630} \\
 &= 714,29 \text{ A} \\
 \text{Constant field current} &If = 6A \\
 Ia &= IL + If \\
 &= 720,29 \text{ A} \\
 \text{Turns required on series field} &= \frac{3600}{720,29} \\
 &= 5
 \end{aligned}$$

2. With series winding of 8 t/p and resistance of $0,06\Omega$

$$\text{Ampere turns required} = 3600$$

$$\text{With 6 turns, series field current} \quad I_f = 3600/8$$

$$\begin{aligned} \text{Current through diverter} \quad R_x &= 720,29 - 450 \\ &= 270 \text{ A} \end{aligned}$$

$$\text{Voltage across diverter} = \text{voltage across series field}$$

$$(I_x)(R_x) = I_f (\text{series}) \times R(\text{series})$$

$$\begin{aligned} R_x &= \frac{450 \times 0,06}{264,29} \\ &= 0,102 \Omega \end{aligned}$$



Activity 1.1

1. Briefly explain why the terminal voltage of a DC shunt excited generator drops, as the current supplied by the machine is increased.
2. What is the function of the commutating poles and compensating windings in a DC machine?
3. Name three methods used for improving poor commutation in a DC generator.
4. State two characteristics of DC motors.
5. Name and explain three methods to improve commutation.
6. Sketch a diagram showing the connections of a self-excited generator indicating the supply, armature, field and measuring instruments for amperes and voltage.
7. Briefly explain how you would change the direction of rotation of a DC motor.
8. A DC motor can be self-regulating due to back EMF. Briefly discuss this statement.
9. Name the practical applications of lap and wave windings in DC machines.
10. Briefly explain the term *commutation*.
11. What is meant by *armature reaction*?



Activity 1.2

A 30,5 kW, 440 V, eight-pole motor has a wave-wound armature with 1 200 conductors, and the commutator has 150 segments. The full-load efficiency is 85% and the shunt current is 1,5 A. The brushes are shifted backwards through 1,4 segments from the geometric neutral.

Calculate the demagnetising and cross-magnetising ampere-turns per pole.

[35882.35; 81.55; 80.05; 3001.88; 13.44; 448.28; 2553.6]



Activity 1.3

An eight-pole, 1 600 kW, 520 V, DC generator has a wave connected winding with 240 armature conductors.

Calculate the number of turns per pole required for the commutating poles. Assume the compole ampere-turns per pole to be about 1,6 times the armature ampere turns per pole and the brushes to be in geometric neutral axis.

[3076.92; 23076.9; 12]



Activity 1.4

An eight-pole, lap-wound, 350 V, shunt-excited DC machine draws an armature current of 7,5 A on no-load at 1 200 rpm. When loaded, it draws an armature current of 80 A from the supply and runs at the same speed. The resistance of the armature circuit is 0,6 Ω and there are 900 armature conductors.

Calculate the following:

1. The generated EMF
2. The useful flux per pole
3. The useful torque developed by the machine in Nm

[302; 0.01678; 192.26]



Activity 1.5

A DC motor with four poles has a wave-connected armature with 1 000 conductors. The brushes are displaced through five angular degrees from the geometrical axis. The armature current is 220 A.

Calculate the following:

1. The demagnetizing and cross-magnetising ampere-turns per pole.
2. The additional field current required to neutralize this demagnetization if the field winding has 2 000 turns/pole.

[2000; 1528; 12222; 0.76]



Activity 1.6

A 450 V, 45 kW, DC motor has to start on full-load and the starting current must not exceed 1,5 times the normal full-load value. If the armature resistance is $0,07 \Omega$ and the starter has 10 elements. Calculate the resistance of the first three elements. The full-load efficiency of the motor is 75%.

[60; 133.33; 200; 1.41; 0.65; 0.461; 0.327]



Activity 1.7

An eight-pole generator has a lap-connected armature with 640 conductors. The ratio of the pole arc per pole pitch is 0,8.

Calculate the ampere-turns per pole of a compensating winding to give uniform air gap density when the total armature current is 960 A.

[0.8; 960; 3840; 162.96]



Activity 1.8

An 88 kW, 540 V shunt generator has 1 800 turns on each pole of its field winding. On no-load a current of 9A in the field winding produces a terminal voltage of 540 V, but on full-load the shunt current has to be increased to 12 A for the same terminal voltage at the same speed.

Calculate the number of series field turns per pole required for level compounding.

[162.96; 21600; 16200; 5400; 34]



Activity 1.9

1. The armature resistance of a six-pole, 500 V wave connected series motor is $0,5 \Omega$ which takes 61 amperes from the supply. The motor has 72 slots with 10 conductors in each slot. The total flux per pole is 50 mWb. Calculate the speed of the motor.
[469.5; 720; 260.8]


2. A 40 kW, 500 V, DC shunt motor has an armature resistance of $0,35 \Omega$. The full-load armature current is 100 A. What resistance should be inserted in series in the armature circuit to obtain a 20% speed reduction and a decrease of 20% of the rated torque? The flux remains constant.

[80; 372; 465; 1.6; 1.25]

3. A 55 kW, 650 V, DC shunt motor has a speed of 1800 r/min and the full load efficiency is 85%. The armature circuit resistance is 0,3 ohms and the total voltage drop is 2,5 V at the brushes. The field current is 3 A.
Calculate:

3.1 the full-load line current
3.2 the full-load shaft torque in Nm

[68.75; 105.77; 102.77; 616.67; 336.22]

 Self-Check		
I am able to:	Yes	No
• Describe the uses of and characteristics of shunt, series and compound motors and generators and welding machines	<input type="checkbox"/>	<input type="checkbox"/>
• Describe speed control and grading of starting resistances	<input type="checkbox"/>	<input type="checkbox"/>
• Describe compensating windings and compound machines	<input type="checkbox"/>	<input type="checkbox"/>
• Calculate speed and starting torque back-EMF	<input type="checkbox"/>	<input type="checkbox"/>
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Module 2

AC Circuit Theory

Learning Outcomes

On the completion of this module the student must be able to:

- Describe single and three-phase systems
- Describe instantaneous, average and RMS values
- Describe star and delta connections
- Calculate mixed circuits using phasors
- Calculate types of waveforms and power

2.1 Introduction



This module describes three-phase systems, instantaneous, average and RMS values, star and delta connections, mixed circuits using phasors and gives examples of waveforms and power.

2.2 Single phase alternating current

2.2.1 Instantaneous values of current and power at different phase angles

During each complete cycle, there are two peak values, one on the positive side and one on the negative. The difference between the two peak values is termed the peak-to-peak value. See **Figure 2.1**.

With a AC waveform, the frequency (f) and the instantaneous time it takes to reach a point (T) are obviously related.



Definition:

A waveform has a frequency of 1 hertz (Hz) when it goes through one complete cycle of change in a period of 1 second.

From this definition we get:

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

So, a waveform that has a time period of 1 ms has a frequency of:

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

$$f = \frac{1}{1 \times 10^{-3}} = 1000 \text{ Hz} = 1 \text{ kHz}$$

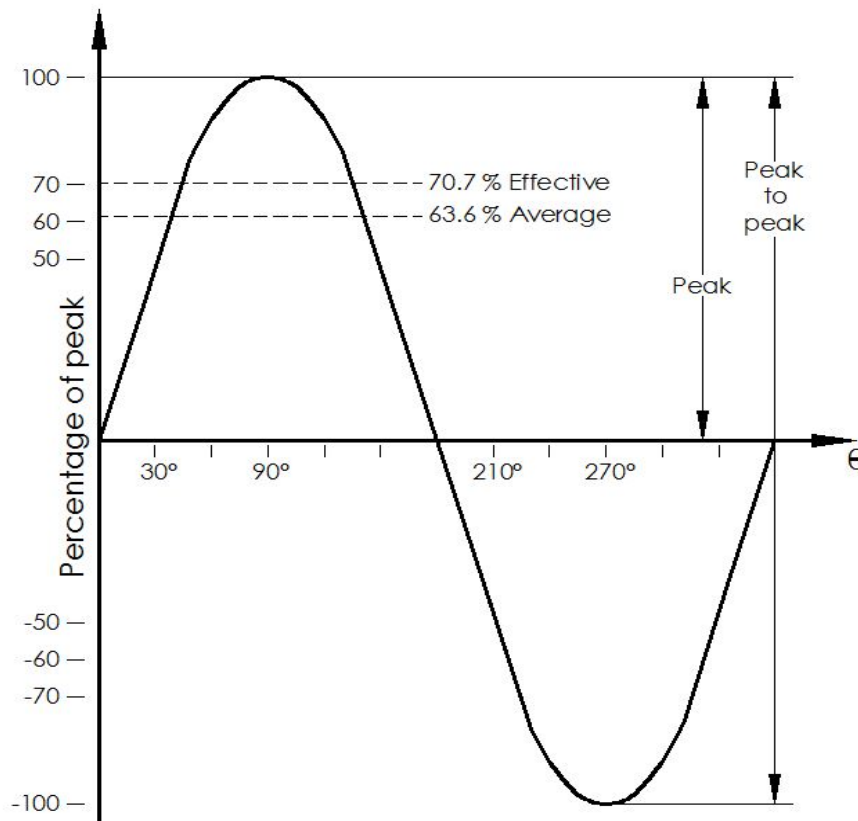


Figure 2.1 Alternating current waveform

If in an AC machine, the conductors rotate one revolution = 360 degrees. If this was measured in radians instead of degrees, then one revolution would equal:

$$\text{One revolution} = 2\pi \text{ radians}$$

If (T) is the time period for one revolution, then:

$$\text{Angular velocity} = \frac{360}{T}$$

$$\text{Angular velocity} = \frac{2\pi}{T}$$

And the phase angle at any instant:

$$\text{Angle} = \frac{2\pi}{T} \times t \text{ radians}$$

$$\text{or it can be written ... Angle} = 2\pi f t$$

$$\text{Angle} = \omega t$$

The instantaneous value of the alternating voltage or current is taken at a particular instant.

$$I_{inst} = I_{max} \sin(\omega t)$$

The power:

$$P_{inst} = P_{max} \sin^2(\omega t)$$

2.2.2 Average and RMS values of current and power

The average value of an alternating current or voltage is the average of ALL the instantaneous values during one alternation.



Note:

Since the voltage increases from zero to peak value and decreases back to zero during one alternation, the average value must be some value between those two limits.

You could determine the average value by adding together a series of instantaneous values of the alternation (between 0° and 180°), and then dividing the sum by the number of instantaneous values used. The computation would show that one alternation of a sine wave has an average value equal to 0.636 times the peak value.

The formula for average voltage is

$$E_{ave} = 0.636 E_{max}$$

where E_{avg} is the average voltage of one alternation, and E_{max} is the maximum or peak voltage. Similarly, the formula for average current is

$$I_{ave} = 0.636 I_{max}$$

where I_{avg} is the average current in one alternation, and I_{max} is the maximum or peak current.



Definition: The effective value

E_{max} , E_{avg} , I_{max} , and I_{avg} are values used in ac measurements. Another value used is the effective value of AC. This is the value of alternating voltage or current that will have the same effect on a resistance as a comparable value of direct voltage or current will have on the same resistance.

In an earlier discussion you were told that when current flows in a resistance, heat is produced. When direct current flows in a resistance, the amount of electrical power converted into heat equals I^2R watts.

However, since an alternating current having a maximum value of 1 ampere does not maintain a constant value, the alternating current will not produce as much heat in the resistance as will a direct current of 1 ampere.

Therefore, the effective value or the RMS value is:

$$I_{eff} = 0.707 I_{max}$$

2.2.3 Power factor

The power factor of an AC electrical power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit.



Note:

A power factor of less than one means that the voltage and current waveforms are not in phase, reducing the instantaneous product of the two waveforms ($V \times I$).

Real power is the capacity of the circuit for performing work in a particular time.

Apparent power is the product of the current and voltage of the circuit.

Due to energy stored in the load and returned to the source, or due to a non-linear load that distorts the wave shape of the current drawn from the source, the apparent power will be greater than the real power.

A negative power factor occurs when the device (which is normally the load) generates power, which then flows back towards the source, which is normally considered the generator.

Linear circuits:

In a purely resistive AC circuit, voltage and current waveforms are in step (or in phase), changing polarity at the same instant in each cycle. All the power entering the load is consumed (or dissipated).



Note:

Where reactive loads are present, such as with capacitors or inductors, energy storage in the loads results in a phase difference between the current and voltage waveforms.

During each cycle of the AC voltage, extra energy, in addition to any energy consumed in the load, is temporarily stored in the load in electric or magnetic fields, and then returned to the power grid a fraction of the period later.

Electrical circuits containing dominantly resistive loads (incandescent lamps, heating elements) have a power factor of almost 1.0, but circuits containing

inductive or capacitive loads (electric motors, solenoid valves, transformers, fluorescent lamp ballasts, and others) can have a power factor well below 1.

AC power flow has three components:

- Real power or active power (P), expressed in watts (W)
- Apparent power (S), usually expressed in volt-amperes (VA)
- Reactive power (Q), usually expressed in reactive volt-amperes (var)

The power factor is defined as the ratio of real power to apparent power. As power is transferred along a transmission line, it does not consist purely of real power that can do work once transferred to the load, but rather consists of a combination of real and reactive power, called apparent power.

The power factor describes the amount of real power transmitted along a transmission line relative to the total apparent power flowing in the line.

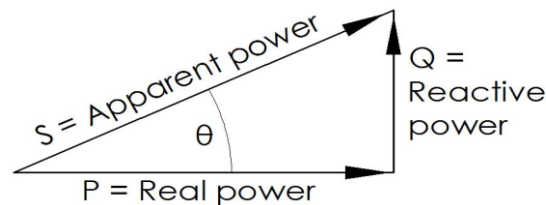


Figure 2.2 Power triangle

We can relate the various components of AC power by using the power triangle. **Figure 2.2.**

Real power extends horizontally in the \hat{i} direction as it represents a purely real component of AC power.

Reactive power extends in the direction of \hat{j} as it represents a purely imaginary component of AC power.

Apparent power represents a combination of both real and reactive power, and therefore can be calculated by using the vector sum of these two components. We can conclude that the mathematical relationship between these components is:

$$S^2 = P^2 + Q^2$$

$$\text{power factor} = \cos\theta = \frac{P, \text{ real power}}{S, \text{ apparent power}}$$

Increasing the Power Factor:

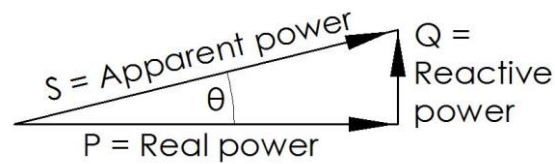


Figure 2.3 Power triangle increased power factor

As the power factor increases, the ratio of real power to apparent power increases and approaches unity (1), while the angle θ decreases and the reactive power decreases. **Figure 2.3.**

Decreasing the Power Factor:

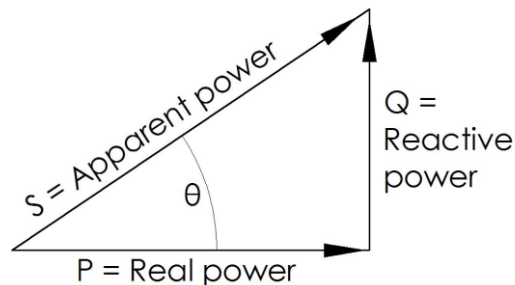


Figure 2.4 Power triangle decreased power factor

As the power factor decreases, the ratio of real power to apparent power also decreases, as the angle θ increases and reactive power increases.

See **Figure 2.4.**

Lagging and Leading Power Factors:

In addition, there is also a difference between a lagging and leading power factor. See **Figure 2.5.**

A lagging power factor signifies that the load is inductive, as the load will “consume” reactive power, and therefore the reactive component Q is positive as reactive power travels through the circuit and is “consumed” by the inductive load.

A leading power factor signifies that the load is capacitive, as the load “supplies” reactive power, and therefore the reactive component Q is negative as reactive power is being supplied to the circuit.

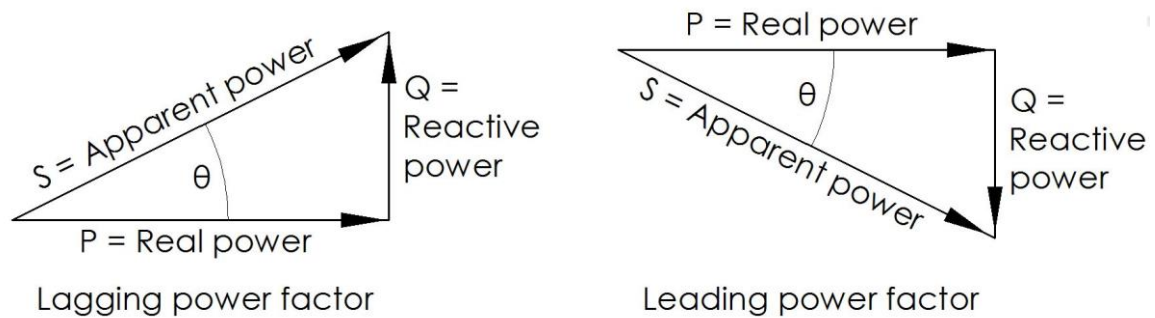


Figure 2.5

If θ is the phase angle between the current and voltage, then the power factor is equal to the cosine of the angle, **$\cos \theta$** :

$$|P| = |S| \cos \theta$$

Since the units are consistent, the power factor is by definition a dimensionless number between -1 and 1 .

When power factor is equal to 0 , the energy flow is entirely reactive and stored energy in the load returns to the source on each cycle.

When the power factor is 1 , all the energy supplied by the source is consumed by the load.

Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle.

**Note:**

Capacitive loads are leading (current leads voltage), and inductive loads are lagging (current lags voltage).

If a purely resistive load is connected to a power supply, current and voltage will change polarity in step, the power factor will be unity (1), and the electrical energy flows in a single direction across the network in each cycle.

Inductive loads such as transformers and motors (any type of wound coil) consume reactive power with current waveform lagging the voltage.

Capacitive loads such as capacitor banks or buried cable generate reactive power with current phase leading the voltage.

Both types of loads will absorb energy during part of the AC cycle, which is stored in the device's magnetic or electric field, only to return this energy back to the source during the rest of the cycle.

Power factor correction of linear loads

A high power factor is generally desirable in a transmission system to reduce transmission losses and improve voltage regulation at the load.

It is often desirable to adjust the power factor of a system to near 1.0. When reactive elements supply or absorb reactive power near the load, the apparent power is reduced.

Power factor correction may be applied by an electric power transmission utility to improve the stability and efficiency of the transmission network. Individual electrical customers who are charged by their utility for low power factor may install correction equipment to reduce those costs.

Power factor correction brings the power factor of an AC power circuit closer to 1 by supplying reactive power of opposite sign, adding capacitors or inductors that act to cancel the inductive or capacitive effects of the load, respectively.



Worked Example 2.1

An AC circuit has a 60 Hz supply voltage with a maximum value of 160 V. If $R = 10$ ohms, find the values of instantaneous current and power at the phase angle $\pi/2$ radians.

Solution:

In a purely resistive circuit:

$$I_{max} = \frac{E_{max}}{R} = \frac{160}{10} = 16 \text{ A}$$

$$P_{max} = I_{max}^2 R = 16^2 \times 10 = 2.56 \text{ kW}$$

$$\text{At the instance } \dots \frac{\pi}{2} \text{ radians: } i = 16 \sin\left(\frac{\pi}{2}\right) = 16 \text{ A}$$

$$\text{At the instance } \dots \frac{\pi}{2} \text{ radians: } p = 2.56 \sin^2\left(\frac{\pi}{2}\right) = 2.56 \text{ kW}$$



Worked Example 2.2

In the AC circuit above where a 60 Hz supply voltage has a maximum value of 160 V, and the $R = 10$ ohms. This time find the RMS value.

Solution:

$$I_{eff} = 0.707 I_{max}$$

$$I_{eff} = 0.707 \times 16 = 11.312 \text{ A}$$

**Worked Example 2.3**

Draw a labelled graph to show the waveform of a 50 Hz, single-phase alternating supply. The waveform must show TWO complete cycles between 0 and 720° (degrees). Calculate the maximum value of the voltage (V_m) if the effective value of the voltage (V_{ms}) 220 volts and calculate the periodic time (T) of ONE cycle. Show both answers V_m and T) on the graph.

Use any suitable scale so that the graph and labelling will not cover more than an A4 size paper. The following intervals are recommended:

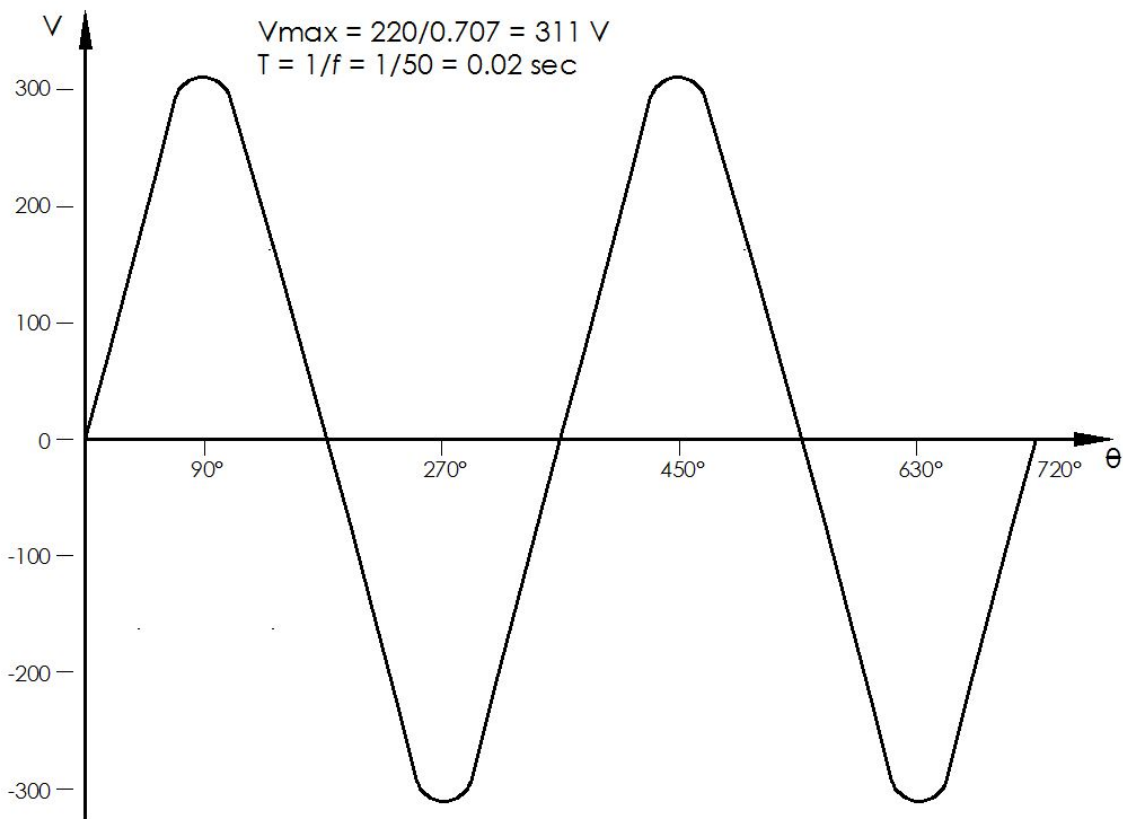
Solution:

Figure 2.6

2.3 Phasors and complex numbers

Sinusoidal waveforms of the same frequency can have a Phase Difference between themselves which represents the angular difference of the two sinusoidal waveforms.

Also the terms “lead” and “lag” as well as “in-phase” and “out-of-phase” were used to indicate the relationship of one waveform to the other with the generalized sinusoidal expression given as:

$A(t) = A_m \sin(\omega t \pm \Phi)$ representing the sinusoid in the time-domain form.

Basically a rotating vector, simply called a “**Phasor**” is a scaled line whose length represents an AC quantity that has both magnitude (“peak amplitude”) and direction (“phase”) which is “frozen” at some point in time.

A phasor is a vector that has an arrow head at one end which signifies partly the maximum value of the vector quantity (V or I) and partly the end of the vector that rotates.

Generally, vectors are assumed to pivot at one end around a fixed zero point known as the “point of origin” while the arrowed end representing the quantity, freely rotates in an anti-clockwise direction at an angular velocity, (ω) of one full revolution for every cycle.



Note:

This anti-clockwise rotation of the vector is considered to be a positive rotation. Likewise, a clockwise rotation is considered to be a negative rotation.

Although the both the terms vectors and phasors are used to describe a rotating line that itself has both magnitude and direction, the main difference between the two is that a vectors magnitude is the “peak value” of the sinusoid while a phasors magnitude is the “RMS value” of the sinusoid.

In both cases the phase angle and direction remains the same.

The phase of an alternating quantity at any instant in time can be represented by a phasor diagram, so phasor diagrams can be thought of as “functions of time”.

A complete sine wave can be constructed by a single vector rotating at an angular velocity of $\omega = 2\pi f$, where f is the frequency of the waveform. Then a **Phasor** is a quantity that has both “Magnitude” and “Direction”.

Generally, when constructing a phasor diagram, angular velocity of a sine wave is always assumed to be: ω in rad/s. Consider the phasor diagram in **Figure 2.7**.

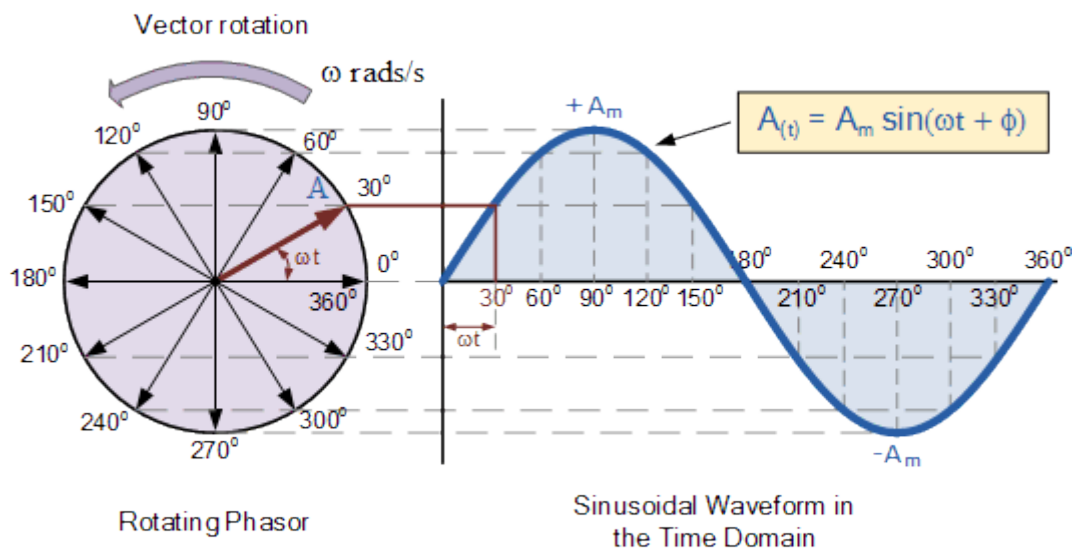


Figure 2.7 Phasor diagram

As the single vector rotates in an anti-clockwise direction, its tip at point A will rotate one complete revolution of 360° or 2π representing one complete cycle.

If the length of its moving tip is transferred at different angular intervals in time to a graph as shown above, a sinusoidal waveform would be drawn starting at the left with zero time.

Each position along the horizontal axis indicates the time that has elapsed since zero time, $t = 0$. When the vector is horizontal the tip of the vector represents the angles at 0° , 180° and at 360° .

Likewise, when the tip of the vector is vertical it represents the positive peak value, $(+A_m)$ at 90° or $\pi/2$ and the negative peak value, $(-A_m)$ at 270° or $3\pi/2$. Then the time axis of the waveform represents the angle either in degrees or radians through which the phasor has moved.

So we can say that a phasor represent a scaled voltage or current value of a rotating vector which is "frozen" at some point in time, (t) and in our example above, this is at an angle of 30° .

But if a second waveform starts to the left or to the right of this zero point or we want to represent in phasor notation the relationship between the two waveforms then we will need to take into account this phase difference, Φ of the waveform.

Consider **Figure 2.8**. From the previous Phase Difference.

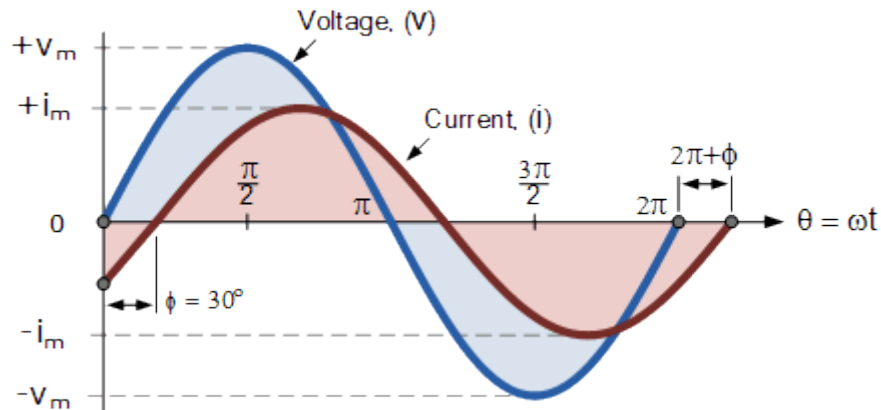


Figure 2.8 Phasor diagram showing phase difference

The current, i is lagging the voltage, v by angle Φ and in our example above this is 30° . So the difference between the two phasors representing the two sinusoidal quantities is angle Φ and the resulting phasor diagram will be.

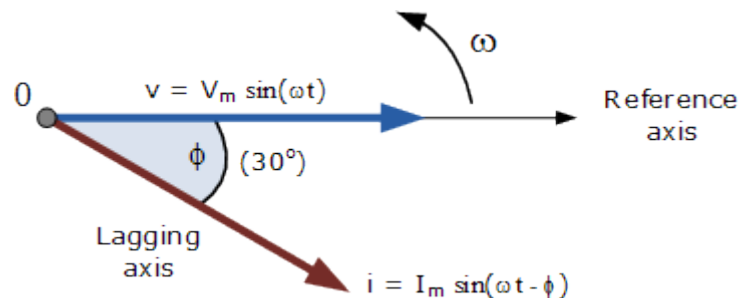


Figure 2.9 Phasor showing the angle difference

The phasor diagram is drawn corresponding to time zero ($t=0$) on the horizontal axis. The lengths of the phasors are proportional to the values of the voltage, (V) and the current, (I) at the instant in time that the phasor diagram is drawn.

The current phasor lags the voltage phasor by the angle, Φ , as the two phasors rotate in an *anticlockwise* direction as stated earlier, therefore the angle, Φ is also measured in the same anticlockwise direction.

If however, the waveforms are frozen at time $t = 30^\circ$, the corresponding phasor diagram would look like the one shown on the right. Once again the current phasor lags behind the voltage phasor as the two waveforms are of the same frequency.

However, as the current waveform is now crossing the horizontal zero axis line at this instant in time we can use the current phasor as our new reference and correctly say that the voltage phasor is “leading” the current phasor by angle, Φ . See **Figure 2.10**.

Either way, one phasor is designated as the reference phasor and all the other phasors will be either leading or lagging with respect to this reference.

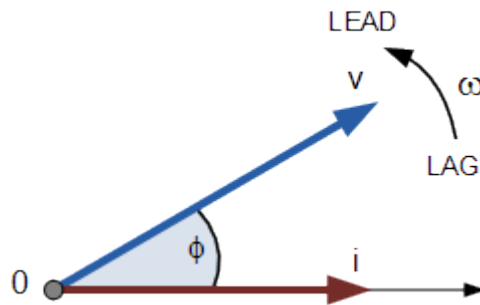


Figure 2.10

2.3.1 Phasor addition

Sometimes it is necessary when studying sinusoids to add together two alternating waveforms, for example in an AC series circuit, that are not in-phase with each other.

If they are in-phase that is, there is no phase shift then they can be added together in the same way as DC values to find the algebraic sum of the two vectors.

For example, if two voltages of say 50 volts and 25 volts respectively are together “in-phase”, they will add or sum together to form one voltage of 75 volts.

If however, they are not in-phase that is, they do not have identical directions or starting point then the phase angle between them needs to be taken into account so they are added together using phasor diagrams to determine their Resultant Phasor or Vector Sum by using the parallelogram law.

Consider two AC voltages, V_1 having a peak voltage of 20 volts, and V_2 having a peak voltage of 30 volts where V_1 leads V_2 by 60° .

The total voltage, V_T of the two voltages can be found by firstly drawing a phasor diagram representing the two vectors and then constructing a parallelogram in which two of the sides are the voltages, V_1 and V_2 as shown in **Figure 2.11**.

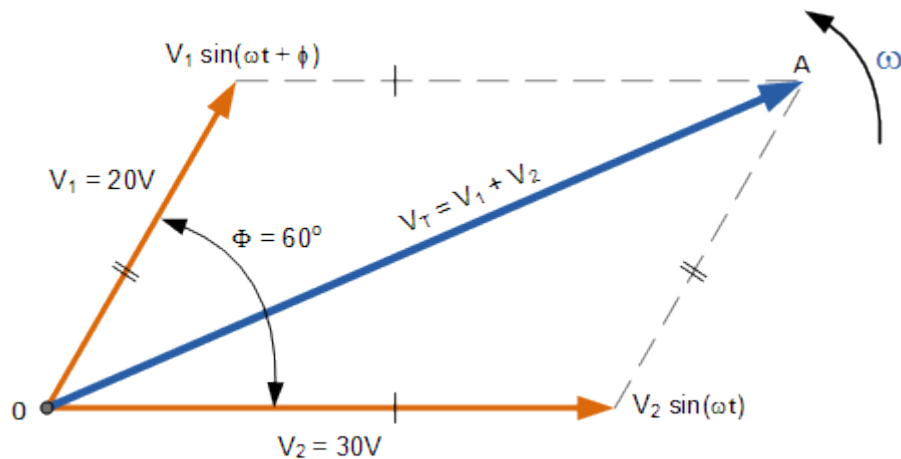


Figure 2.11 Phasor addition

By drawing out the two phasors to scale onto graph paper, their phasor sum $V_1 + V_2$ can be easily found by measuring the length of the diagonal line, known as the “resultant r-vector”, from the zero point to the intersection of the construction lines O-A.

The downside of this graphical method is that it is time consuming when drawing the phasors to scale. Also, while this graphical method gives an answer which is accurate enough for most purposes, it may produce an error if not drawn accurately or correctly to scale.



Note:

One way to ensure that the correct answer is always obtained is by an analytical method.

Mathematically we can add the two voltages together by firstly finding their “vertical” and “horizontal” directions, and from this we can then calculate both the “vertical” and “horizontal” components for the resultant “r vector”, V_r .

This analytical method which uses the cosine and sine rule to find this resultant value is commonly called the Rectangular Form.

In the rectangular form, the phasor is divided up into a real part, x and an imaginary part, y forming the generalized expression $Z = x \pm jy$. (we will discuss this in more detail in the next tutorial). This then gives us a mathematical expression that represents both the magnitude and the phase of the sinusoidal voltage as:

2.3.2 Phasor subtraction

Phasor subtraction is very similar to the above rectangular method of addition, except this time the vector difference is the other diagonal of the parallelogram between the two voltages of V_1 and V_2 as shown in **Figure 2.12**.

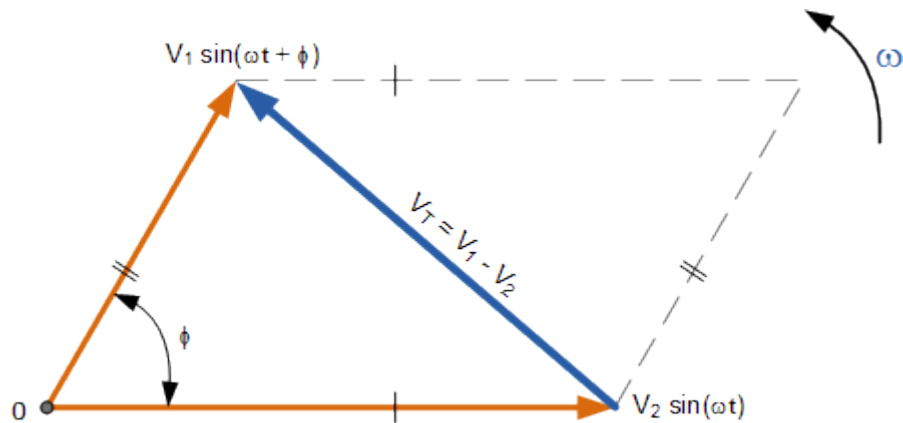


Figure 2.12 Phasor subtraction

This time instead of “adding” together both the horizontal and vertical components we take them away, subtraction.

2.3.3 Phasor diagram summary

In their simplest terms, phasor diagrams are a projection of a rotating vector onto a horizontal axis which represents the instantaneous value.

As a phasor diagram can be drawn to represent any instant of time and therefore any angle, the reference phasor of an alternating quantity is always drawn along the positive x-axis direction.

- Vectors, Phasors and Phasor Diagrams ONLY apply to sinusoidal AC waveforms.
- A Phasor Diagram can be used to represent two or more stationary sinusoidal quantities at any instant in time.
- Generally, the reference phasor is drawn along the horizontal axis and at that instant in time the other phasors are drawn. All phasors are drawn referenced to the horizontal zero axis.
- Phasor diagrams can be drawn to represent more than two sinusoids. They can be either voltage, current or some other alternating quantity but the frequency of all of them must be the same.
- All phasors are drawn rotating in an anticlockwise direction. All the phasors ahead of the reference phasor are said to be “leading” while all the phasors behind the reference phasor are said to be “lagging”.
- Generally, the length of a phasor represents the RMS value of the sinusoidal quantity rather than its maximum value.
- Sinusoids of different frequencies cannot be represented on the same phasor diagram due to the different speed of the vectors. At any instant in time the phase angle between them will be different.
- Two or more vectors can be added or subtracted together and become a single vector, called a Resultant Vector.
- The horizontal side of a vector is equal to the real or x vector. The vertical side of a vector is equal to the imaginary or y vector. The hypotenuse of the resultant right angled triangle is equivalent to the r vector.

- In a three-phase balanced system each individual phasor is displaced by 120° .



Worked Example 2.4

Two sinusoidal quantities are given as $v_1 = 120 \sin \theta$ and $v_2 = 75 \sin(\theta - 30^\circ)$. Find the resultant obtained by:

- The quantities are added
- The quantities are subtracted

Solution:

- See **Figure 2.11**

$$\begin{aligned} \text{Horizontal component of } v_1 &= 120 \\ \text{Horizontal component of } v_2 &= 75 \cos 30 = 65 \\ \text{Horizontal component of } v_3 &= 120 + 65 = 185 \end{aligned}$$

$$\begin{aligned} \text{Vertical component of } v_1 &= 0 \\ \text{Vertical component of } v_2 &= -75 \sin 30 = -37.5 \\ \text{Vertical component of } v_3 &= 0 - 37.5 = -37.5 \end{aligned}$$

$$v_3 = \sqrt{185^2 + 37.5^2} = 188.8$$

$$\text{Angle } \alpha = \tan^{-1} \left[\frac{v_3 \text{ vertical component}}{v_3 \text{ horizontal component}} \right]$$

$$\alpha = \tan^{-1} \left[\frac{37.5}{185} \right] = 11.5^\circ$$

$$v_3 = 188.8 \sin(\theta - 11.5)$$

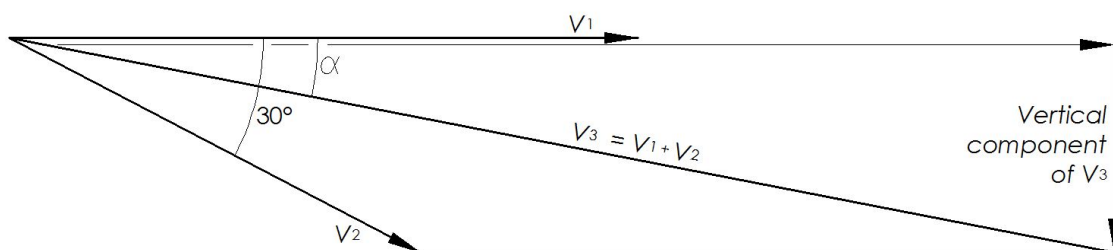


Figure 2.11 Phasor addition

b. See **Figure 2.13**

$$\begin{aligned} \text{Horizontal component of } v_1 &= 120 \\ \text{Horizontal component of } -v_2 &= 75 \cos(180 - 30) = -65 \\ \text{Horizontal component of } v_4 &= 120 - 65 = 55 \end{aligned}$$

$$\begin{aligned} \text{Vertical component of } v_1 &= 0 \\ \text{Vertical component of } v_2 &= 75 \sin(180 - 30) = 37.5 \\ \text{Vertical component of } v_4 &= 0 + 37.5 = 37.5 \end{aligned}$$

$$v_4 = \sqrt{55^2 + 37.5^2} = 66.6$$

$$\alpha = \tan^{-1} \left[\frac{37.5}{55} \right] = 34.3^\circ$$

$$v_4 = 66.6 \sin(\theta + 34.3)$$

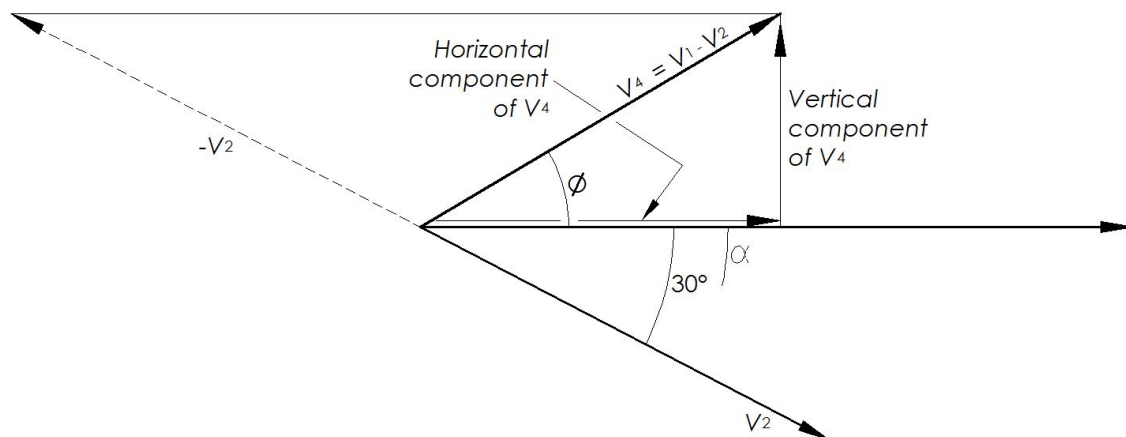


Figure 2.13 Phasor subtraction

2.4 Generating three-phase EMF

2.4.1 Three phase supply

Three-phase systems use three coils. Say Red yellow and blue rotating anticlockwise as shown in **Figure 2.14** inside a magnetic field. Each coil is on the same rotating shaft kept 120° apart.

Each loop creates an identical sinusoidal waveform. in other words, three identical voltages.

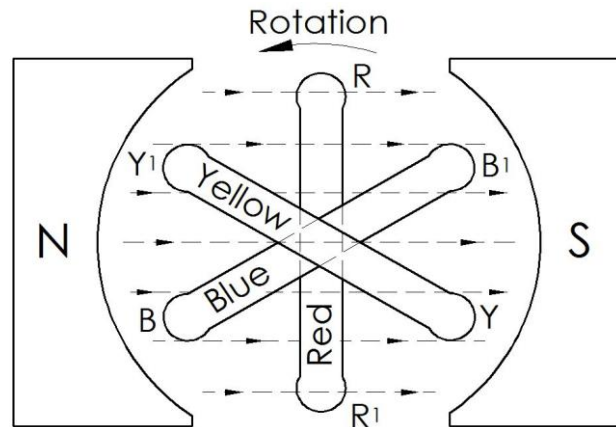


Figure 2.14 Three phase EMF

These three EMF's generated are represented in **Figure 2.15** by three equally spaced, similar curves.

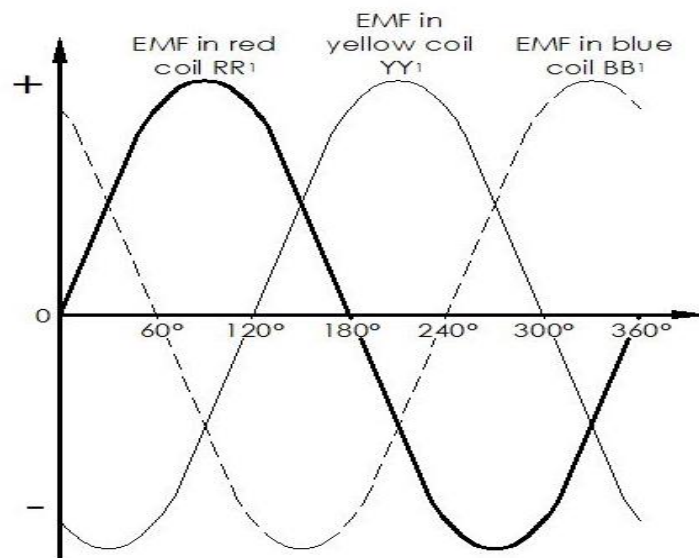


Figure 2.15 Three phase EMF waveforms

It is clear after considering **Figure 2.16** that the three instantaneous EMF's must be:

$$\text{The instantaneous EMF red coil } e_{red} = E_{max} \sin(\theta)$$

$$\text{The instantaneous EMF yellow coil } e_{yel} = E_{max} \sin(\theta - 120^\circ)$$

$$\text{The instantaneous EMF blue coil } e_{blue} = E_{max} \sin(\theta - 240^\circ)$$

2.4.2 Star / delta connections

Star connection

With **star** the start of each of the three phases is connected together. Connections are taken from the ends of the three phases to give the three phases.



Definition: Star

The line voltage between any two phases is the same as the current in the line connected to it; this is $\sqrt{3}$ times voltage induced in any one phase coil in the current in each phase coil.

With star a fourth wire can be added, giving the option of having both a single and three phase supply. We tend to use this when we have an unbalanced load.

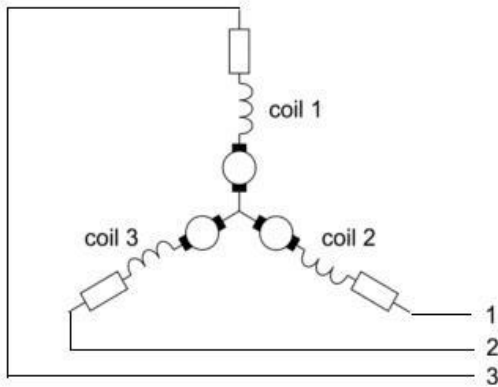


Figure 2.17 Start connection

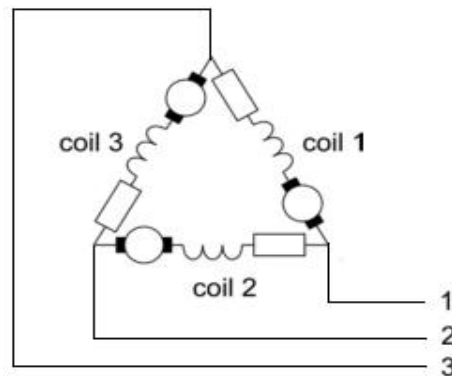


Figure 2.18 Delta connection

Delta connection

With **Delta** the starts and ends of the phases are connected. The end of phase 1 is connected to the start of phase 2, the end of phase 2 to the start of phase 3, and the end of phase 3 to the start of phase 1.

Connections are taken from the three start-end points to give the three phases.



Definition: Delta

The line voltage between any two phases is equal to the phase voltage; the line current is $\sqrt{3}$ times the phase current. We tend to use this when we have a balanced load.

In both cases the three output wires are then connected to Bridge Rectifiers to rectify the generated AC voltage into DC voltage which can then be used to charge a battery bank.

The difference between Star and Delta?

The basic difference between star and delta is that star generates a high voltage at a low current, and delta generates a low voltage at a high current. The total (no load) power generated is the same.

To calculate the output AC voltage and current of a three-phase generator / alternator wired in star or delta it is only necessary to measure the voltage and current of one of the coils.

Multiply the voltage of one coil by the number of coils per phase to obtain the phase voltage.

The square root of the number of phases (3) = 1,732 can be used to calculate the total outputs with either configuration.



Worked Example 2.5

Out of the three phases, one phase gives 20 Volts at 12 Amps. How is the voltage and current affected with a star connection and with a delta connection?

Solution:

1. Star - Voltage = $20 \times 1,732 = 34,6V$, Current is unchanged at 12 Amps.
2. Delta - Voltage is unchanged at 20 Volts, Current = $12 \times 1,732 = 20,8$ Amps.



Note:

Since power is equal to the voltage multiplied by the current, in both cases the power is around 415 Watts in the example above.

2.4.3 Star connected system

Figure 2.19 shows a positive EMF acting from the neutral in the centre of the diagram outwards. The RMS values are represented by V_R , V_Y and V_B . Note that $V_{RY} = V_{BR} - V_{YB}$.

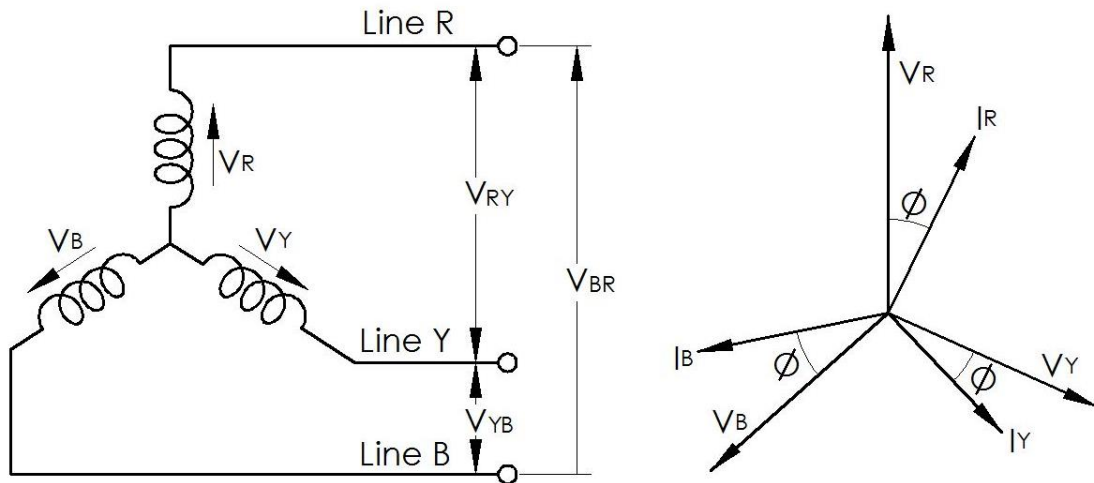


Figure 2.19 Star connected generator with phasor diagram

$$E_{RY} = 2 E_{R\text{Neu}} \cos \phi = \sqrt{3} E_{R\text{Neu}}$$

The line voltage $V_L = 1.73$ the phase voltage V_{Ph}

$$V_L = 1.73 V_{Ph}$$

$$I_L = I_{Ph}$$

2.4.4 Delta connected system

In delta connection, there are three wires alone and no neutral terminal. Normally delta connection is preferred for short distance due to the problem of unbalanced current in the circuit. Figure 2.20 shows a delta connection.

$$E_{Line} = E_{phase} \text{ and } I_{Line} = \sqrt{3} I_{Phase}$$

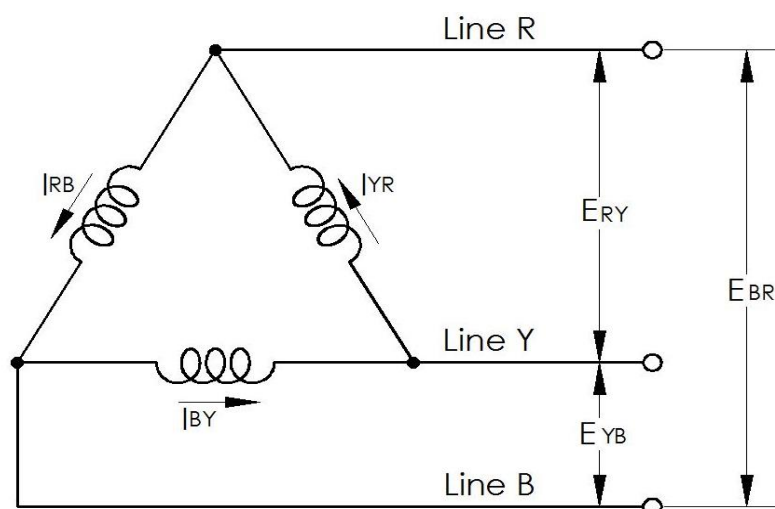


Figure 2.20 Delta connected generator

$$E_R = 2 I_{RB} \cos \phi = \sqrt{3} I_{RB}$$

$$I_L = 1.73 I_{Ph}$$

$$V_L = V_{Ph}$$

2.4.5 Power in a three-phase system

The total power in a balanced system = $I_{Ph} V_{Ph} \times \text{Power factor}$

For a star – connected system $V_{Ph} = \frac{V_L}{1.73}$ and $I_P = I_L$

For a star – connected system: Total power = $1.73 I_L V_L \times \text{Power factor}$

For a mesh – connected system $I_P = \frac{I_L}{1.73}$ and $V_P = V_L$

For a mesh – connected system: Total power = $1.73 I_L V_L \times \text{Power factor}$



Worked Example 2.6

Sketch the phasor diagram for a series circuit at resonance.

The following coordinates were taken during a half cycle of a symmetrical alternating current wave. The current varying in a linear manner between successive points:

Phase angle in degrees	0	30	60	90	120	150	180
Current in amperes	0	10,1	22,4	30	27	22,4	0

Without plotting the graph, determine the following:

1. The mean value
2. The RMS value

Solution:

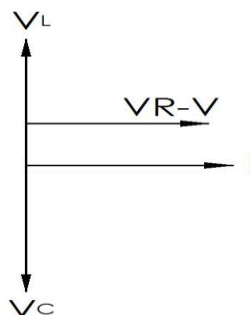


Figure 2.21

$$1. \quad i_1 = \frac{(0+10,1)}{2} = 5,05 \text{ A}$$

$$i_2 = \frac{(10,1+22,4)}{2} = 16,25$$

$$i_3 = \frac{(22,4+30)}{2} = 26,2$$

$$i_4 = \frac{(30+27)}{2} = 28,5$$

$$i_5 = \frac{(27+22,4)}{2} = 24,7$$

$$i_6 = \frac{(22,4+0)}{2} = 11,2$$

$$\begin{aligned} I_{Ave} &= \frac{i_1+i_2+i_3+i_4+i_5+i_6}{n} \\ &= \frac{5,05+16,25+26,2+28,5+24,7+11,2}{6} \\ &= \frac{111,9}{6} \\ &= 18,65 \text{ A} \end{aligned}$$

$$\begin{aligned} 2. \quad I_{RMS} &= \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_6^2 \div n} \\ &= \sqrt{\frac{2523,79}{6}} \\ &= 20,5 \text{ A} \end{aligned}$$



Worked Example 2.7

A coil with a resistance of 10Ω and an inductance of $0,0191 \text{ H}$ is connected in parallel with a circuit with a $75 \mu\text{F}$ capacitor in series with a 5Ω resistance. The circuit is connected to a 12 V , 50 Hz supply.

Determine:

1. The current in each branch
2. The total supply current, power factor and power

Solution:

$$1. \quad XC = \frac{1}{2\pi fc}$$

$$= \frac{1}{2\pi \times 50 \times 75 \times 10^{-6}}$$

$$= 42,44 \, \Omega$$

$$XL = 2\pi fL$$

$$= 2\pi \times 50 \times 0,0191$$

$$= 6 \, \Omega$$

$$I_A = \frac{VT}{Z_A} = \frac{120}{10+j6} = \frac{120\angle 0}{11,6\angle 30,9} = 10,29\angle -30,9$$

$$I_B = \frac{VT}{Z_B} = \frac{120}{5-j42,44} = \frac{120\angle 0}{42,734\angle -83,3} = 2,8\angle 83,3$$

$$2. \quad IT = I_1 + I_2 = 10,29\angle(-30,9) + 2,8\angle 83,3 \text{ A}$$

$$= 8,83 - j5,28 + 0,326 + j2,78$$

$$= 9,156 - j2,499$$

$$= 9,49 \angle -15,26$$

$$Pf = \cos(15,26) \text{ lagging}$$

$$= 0,964 \text{ lagging}$$

$$P = VI \cos \Phi$$

$$= 120 \times 9,49 \times 0,964$$

$$= 1\,097,8 \text{ W}$$

**Worked Example 2.8**

The following ordinates were taken during a half cycle of a symmetrical alternating current wave. The current varies in a linear manner between successive points:

Phase angle in degrees	0	30	60	90	120	150	180
Current in amperes	0	12,6	24,4	31	29	24,4	0

Determine the following without plotting the graph:

1. The mean value
2. The RMS value

Solution:

$$1. \quad i_1 = \frac{(0+12,6)}{2} = 6,3 \text{ A}$$

$$i_2 = \frac{(12,6+24,4)}{2} = 18,5$$

$$i_3 = \frac{(24,4+31)}{2} = 27,7$$

$$i_4 = \frac{(31+29)}{2} = 30$$

$$i_5 = \frac{(29+24,4)}{2} = 26,7$$

$$i_6 = \frac{(24,4+0)}{2} = 12,2$$

$$\begin{aligned} I_{ave} &= \frac{i_1+i_2+i_3+i_4+i_5+i_6}{n} \\ &= \frac{6,3+18,5+27,7+30+26,7+12,2}{6} \\ &= \frac{121,4}{6} \\ &= 20,23 \text{ A} \end{aligned}$$

$$\begin{aligned} 2. \quad I_{rms} &= \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_6^2 \div n} \\ &= \sqrt{\frac{6,3^2+18,5^2+27,7^2+30^2+26,7^2+12,2^2}{n}} \\ &= \sqrt{\frac{2910,96}{6}} \\ &= 22,03 \text{ A} \end{aligned}$$



Worked Example 2.9

A resonant circuit comprising of a coil of inductance $650 \mu\text{H}$ and a resistance of 60 ohms in parallel with a variable capacitor, is connected in series with a resistor of $9\,900 \text{ ohms}$. The supply across this circuit is 80 V , with a frequency of $1,5 \text{ MHz}$.

Calculate the:

1. Value of the capacitor at resonance
2. Impedance of the parallel circuit
3. Current in each branch

Solution:

$$1. \quad XL = 2\pi fL$$

$$= 2\pi \times 1,5 \times 10^6 \times 650 \times 10^{-6} = 6126,11 \Omega$$

$$f(res) = \frac{1}{2}\pi\sqrt{LC}$$

$$1,5 \times 10^6 = \frac{1}{2}\pi\sqrt{650 \times 10^{-6} \times C}$$

$$\sqrt{650 \times 10^{-6} \times C} = 1 / \sqrt{2\pi \times 10^6 \times 1,5}$$

$$650 \times 10^{-6} \times C = (1 / 2\pi \times 10^6 \times 1,5)^2$$

$$C = 1,73 \times 10^{-11}$$

$$= 1,73 \times 10^{-12} F$$

$$2. \quad Z_{parallel} = L/CR$$

$$= \frac{650 \times 10^{-6}}{17,3 \times 10^{-12} \times 60}$$

$$= 626,204 k \Omega$$

$$3. \quad I = V/ZT$$

$$= \frac{80}{9900} + 626\,204$$

$$= \frac{80}{636104}$$

$$= 0,126 mA$$

$$pd \text{ across coil} = 0,126 \times 10^{-3} \times 626204 = 78,9 V$$

$$1 \text{ coil} = 78,9 / \sqrt{(60)^2 + (6126,11)^2}$$

$$= 12,88 mA$$

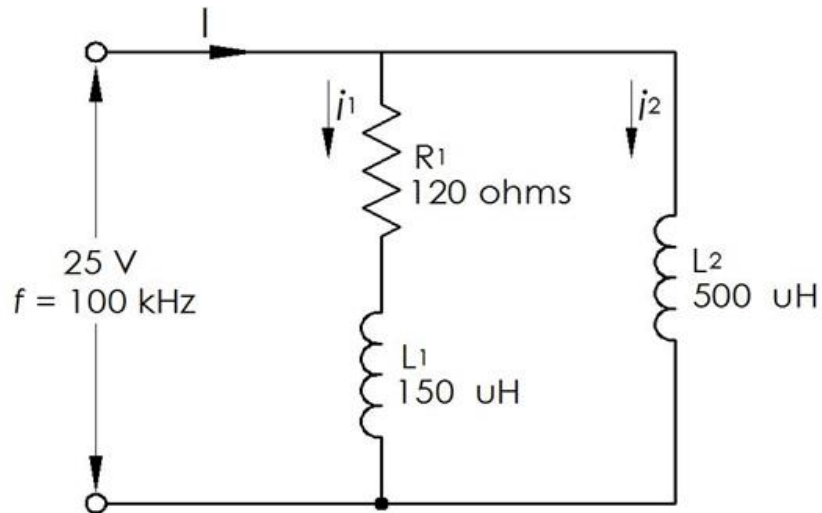
$$1 \text{ cap} = 2\pi \times 1,5 \times 10^6 \times 1,73 \times 10^{-12} \times 78,9$$

$$= 0,129 mA$$



Activity 2.1

Calculate i_1 , i_2 and I in **Figure 2.13** below. Then replace R_1 and L_1 with their parallel equivalent circuits. Calculate all branch currents and the supply current.



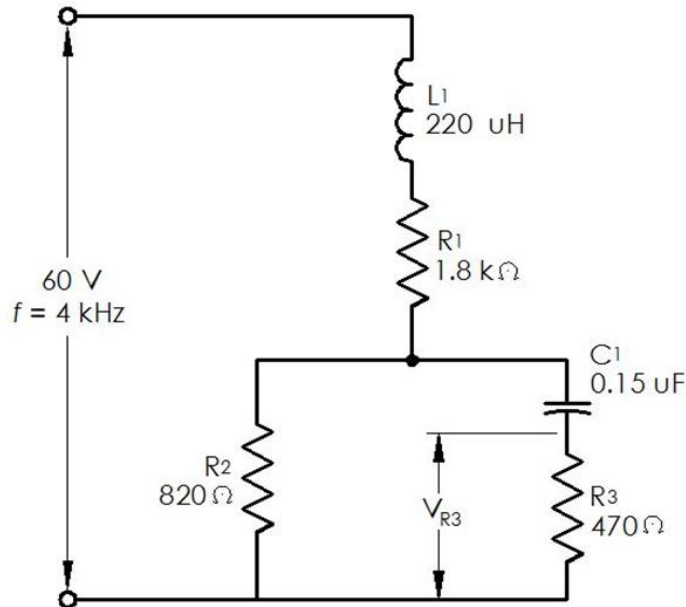
[163.8 mA $\angle -38.1^\circ$; 79.6 mA $\angle -90^\circ$; 221.9 mA $\angle -54.5^\circ$; 128.9 mA $\angle 0^\circ$;
101 mA $\angle -90^\circ$; 79.6 mA $\angle -90^\circ$; 221.9 mA $\angle -54.5^\circ$]

Figure 2.22



Activity 2.2

Determine V_{R3} in the circuit **Figure 2.23**.



$$[3.04 \text{ V } \angle -57.1^\circ]$$

Figure 2.23



Activity 2.3

Two circuits are connected parallel to a 350 V, 50 Hz supply. The total current taken by the combination is 30 A, at unity power factor. Circuit A consists of a $8,5 \Omega$ resistor and a $185 \mu\text{f}$ capacitor connected in series. Circuit B consists of a resistor and an inductive reactance in series.

Calculate for circuit B:

1. The current
2. The power factor
3. The impedance
4. The reactance
5. The resistance

$$[-63.72; 63.72; 0.648 \text{ lag}; 10.57 + j12.41]$$



Activity 2.4

The voltage across a certain circuit element is:

$v(t) = 755 \sin(628 t + 30^\circ)V$ and the current flowing in this element is:

$i(t) = 8,8 \sin(628 t + 30^\circ)A$

Determine the following:

1. The nature and magnitude of this element
2. The time period of the waveform

[85.8; 6.22; 85.8; 10]



Activity 2.5

An impedance of $6 + j18 \Omega$ is connected in series with two impedances in parallel, one of $13 + j18 \Omega$ and the other of $14 - j13 \Omega$.

The combination is then connected across a 245 V, AC supply.

Calculate the following:

1. The total impedance
2. The total current drawn from the supply
3. The power factor

[15.44+j0.21; 28.13/40.34; 8.71/40.34; cos -40.34; 0.76 lag]




Activity 2.6


An impedance of $9 + j11 \Omega$ is connected in series with two impedances in parallel, one of $11 + j15 \Omega$ and the other of $15 - j8 \Omega$. This combination is then connected across a 150 V alternating current supply.


Calculate the following:

1. The total impedance
2. The total current
3. The power factor

[14.21<50.7; 17<-28.07; 18.6<53.75; 24.39<32.65; 6.15<-32.65; 0.84 Lag]

	<h3 style="margin: 0;">Activity 2.7</h3> <p>A coil with a resistance of $30\ \Omega$ and an inductance of $0,06\ \text{H}$, is connected in parallel with a circuit consisting of a $190\ \mu\text{f}$ capacitor in series with a $28\ \Omega$ resistor. The supply is $280\ \text{V}$, $50\ \text{Hz}$.</p> <p>Calculate the following:</p> <ol style="list-style-type: none"> 1. The total line current and the current in each branch 2. Power and power factor <p>[16.75; 7.9<-32.14; 3892]</p>
---	--

	<h3 style="margin: 0;">Activity 2.8</h3> <p>A circuit, with a resistance of $8,5\ \Omega$, an inductance of $0,7\ \text{H}$ and a variable capacitance in series, is connected across a $180\ \text{V}$, $50\ \text{Hz}$ supply.</p> <p>Calculate:</p> <ol style="list-style-type: none"> 1. The capacitance to give resonance 2. The voltages across the inductance and the capacitance <p>[14.47; 21.18; 4657.73]</p>
---	---

	<h3 style="margin: 0;">Self-Check</h3>		
I am able to:	Yes	No	
• Describe single and three-phase systems			
• Describe instantaneous, average and RMS values			
• Describe star and delta connections			
• Calculate mixed circuits using phasors			
• Calculate types of waveforms and power			
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.			

Module 3

Transformers

Learning Outcomes

On the completion of this module the student must be able to:

- Describe the use, construction and operation of three-phase transformers
- Describe useful and leakage flux and reactance
- Describe transformers in parallel, no-load and on load
- Describe equivalent circuits and sharing load
- Calculate currents and power

3.1 Introduction



This module describes the use, construction and operation of three-phase transformers. It describes useful and leakage flux and reactance, transformers in parallel, no-load and on load, equivalent circuits and sharing load. It also gives examples of the calculations used in currents and power.

3.2 Construction of three-phase transformers

There are many different types of transformers.

Below is a list of a few of them:



Definitions:

Autotransformer:

Transformer in which part of the winding is common to both primary and secondary circuits.

Capacitor voltage transformer:

Transformer in which capacitor divider is used to reduce high voltage before application to the primary winding.

Distribution transformer, power transformer:

International standards make a distinction in terms of distribution transformers being used to distribute energy from transmission lines and networks for local

consumption and power transformers being used to transfer electric energy between the generator and distribution primary circuits.

Phase angle regulating transformer:

A specialized transformer used to control the flow of real power on three-phase electricity transmission networks.

Scott-T transformer:

Transformer used for phase transformation from three-phase to two-phase and vice versa.

Poly-phase transformer:

Any transformer with more than one phase.

3.2.1 Uses of three-phase transformers

Transformers are used to increase (or step-up) voltage before transmitting electrical energy over long distances through wires.

Wires have resistance which loses energy through joule heating at a rate corresponding to square of the current. By transforming power to a higher voltage transformers enable economical transmission of power and distribution.

Consequently, transformers have shaped the electricity supply industry, permitting generation to be located remotely from points of demand.

Transformers are also used extensively in electronic products to decrease (or step-down) the supply voltage to a level suitable for the low voltage circuits they contain.

The transformer also electrically isolates the end user from contact with the supply voltage.

3.2.2 Construction of three-phase transformers

The core:

Distribution transformers are made using a core made from laminations of sheet steel stacked and either glued together with resin or banded together with steel straps.

Where large numbers of transformers are made to standard designs, a wound C-shaped core is economic to manufacture.

A steel strip is wrapped around a former, pressed into shape and then cut into two C-shaped halves, which are re-assembled on the copper windings.

Windings:

The primary coils are wound from enamel coated copper or aluminum wire and the high current, low voltage secondary's are wound using a thick ribbon of aluminum or copper.

The windings are insulated with resin-impregnated paper. The entire assembly is baked to cure the resin and then submerged in a powder coated steel tank which is then filled with transformer oil (or other insulating liquid), which is inert and non-conductive.

Cooling:

The transformer oil cools and insulates the windings, and protects the transformer winding from moisture, which will float on the surface of the oil. The tank is temporarily depressurized to remove any remaining moisture that would cause arcing and is sealed against the weather with a gasket at the top.

The tank of liquid filled transformers often have radiators through which the liquid coolant circulates by natural convection or fins. Some large transformers employ electric fans for forced-air cooling, pumps for forced-liquid cooling, or have heat exchangers for water-cooling.

**Note:**

An oil-immersed transformer may be equipped with a Buchholz relay, which, depending on severity of gas accumulation due to internal arcing, is used to either alarm or de-energize the transformer.

Bushings:

Larger transformers are provided with high-voltage insulated bushings made of polymers or porcelain. A large bushing can be a complex structure since it must provide careful control of the electric field gradient without letting the transformer leak oil.^[83]

3.2.3 Operation of three-phase transformers

In electrical engineering, three-phase electric power systems have at least three conductors carrying alternating current voltages that are offset in time by one-third of the period.

A three-phase system may be arranged in delta (Δ) or star (Y) (also denoted as wye in some areas). A wye system allows the use of two different voltages from all three phases, such as a 230/400 V system which provides 230 V between the neutral (centre hub) and any one of the phases, and 400 V across any two phases.

A delta system arrangement only provides one voltage magnitude, however it has a greater redundancy as it may continue to operate normally with one of the three supply windings offline, albeit at 57.7% of total capacity. Harmonic

currents in the neutral may become very large if non-linear loads are connected.

Generally, in electric power systems, the loads are distributed as evenly as is practical between the phases. It is usual practice to discuss a balanced system first and then describe the effects of unbalanced systems as deviations from the elementary case.

An important property of three-phase power is that the power available to a resistive load, is constant at all times.

$$\text{Constant power } P = VI = \frac{1}{R} V^2$$



Note:

If the neutral current is zero we can remove the neutral core and it will have no effect on the circuit, provided the system is balanced.

Such connections are generally used only when the load on the three phases is part of the same piece of equipment (for example a three-phase motor), as otherwise switching loads and slight imbalances would cause large voltage fluctuations.

In practice, systems rarely have perfectly balanced loads, currents, voltages and impedances in all three phases. The analysis of unbalanced cases is greatly simplified by the use of the techniques of symmetrical components.

An unbalanced system is analyzed as the superposition of three balanced systems, each with the positive, negative or zero sequence of balanced voltages.

When specifying wiring sizes in a three-phase system, we only need to know the magnitude of the phase and neutral currents. The neutral current can be determined by adding the three phase currents together as complex numbers and then converting from rectangular to polar co-ordinates.

If the three-phase root mean square (RMS) currents are I_{L1} , I_{L2} and I_{L3} , the neutral RMS current is:

$$I_{L1} + I_{L2} \cos \frac{2}{3} \pi + j I_{L2} \sin \frac{2}{3} \pi + I_{L3} \cos \frac{4}{3} \pi + j I_{L3} \sin \frac{4}{3} \pi$$

$$I_{L1} - I_{L2} \frac{1}{2} - I_{L3} \frac{1}{2} + j \frac{\sqrt{3}}{2} (I_{L2} - I_{L3})$$

The polar magnitude of this is the square root of the sum of the squares of the real and imaginary parts, which reduces to:

$$\sqrt{I_{L1}^2 + I_{L2}^2 + I_{L3}^2 - I_{L1} I_{L2} - I_{L1} I_{L3} - I_{L2} I_{L3}}$$

3.3 Welding machines

3.3.1 Power supply

A transformer-style welding power supply converts the moderate voltage and moderate current electricity from the utility mains (typically 230 or 115 VAC) into a high current and low voltage supply, typically between 17 to 45 (open-circuit) volts and 55 to 590 amperes.



Note:

A rectifier converts the AC into DC on more expensive machines.

This design typically allows the welder to select the output current by:

- Various moving a primary winding closer or farther from a secondary winding.
- Moving a magnetic shunt in and out of the core of the transformer.
- Using a series saturating reactor with a variable saturating technique in series with the secondary current output.
- Permitting the welder to select the output voltage from a set of taps on the transformer's secondary winding.

3.3.2 Welding transformer leakage

A triac may be used to control the welding transformer leakage reactance and thus the welding currents.

This new method keeps the input and output currents and voltages in sinusoidal wave forms.

The triac is connected across the terminals of a coil wound on a fixed limb magnetic shunt.

A simple triggering circuit is used to control the current of the triac and thus the current of magnetic shunt coil. This leads to variation of welding transformer leakage flux, leakage reactance and thus a variation of welding current.

3.3.3 Operation of three-phase welding machines

For clarity, electrical equipment has been omitted from **Figure 3.1**. These include:

A noise filter, The inrush current protection circuit, the smoothing circuit, the control circuit and the overload detection circuit.

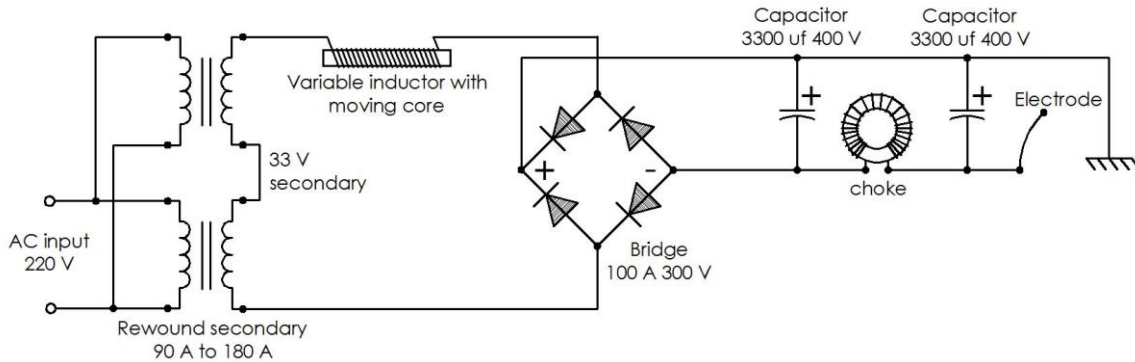


Figure 3.1 Welding machine circuit

3.4 Useful flux and leakage

A varying current in the transformer's primary winding creates a varying magnetic flux in the transformer core and a varying field impinging on the transformer's secondary winding.

This varying magnetic field at the secondary winding induces a varying electromotive force (EMF) or voltage in the secondary winding due to electromagnetic induction.

3.4.1 Inductive reactance

All the flux in transformer will not be able to link with both the primary and secondary windings. A small portion of flux will link with either winding but not both.

This portion of flux is called leakage flux. Due to this leakage flux in a transformer, there will be self-reactance in the winding. This self-reactance of a transformer is alternatively known as leakage reactance.

This self-reactance associated with the resistance of a transformer is impedance. Due to this impedance of a transformer, there will be voltage drops in both primary and secondary transformer windings.

3.4.2 Resistance of a transformer

Generally, both primary and secondary windings of electrical power transformer are made of copper. Copper is a very good conductor of current but not a super conductor.



Note:

Both primary and secondary windings will have resistance and leakage reactance.

This resistance is combined to the reactance and makes up the impedance of transformer. If R_1 & R_2 and X_1 & X_2 are primary & secondary resistance & leakage reactance of transformer respectively, then Z_1 & Z_2 impedance of the primary & secondary windings are:

$$Z_1 = R_1 + jX_1$$

And:

$$Z_2 = R_2 + jX_2$$

The Impedance of transformer plays a vital role during parallel operation of transformer.

3.4.3 Leakage flux

In an ideal transformer, all the flux will link with both primary and secondary windings, but in reality, it is impossible to link all the flux in a transformer with both primary and secondary windings.

Most of the flux will link with both windings through the core of a transformer but still there will be a small amount of flux which will link with either winding but not with both. See **Figure 3.2**.

This flux is called leakage flux which will pass through the winding insulation and transformer oil instead of passing through core.

Due to this **leakage flux in a transformer**, both primary and secondary windings have leakage reactance. The reactance of a transformer is the **leakage reactance of transformer**. This phenomenon in a transformer is known as Magnetic leakage.

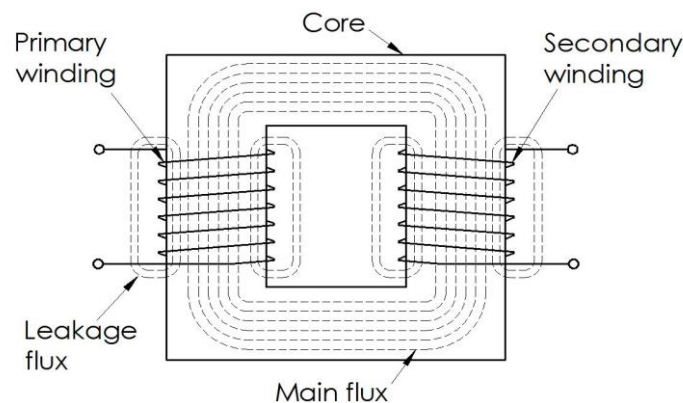


Figure 3.2 Leakage in a transformer

Voltage drop in the windings occur due to impedance of the transformer. Impedance is a combination of resistance and leakage reactance of transformer.

If we apply a voltage V_1 across the primary windings of a transformer, there will be a component $I_1 X_1$ to balance the primary self-induced EMF due to the primary leakage reactance. (where X_1 is primary leakage reactance). Now if


we also consider the voltage drop due to the primary resistance of the transformer, then the voltage equation of a transformer is:

$$V_1 = E_1 + I_1 (R_1 + jX_1)$$

Similarly, for the secondary leakage reactance, the voltage equation of secondary side is,

$$V_2 = E_2 + I_2 (R_2 + jX_2)$$

Here in **Figure 3.2**, the primary and secondary windings are shown in separate limbs and this arrangement could result a large leakage flux in the transformer because there is much room for leakage.

	<p>Note: Leakage in primary and secondary windings could be eliminated if the windings could be made to occupy the same space. This of course is physically impossible but, by placing secondary and primary in a concentric manner can solve the problem to an extent.</p>
---	--

3.4.4 Reducing inductive reactance

There are a number of ways to reduce the negative effects of leakage flux:

- Change the shape of the core by increasing the distance between the windings. This ratio of width to length is limited to about 4.
- Place the primary windings next to the core and the secondary windings on the outside. This is usual practice.
- Sandwich the primary winding between two secondary windings.
- Use the shell type of core. The iron in the centre between the windings act as a barrier.

3.5 On load and off load

3.5.1 Transformer at no-load having no winding resistance and no leakage

A transformer has only core losses but no copper loss and no leakage reactance.

When an alternating source is applied in the primary, the source will supply the current for magnetizing the core of the transformer. But this current is not the actual magnetizing current, it is little bit greater than actual magnetizing current.

The total current supplied from the source has two components, one is magnetizing current which is merely utilized for magnetizing the core and other component of the source current is consumed for compensating the core losses in transformer.

Because of this core loss component, the source current in the transformer on no-load condition is not lagging at 90° to the voltage, but lags at an angle θ ... less than 90° .

If the total current supplied from the source is I_0 , it will have one component in phase with the supply voltage V_1 , and one component of the current I_w , which is the core loss component.

This component is taken in phase with the source voltage, because it is associated with active or working losses in transformer. The other component of the source current is denoted as I_μ .



Note:

This component produces the alternating magnetic flux in the core, so it is watt-less; meaning it is a reactive part of the transformer source current.

Hence I_μ will be in quadrature with V_1 and in phase with alternating flux Φ . Hence, total primary current in transformer on no-load condition can be represented as:

$$I_0 = I_u + I_w$$

$$|I_u| = |I_0| \cos \theta$$

$$|I_w| = |I_0| \sin \theta$$

$$|I_w| = \sqrt{|I_u|^2 + |I_w|^2}$$

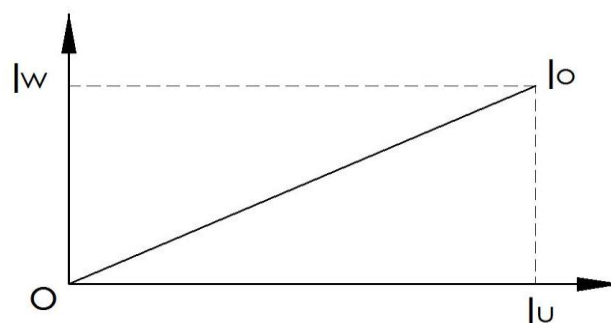


Figure 3.3 Excitation current transfer

3.5.2 Transformer at on-load having no winding resistance and no leakage

The transformer on load, means load is connected to the secondary terminals.

A transformer having core loss but no copper loss and leakage reactance. Whenever load is connected to the secondary winding, load current will start to flow through the primary as well as secondary winding.

This load current solely depends upon the characteristics of the load and also upon secondary voltage of the transformer. This current is called secondary current or load current, here it is denoted as I_2 .

As I_2 is flowing through the secondary, a self MMF in secondary winding will be produced. Here it is $N_2 I_2$, where, N_2 is the number of turns of the secondary winding of transformer.

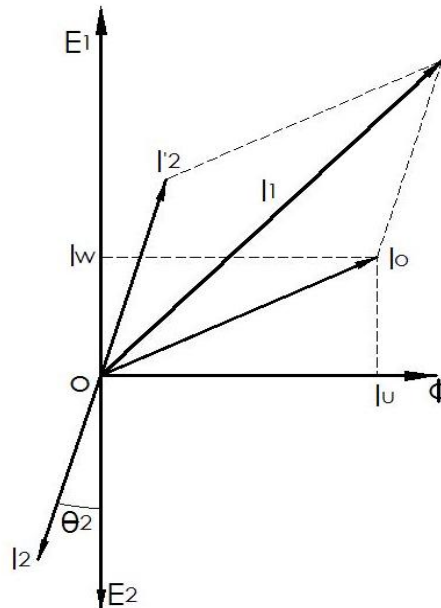


Figure 3.4 On-load primary current transfer

This MMF or magneto motive force in the secondary winding produces flux ϕ_2 . This ϕ_2 will oppose the main magnetizing flux and momentarily weakens the main flux and tries to reduce primary self-induced EMF E_1 .

If E_1 falls below the primary source voltage V_1 , there will be an extra current flowing from source to primary winding. This extra primary current I_2' produces extra flux ϕ' in the core which will neutralize the secondary counter flux ϕ_2 .



Note:

Hence the main magnetizing flux of core, Φ remains unchanged irrespective of load.

So total current, this transformer draws from source can be divided into two components, first one is utilized for magnetizing the core and compensating the core loss i.e. I_0 . It is no-load component of the primary current.

Second one is utilized for compensating the counter flux of the secondary winding. It is known as load component of the primary current. Hence total no

load primary current I_1 of a electrical power transformer having no winding resistance and leakage reactance can be represented as follows:

$$I_1 = I_0 + I'_2$$

Where θ_2 is the angle between Secondary Voltage and Secondary Current of transformer. Now we will proceed one further step toward more practical aspect of a transformer.

3.5.3 Transformer at on-load having winding resistance but no leakage

The winding resistance of a transformer with no leakage reactance. So far we have discussed the transformer which has ideal windings, which means having winding with no resistance and leakage reactance, but now we will consider a transformer which has internal resistance in the winding but no leakage reactance.

As the windings are resistive, there would be a voltage drop in the windings.

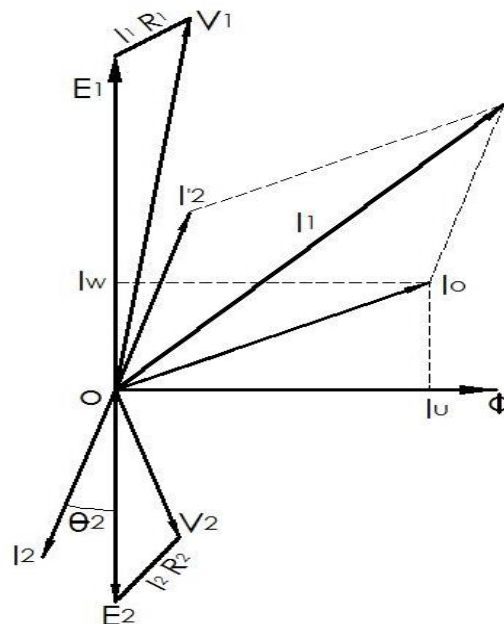


Figure 3.5 On-load current transfer with resistive winding

Total primary current from the source on load is I_1 . The voltage drop in the primary winding with resistance, R_1 is $R_1 I_1$. Obviously, induced EMF across primary winding E_1 , is not exactly equal to source voltage V_1 . E_1 is less than V_1 by voltage drop $I_1 R_1$.

$$V_1 = E_1 + I_1 R_1$$

The voltage induced across the secondary winding, E_2 does not totally appear across the load since it also drops by an amount $I_2 R_2$, where R_2 is the secondary winding resistance and I_2 is secondary current or load current. Similarly, voltage equation of the secondary side of the transformer will be:

$$V_2 = E_2 + I_2 R_2$$

3.5.4 Transformer at on-load having winding resistance and leakage

Now we will consider the condition, when there is leakage reactance of transformer as well as winding resistance of transformer.

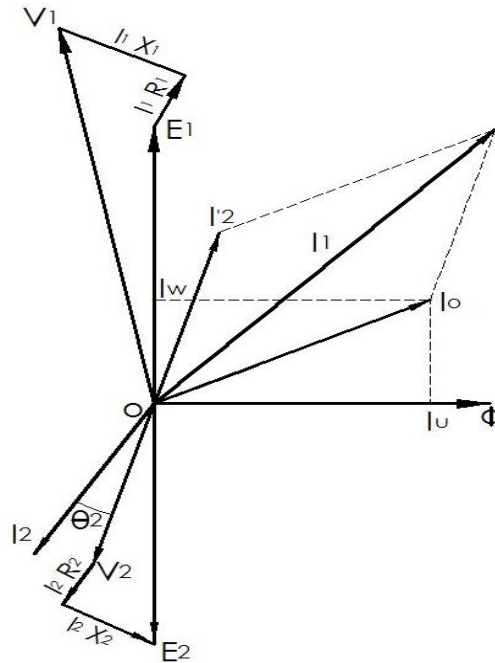


Figure 3.6 On-load current transfer

Let leakage reactances of primary and secondary windings of the transformer be X_1 and X_2 respectively.

Hence total impedance of primary and secondary winding of transformer with resistance R_1 and R_2 respectively, can be represented as:

$$\text{Impedance of the primary winding } Z_1 = R_1 + jX_1$$

$$\text{Impedance of the secondary winding } Z_2 = R_2 + jX_2$$

We have already established the voltage equation of a transformer on load, with only resistances in the windings, where voltage drops in the windings occur only due to resistive voltage drop.

But when we consider leakage reactances of transformer windings, voltage drop occurs in the winding not only because of resistance, but because of impedance of transformer windings.

**Note:**

Hence, actual voltage equation of a transformer can easily be determined by just replacing resistances R_1 & R_2 in the previously established voltage equations by Z_1 and Z_2 .

3.5 Equivalent circuit of a transformer

Equivalent impedance of a transformer is necessary to know so the design of a new transformer may be compared to this standard to meet the power requirements.

Percentage impedance is also a very essential parameter of a transformer. Special attention is to be given to this parameter during installing a transformer in an existing electrical power system.

**Note:**

Percentage impedance of different power transformers should be properly matched during parallel operation of power transformers.

The percentage impedance can be derived from the equivalent impedance of a transformer. It can be said that equivalent circuit of a transformer is also required during calculation of % impedance.

3.5.1 Primary equivalent circuit

For drawing an equivalent circuit of a transformer referring to the primary. First, establish the general equivalent circuit of a transformer then, modify it according to the primary side. **Figure 3.7.**

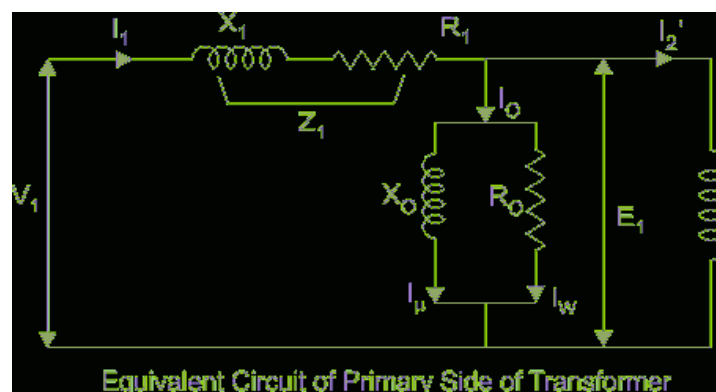


Figure 3.7

3.5.2 Approximate equivalent circuit

Since I_0 is very small compared to I_1 , it is less than 5% of full load primary current, I_0 changes the voltage drop insignificantly.

Hence, it is good approximation to ignore the excitation circuit in approximate equivalent circuit of transformer. The winding resistance and reactance being in series can now be combined into equivalent resistance and reactance of

transformer, referred to any particular side. In this case it is side 1 or primary side.

$$V'_2 = K V_2$$

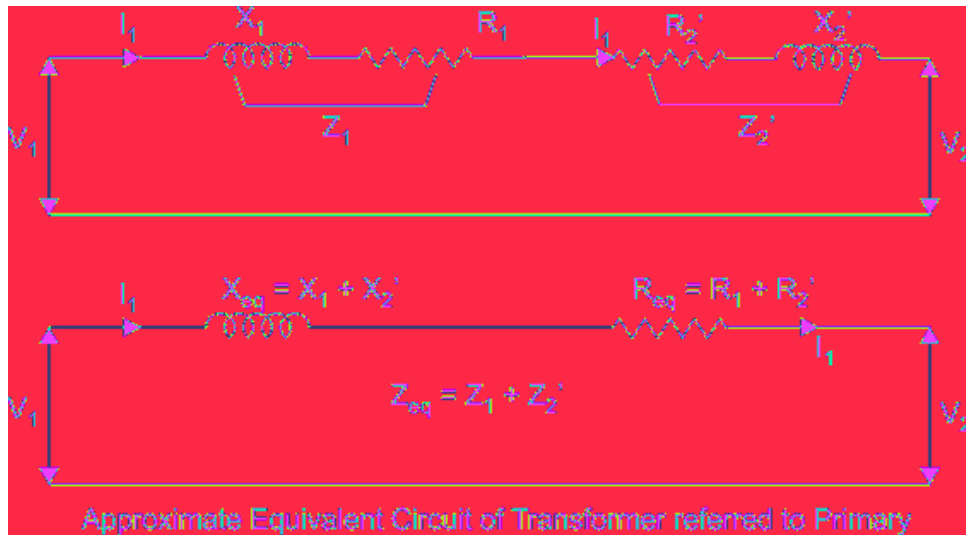


Figure 3.8

3.5.3 Equivalent circuit on secondary

In similar way, approximate equivalent circuit of transformer referred to secondary can be drawn.

Where equivalent impedance of transformer referred to secondary, can be derived as:

$$Z'_1 = \frac{Z_1}{K^2}$$

$$R'_1 = \frac{R_1}{K^2}$$

$$X'_1 = \frac{X_1}{K^2}$$

$$V'_1 = \frac{V_1}{K}$$

3.6 Voltage regulation of a transformer

If an electrical power transformer is open circuited, it means load is not connected with secondary terminals.

In this situation, the secondary terminal voltage of the transformer will be its secondary induced EMF E_2 . Whenever full load is connected to the secondary

terminals of the transformer, rated current I_2 flows through the secondary circuit and voltage drop comes into picture.

At this situation, primary winding will also draw equivalent full load current from source. The voltage drop in the secondary is $I_2 Z_2$ where Z_2 is the secondary impedance of transformer.

Now if at this loading condition, the voltage between the secondary terminals is measured, a voltage V_2 across load terminals is obtained which is obviously less than no load secondary voltage E_2 and this is because of $I_2 Z_2$ voltage drop in the transformer.

3.6.1 Voltage regulation of a transformer

Expression of Voltage Regulation of Transformer, represented in

$$\text{Percentage voltage regulation} = \frac{E_2 - V_2}{V_2} \times 100 \%$$

3.6.2 Voltage regulation of a transformer for a lagging power factor

Now we will derive the expression of voltage regulation in detail. Say lagging power factor of the load is $\cos \theta_2$, that means angle between secondary current and voltage is θ_2

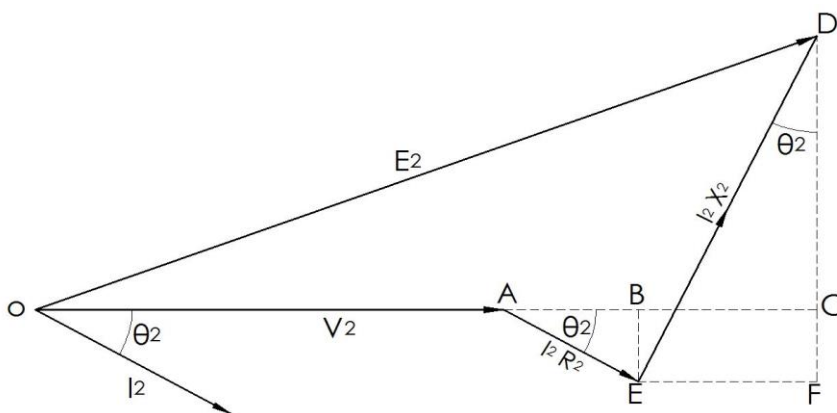


Figure 3.9 Voltage regulation with lagging power factor

$$\text{From Figure 3.9 } BC = DE \sin \theta_2 = I_2 X_2 \sin \theta_2$$

Angle between OC & OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

Voltage regulation of transformer at lagging power factor:

$$\text{Percentage voltage regulation} = \frac{E_2 - V_2}{V_2} \times 100 \%$$

$$\text{Percentage voltage regulation} = \frac{I_2 R_2 \cos \theta_2 - I_2 X_2 \sin \theta_2}{V_2} \times 100 \%$$

3.6.3 Voltage regulation of a transformer for a leading power factor

Let's derive the expression of voltage regulation with leading current, say leading power factor of the load is $\cos \theta_2$, that means angle between secondary current and voltage is θ_2 .

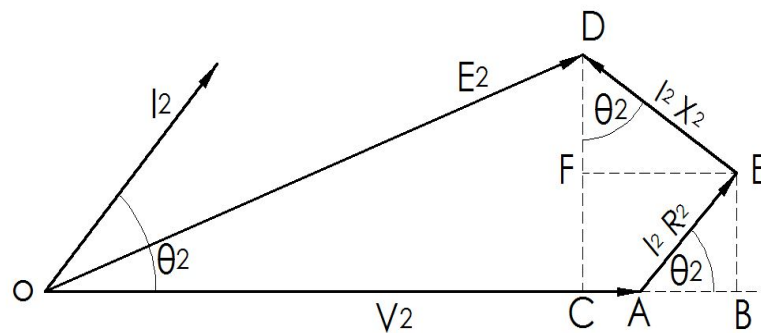


Figure 3.10 Voltage regulation with leading power factor

3.7 Transformers in parallel

It is economical to install numbers of smaller rated transformers in parallel than installing a bigger rated electrical power transformers.

This has mainly the following advantages,

- To maximize electrical power system efficiency: Generally, electrical power transformer gives the maximum efficiency at full load. If a number of transformers are run in parallel, only those transformers which will give the total power demand need be switched on. When the load increases, more can be brought into service. This ensures maximum efficiency.
- Transformers can be brought out of service for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.
- If one transformer trips due to a fault, the other parallel transformers in the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.
- To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future. This can easily be done with this system.

3.7.1 Conditions of parallel operation

When two or more transformers run in parallel, they must satisfy the following conditions for satisfactory performance.

These are the conditions for parallel operation of transformers.

- Same voltage and Turns Ratio (both primary and secondary voltage rating is same)

- Same Percentage Impedance and X/R ratio
- Identical Position of Tap changer
- Same KVA ratings
- Same Phase angle shift (vector group are same)
- Same Frequency rating
- Same Polarity
- Same Phase sequence

With two transformers, T_1 and T_2 :

$$\text{The power} = VI = \text{Load of } T_1 + \text{Load of } T_2$$

$$\text{Load of } T_1 = VI \frac{Z_2}{Z_1 + Z_2}$$

$$\text{Load of } T_2 = VI \frac{Z_1}{Z_1 + Z_2}$$

3.7.2 Load sharing

Connecting transformers in parallel with the same parameters results in equal load sharing and no circulating currents in the transformer windings.

Connecting two 2000 kVA, 5.75% impedance transformers in parallel, each with the same turn ratios to a 4000 kVA load.

- Loading on the transformers-1 = $kVA_1 = [(kVA_1 / \%Z) / ((kVA_1 / \%Z_1) + (kVA_2 / \%Z_2))] \times 4000$ kVA
- $kVA_1 = 348 / (348 + 348) \times 4000$ kVA = 2000 kVA.
- Loading on the transformers-2 = $kVA_2 = [(kVA_2 / \%Z) / ((kVA_1 / \%Z_1) + (kVA_2 / \%Z_2))] \times 4000$ kVA
- $kVA_2 = 348 / (348 + 348) \times 4000$ kVA = 2000 kVA
- Hence $kVA_1 = kVA_2 = 2000$ kVA

This Parameter is not in common practice for new installations, sometimes two transformers with different kVAs and the same percent impedances are connected to one common bus.

In this situation, the current division causes each transformer to carry its rated load. There will be no circulating currents because the voltages (turn ratios) are the same.

Connecting 3000 kVA and 1000 kVA transformers in parallel, each with 5.75% impedance, each with the same turn ratios, connected to a common 4000 kVA load.

Loading on Transformer-1 = $kVA_1 = 522 / (522 + 174) \times 4000 = 3000$ kVA

Loading on Transformer-2 = $kVA_2 = 174 / (522 + 174) \times 4000 = 1000$ kVA

From above calculation it is seen that different kVA ratings on transformers connected to one common load, that current division causes each transformer to only be loaded to its kVA rating.

**Note:**

The key here is that the percent impedance are the same.

3.7.3 Tap changing

A tap changer is a connection point selection mechanism along a power transformer winding that allows a variable number of turns to be selected in discrete steps.

A transformer with a variable turns ratio is produced, enabling stepped voltage regulation of the output. The tap selection may be made via an automatic or manual tap changer mechanism.

If only one tap changer is required, manually operated tap points are usually made on the high voltage (primary) or lower current winding of the transformer to minimize the current handling requirements of the contacts.

However, a transformer may include a tap changer on each winding if there are advantages to do so. For example, in power distribution networks, a large step-down transformer may have an off-load tap changer on the primary winding and an on-load automatic tap changer on the secondary winding or windings.

**Note:**

The high voltage tap is set to match long term system profile on the high voltage network (typically supply voltage averages) and is rarely changed.

The low voltage tap may be requested to change positions multiple times each day, without interrupting the power delivery, to follow loading conditions on the low-voltage (secondary winding) network.

Mechanical tap changers:

A mechanical tap changer physically makes the new connection before releasing the old using multiple tap selector switches, but avoids creating high circulating currents by using a diverter switch to temporarily place a large diverter impedance in series with the short-circuited turns.

This technique overcomes the problems with open or short circuit taps. In a resistance type tap changer, the changeover must be made rapidly to avoid overheating of the diverter.

A reactance type tap changer uses a dedicated preventive autotransformer winding to function as the diverter impedance, and a reactance type tap changer is usually designed to sustain off-tap loading indefinitely.

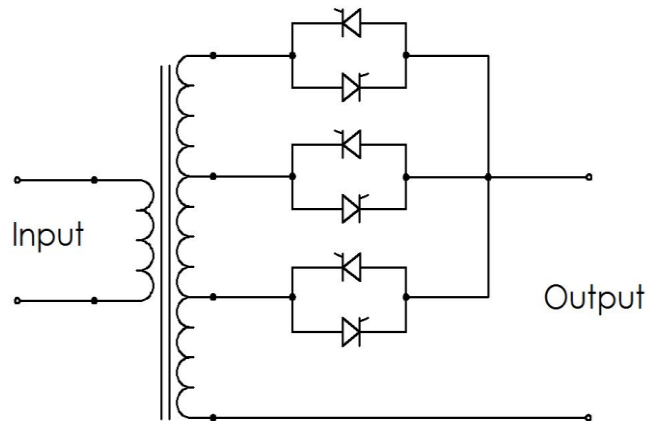


Figure 3.11 Tap changing



Worked Example 3.1

A 12 kVA, 2 500/500 V single-phase transformer, operating at no-load, has resistances and leakage reactance as follows:

Primary winding: Resistance 8,5 Ω , reactance 15 Ω

Secondary winding: Resistance 0,5 Ω , reactance 0,9 Ω

Determine the approximate value of the secondary voltage at full-load, with a power factor of 0,85 (lagging), when the primary supply voltage is 2 500 V.

Solution:

Single-phase transformer 12 kVA

$$\frac{V_1}{V_2} = \frac{250}{500} = \frac{N_1}{N_2}$$

$$R_1 = 8,5 \Omega \quad R_2 = 0,5 \Omega \times 1 = 15 \Omega \times 2 = 0,9 \Omega \quad V_1 = 2\,500 \text{ V} \quad \cos \Phi = 0,85$$

$$I_1 = \frac{V_a}{V_1}$$

$$= \frac{12000}{2500}$$

$$= 4,8 \text{ A}$$

$$R_e = R_1 + R_2 \left(\frac{N_1}{N_2} \right)^2$$

$$= 8,5 + 0,5(5)^2$$

$$= 8,5 + 12,5$$

$$= 21$$

$$X_e = X_1 + X_2 \left(\frac{N_1}{N_2} \right)^2$$

$$= 15 + 0,9(5)^2$$

$$= 15 + 22,5$$

$$= 37,5 \Omega$$

$$Z_e = \sqrt{(R_e)^2 + (X_e)^2}$$

$$Z_e = R_e + j X_e$$

$$= \sqrt{(21)^2 + (37,5)^2} \quad \text{OR}$$

$$= 21 + j 37,5$$

$$= 42,98 \Omega$$

$$= 42,98 \angle 60,75$$

$$Reg = I_1(R_e \cos \Phi + X_e \sin \Phi)/V_1$$

$$= 4,8 [(21)(0,85) + (37,5)(0,527)]/2500$$

$$= 0,072 \text{ per unit}$$

$$\text{Full } V_2 = \text{No Load } V_2 - \text{Change}$$

$$= (500) - (N/L \ V_2 \times reg)$$

$$= 500 - (500 \times 0,072)$$

$$= 500 - 36$$

$$= 464 \text{ V}$$



Worked Example 3.2

Two single-phase transformers are connected in parallel to a load of 900 A, at a power factor of 0,8 lagging

Test data:

Open-circuit: 12 000/2 800 V for each transformer
 Short-circuit with high voltage winding short-circuited:
 Transformer A: secondary input 400 V, 450 A, 30 kW
 Transformer B: secondary input 250 V, 450 A, 35 kW

Calculate the:

1. Voltage secondary
2. Output and power factor of transformer A
3. Output and power factor of transformer B

Solution:

$$1. \quad S = 2800 \angle 0 \times 900 \angle -36,87 \\ = 2520 \angle -36,87 \text{ kVA}$$

TRF A

$$P = I V \cos \Phi$$

$$30\,000 = 450 \times 400 \times \cos \Phi$$

$$\cos \Phi = 0,167$$

$$\Phi = 80,39$$

$$I_A = 450 \angle -80,39$$

$$Z_A = V/I = \frac{400 \angle 0}{450 \angle -80,39} = 0,889 \angle 80,39$$

$$= 0,148 + j 0,88$$

TRF B

$$P = I V \cos \Phi$$

$$35\,000 = 450 \times 250 \times \cos \Phi$$

$$\cos \Phi = 3,1$$

$$\Phi = 71,94$$

$$I_B = 450 \angle -71,94$$

$$Z_B = V/I = \frac{250 \angle 0}{450 \angle -71,94} = 0,556 \angle 71,94$$

$$= 0,17 + j 0,53$$

$$Z_A + Z_B = 0,148 + j 0,88 + 0,17 + j 0,53$$

$$= 0,318 + j 1,4$$

$$= 1,44 \angle 77,2$$

$$Z_T = \frac{Z_A \times Z_B}{Z_A + Z_B} = \frac{0,889 \angle 80,39 \times 0,556 \angle 71,94}{1,44 \angle 77,2}$$

$$= 0,343 \angle 75,13$$

$$V_D = I_L \times Z_T$$

$$= 900 \angle -36,87 \times 0,343 \angle 75,13$$

$$= 308,7 \angle 38,26$$

$$= 242,39 + j 191,16$$

$$V_S = V(\text{NOLOAD}) - V_D$$

$$= 2800 \angle 0 - 308,7 \angle 38,26$$

$$= ((2800 + j 0) - (242,39 + j 191,16)) = 2800 + j 0 - 242,39 - j 191,16$$

$$= 2557,61 - j 191,16$$

$$= 2564,74 \angle -4,27$$

$$2. \quad S = V_S \times I(\text{LOAD})$$

$$= 2564,74 \angle -4,27 \times 900 \angle -36,87$$

$$= 2308,27 \angle -41,14 \text{ kVA}$$

$$S_A = \frac{S \times Z_B}{Z_A + Z_B} = \frac{2308,27 \angle -41,14 \times 0,556 \angle 71,94}{1,44 \angle 77,2}$$

$$= 891,25 \angle -46,4 \text{ kVA}$$

$$\text{COS } \Phi = 0,69 \text{ lagging}$$

$$3. \quad S_B = \frac{S \times Z_A}{Z_A + Z_B} = \frac{2308,27 \angle -41,14 \times 0,889 \angle 80,39}{1,44 \angle 77,2}$$

$$= 1425 \angle -37,95 \text{ kVA}$$

$$\text{COS } \Phi = 0,789 \text{ lagging}$$



Worked Example 3.3

A three-phase delta-connected load, each phase of which has an inductive reactance of 55Ω and a resistance of 34Ω , is supplied from the secondary of a three-phase star-connected transformer, which has a phase voltage of 270 V .

Calculate the following:

1. The potential difference across each phase of the load
2. The current in each phase of the load
3. The current in the transformer secondary windings
4. Total power drawn from the supply and its power factor

Solution:

$$1. \quad V_L = \sqrt{3} V_P = \sqrt{3} \times 270 = 467,65 \text{ V} = 467,65$$

$$2. \quad \begin{aligned} I_P(\text{load}) &= V_P / Z_P \\ &= 467,65 \angle 0^\circ / 64,66 \angle 58,28^\circ \\ &= 7,23 \angle -58,28^\circ \end{aligned}$$

$$3. \quad I_L = \sqrt{3} \times 7,23 = 12,52 \text{ A}$$

$$4. \quad \begin{aligned} P &= \sqrt{3} I_L V_L \cos \Phi \\ &= \sqrt{3} \times 12,52 \times 467,65 \times 0,526 \\ &= 5,33 \text{ kW} \end{aligned}$$

$$\cos \Phi = \cos 58,28^\circ$$

$$pf = 0,526$$



Worked Example 3.4

The ratio of turns of a single-phase transformer is 5 (five). The resistances of the primary and secondary windings are $0,75 \Omega$ and $0,016 \Omega$ and $0,13 \Omega$ respectively.

Calculate the voltage to be applied to the primary to obtain a current of 240 A in the secondary when the secondary terminals are short-circuited. Ignore the magnetizing current.

Solution:

$$N_1/N_2 = 5/1 \quad R1 = 0,75 \quad R2 = 0,016 \times 1 = 5,8 \times 2 = 0,13 \quad I_2 = 240 \text{ A}$$

$$N_1/N_2 = I_2/I_1$$

$$I_1 = I_2 \times N_2/N_1$$

$$= 240 \times 1/5$$

$$= 48 \text{ A}$$

Refer values to primary side:

$$R_e = R1 + R2(N1/N2)^2$$

$$= 0,75 + 0,016(5)^2$$

$$= 1,15 \text{ ohms}$$

$$X_e = X1 + X2(N1/N2)^2$$

$$= 5,8 + 0,13(5)^2$$

$$= 9,05 \text{ ohms}$$

$$Z_e = R_e + j X_e$$

$$= 1,15 + j 9,05$$

$$= 9,12 \angle 82,8^\circ$$

$$V1 = I \times Z_e$$

$$= 48 \times 9,12 \angle 82,8^\circ$$

$$= 437,76 \text{ V}$$

**Worked Example 3.5**

A single phase transformer with a supply voltage of 310 V as an equivalent resistance of $0,4 \Omega$ and an equivalent leakage reactance of $0,95 \Omega$, referred to the primary.

The secondary is connected to a coil with a resistance of 50Ω and a reactance of 180Ω . The secondary winding has 5 times as many turns as the primary.

Calculate the secondary terminal voltage.

Solution:

$$\tan \Phi_2 = \frac{X}{R} = \frac{180}{350} = 0,514$$

$$\Phi_2 = 27,2$$

$$R_t = R_e + R_l \left(\frac{N_1}{N_2} \right)^2$$

$$= 0,4 + 350 \left(\frac{1}{5} \right)^2$$

$$= 14,4 \Omega$$

$$X_t = X_e + X_L \left(\frac{N_1}{N_2} \right)^2 = 0,95 + 180 \left(\frac{1}{5} \right)^2$$

$$= 8,15 \Omega$$

$$Z_t = \sqrt{(R_t)^2 + (X_t)^2}$$

$$= \sqrt{(14,4)^2 + (8,15)^2}$$

$$= 16,55 \Omega$$

or

$$= R_t + j X_L$$

$$= 14,4 + j 8,15$$

$$= 16,55 \angle 29,5$$

$$I_i = \frac{V_1}{Z_t} = \frac{310}{16,55} = 18,73 \text{ A}$$

$$V_{reg} = I_i (R_e \cos \Phi + X_e \sin \Phi)$$

$$= \frac{18,73(0,4 \cos 27,2 + 0,95 \sin 27,2)}{310}$$

$$= 0,0477 \text{ (4,8\%)}$$

$$V_{2(NO\ LOAD)} = V_1 \times \frac{N_2}{N_1} = 310 \times \frac{5}{1} = 1550 \text{ V}$$

$$\text{Difference} = V_{2(NO\ LOAD)} \times reg$$

$$= 1550 \times 0,048$$

$$= 74,4 \text{ V}$$

$$V(\text{terminal}) = 1550 - 74,4 (\cos \Phi \text{ lagging})$$

$$= 1475,6 \text{ V}$$



Activity 3.1

1. Explain how iron losses are affected when the frequency of a transformer is changed.
2. Name one method that can be used to minimize eddy current losses in a transformer.
3. If one transformer is too small, then we can connect a second transformer in parallel to the first one. Name four requirements necessary before the two transformers can be connected in parallel.
4. Name four methods of reducing leakage flux in transformers.
5. Name two conditions for a three-phase system to be balanced.
6. Name two methods that are used to cool transformers.
7. Does a transformer draw any current when its secondary is open-circuited? Motivate your answer.
8. List three types of losses that occur in transformers.
9. Explain mutual induction as applicable to transformers.



Activity 3.2

A 310 kVA transformer has 660 turns on the primary and 220 turns on the secondary. The primary and secondary resistances are $0,8 \Omega$ and $0,06 \Omega$ and the leakage reactance are $1,7 \Omega$ and $0,07 \Omega$ respectively. The supply voltage is 2 700 V.

Calculate:

1. The equivalent impedance referred to the primary circuit.
2. Voltage regulation for power factor of 0,8 lagging, and the secondary terminal voltage on full load.
3. Voltage regulation for power factor of 0,8 leading and secondary terminal voltage on full load.

[1.34; 2.33; 2.69; 900; 94.5; 805.5; 0.0139; 12.51; 912.51]



Activity 3.3

A three phase transformer has 510 turns on the primary and 30 turns on the secondary winding. The supply voltage is 2 600 V.

Calculate the secondary line voltage on no-load when the transformer is connected in:

1. Star-delta
2. Delta-star

[88.3; 264.9]



Activity 3.4

A 950 kVA, 45 kV/15 kV single-phase transformer with a resistance voltage drop of 1,8 percent and a reactance voltage drop of 5% is connected in parallel with a 1 400 kVA, 45 kV/15 kV single-phase transformer with a resistance voltage drop of 4% and a reactance voltage drop of 8%.

Determine the kVA loading and operating power factor of each transformer when the total load is 2000 kVA at a power factor of 0,8 lagging.

[7.82<70.2; 8.94<63.43; 16.75<66.6; 0.77 Lag; 933.73<-33.27; 0.84 Lag]



Activity 3.5

A three phase delta connected load, each phase of which has an inductive reactance of 75Ω and a resistance of 50Ω , is supplied from the secondary of a three phase star connected transformer, which has a phase voltage of 260 V.

Calculate the following:

1. The potential difference across each phase of the load.
2. The current in each phase of the load.
3. The current in the transformer secondary windings.
4. Total power drawn from the supply and its power factor.

[450.33; 5<-56.31; 8.66; 3.72; 0.55]



Activity 3.6

A 15 kVA, 3500/700 volt single-phase transformer, operating at no-load, has resistances and leakage reactance as follows:

Primary winding: Resistance $7,5 \Omega$, reactance 15Ω

Secondary winding: Resistance $0,5 \Omega$, reactance $0,65 \Omega$

Determine the approximate value of the secondary voltage at full-load, with a power factor of 0,8 (lagging), when the primary supply voltage is 3500 V.

[4.29; 20; 31.25; 37.1; 0.043; 669.9]



Activity 3.7

Three similar inductors, each of resistance 29Ω and inductance $0,028 \text{ H}$, are delta-connected to a three-phase, 400 V , 50 Hz sinusoidal supply.

Calculate the following:

1. Line current
2. Power factor

[22.72; 0.96 Lag]



Self-Check

I am able to:	Yes	No
• Describe the use, construction and operation of three-phase transformers		
• Describe useful and leakage flux and reactance		
• Describe transformers in parallel, no-load and on load		
• Describe equivalent circuits and sharing load		
• Calculate currents and power		

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

Module 4

AC Machines

Learning Outcomes

On the completion of this module the student must be able to:

- Describe the use, construction and working principle of the alternator
- Describe the use, construction and working principle of the synchronous motor
- Describe the use, construction and working principle of the induction motor
- Describe parallel operation, hunting, slip, reversal and rotating field
- Calculate starting torque, torque, power

4.1 Introduction



This module describes the use, construction and working principles of the alternator, synchronous motor and induction motor. It also describes parallel operation, hunting, slip, reversal and rotating field and describes calculations: starting torque, torque, power.

4.2 The alternator

In principle, any AC electrical generator can be called an alternator, but usually the term refers to small rotating machines driven by automotive and other internal combustion engines.



Definition: Magneto

An alternator that uses a permanent magnet for its magnetic field is called a magneto.

Alternators in power stations driven by steam turbines are called turbo-alternators. Large 50 or 60 Hz three phase alternators in power plants generate most of the world's electric power, which is distributed by electric power grids.

4.2.1 Principle of operation

A conductor moving relative to a magnetic field develops an electromotive force (EMF) in it (Faraday's Law). This EMF reverses its polarity when it moves under magnetic poles of opposite polarity.

**Note:**

Typically, a rotating magnet, called the rotor turns within a stationary set of conductors wound in coils on an iron core, called the stator. The field cuts across the conductors, generating an induced EMF (electromotive force), as the mechanical input causes the rotor to turn.

The rotating magnetic field induces an AC voltage in the stator windings. Since the currents in the stator windings vary in step with the position of the rotor, an alternator is a synchronous generator.

The rotor's magnetic field may be produced by permanent magnets, or by a field coil electromagnet. Automotive alternators use a rotor winding which allows control of the alternator's generated voltage by varying the current in the rotor field winding.

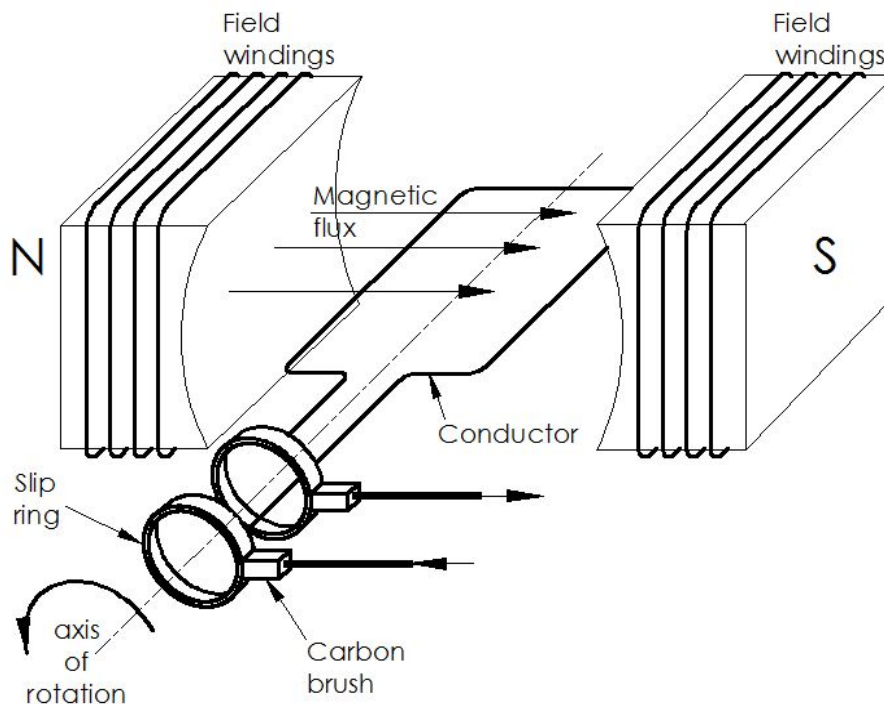


Figure 4.1 Simplified principle of an alternator

An automatic voltage control device controls the field current to keep output voltage constant. If the output voltage from the stationary armature coils drops due to an increase in demand, more current is fed into the rotating field coils through the voltage regulator (VR).

This increases the magnetic field around the field coils which induces a greater voltage in the armature coils. Thus, the output voltage is brought back up to its original value.

Alternators used in central power stations also control the field current to regulate reactive power and to help stabilize the power system against the effects of momentary faults.

Often there are three sets of stator windings, physically offset so that the rotating magnetic field produces a three phase current, displaced by one-third of a period with respect to each other.

Stator windings can be single-layer or double-layer.

The magnetic flux cutting a conductor in 1 revolution = $\phi \times 2 P$

The magnetic flux cutting a conductor in 1 second = $\phi \times 2 P \times N$

The average EMF generated in one conductor = $2 \phi P N$ volts

The average EMF generated per phase = $Z \times 2 \phi P N$ volts

RMS value of EMF per phase for one slot = $1.11 \times 2 Z \phi P N$

The distribution factor improves the waveform because when the windings are distributed in multiple slots per pole per phase the number of conductors per slot is reduced.

The waveform is improved by making the coil pitch less than the pole pitch. This gives rise to a pitch factor shown below.

The distribution factor $K_d = \frac{\text{EMF with a distributed winding}}{\text{EMF with a concentrated winding}}$

The pitch factor $K_p = \frac{\text{EMF with a short pitch coil}}{\text{EMF with a full pitch coil}}$

RMS value of EMF per phase = $2.22 K_d K_p Z f \phi$

4.2.2 Synchronous speeds

One cycle of alternating current is produced each time a pair of field poles passes over a point on the stationary winding. The relation between speed and frequency is

$$\text{Rotational speed } N = \frac{120 f}{P}$$

f is the frequency in Hz (cycles per second)

P is the number of pair of poles

The output frequency of an alternator depends on the number of poles and the rotational speed. The speed corresponding to a particular frequency is called the synchronous speed for that frequency.

To connect alternators in parallel, the following must be true:

- The frequency of the two alternators must be the same.
- The EMF generated in both alternators must be the same.
- The EMF of both alternators must be in phase.

4.2.3 Uses for the alternator

Electric AC generators:

Most power generation stations use synchronous machines as their generators. Connection of these generators to the utility grid requires synchronization conditions to be met.

Automotive alternators:

Alternator mounted on an automobile engine with a serpentine belt pulley. Alternators are used in modern automobiles to charge the battery and to power the electrical system when its engine is running.



Did you know?

Until the 1960s, automobiles used DC dynamo generators with commutators. With the availability of affordable silicon diode rectifiers, alternators were used instead.

Diesel electric locomotive alternator:

In later diesel electric locomotives and diesel electric multiple units, the prime mover turns an alternator which provides electricity for the traction motors (AC or DC).

The traction alternator usually incorporates integral silicon diode rectifiers to provide the traction motors with up to 1200 volts DC (DC traction, which is used directly) or the common inverter bus (AC traction, which is first inverted from DC to three-phase AC).

Marine alternators:

Marine alternators used in yachts are similar to automotive alternators, with appropriate adaptations to the salt-water environment. Marine alternators are designed to be explosion proof so that brush sparking will not ignite explosive gas mixtures in an engine room environment.

They may be 12 or 24 volt depending on the type of system installed. Larger marine diesels may have two or more alternators to cope with the heavy electrical demand of a modern yacht.

On single alternator circuits, the power may be split between the engine starting battery and the domestic or house battery (or batteries) by use of a split-charge diode (battery isolator) or a voltage-sensitive relay.

4.3 Alternators in parallel operation

Alternators are connected in parallel to:

- increase the output capacity of a system beyond that of a single unit,
- serve as additional reserve power for expected demands,
- permit shutting down one machine and cutting in a standby machine without interrupting power distribution.



Think about it!

When alternators are of sufficient size, and are operating at different frequencies and terminal voltages, severe damage may result if they are suddenly connected to each other through a common bus.

To avoid this, the machines must be synchronized as closely as possible before connecting them together.

This may be accomplished by connecting one generator to the bus (referred to as bus generator), and then synchronizing the other (incoming generator) to it before closing the incoming generator's main power contactor.

The generators are synchronized when the following conditions are set:

- Equal terminal voltages. This is obtained by adjustment of the incoming generator's field strength.
- Equal frequency. This is obtained by adjustment of the incoming generator's prime-mover speed.
- Phase voltages in proper phase relation. The procedure for synchronizing generators is not discussed in this chapter. At this point, it is enough for you to know that the above must be accomplished to prevent damage to the machines.

$$I = \frac{E_Z}{2 Z_S} \quad \text{and} \quad \alpha = \tan^{-1} \frac{X_S}{R}$$

R is the resistance of each alternator

X_S is the synchronous reactance of each alternator

Z_S is the synchronous impedance of each alternator

If the exciting current of the second alternator is increased, the effect will be:

$$\text{Terminal voltage} = E_A + \frac{E_Z}{2}$$

4.4 Rotating field by a three-phase current

**Note:**

A rotating magnetic field is a magnetic field that has moving polarities in which its opposite poles rotate about a central point or axis.

Ideally the rotation changes direction at a constant angular rate. This is a key principle in the operation of the alternating-current motor.

Rotating magnetic fields are often utilized for electromechanical applications such as induction motors and electric generators. However, they are also used in purely electrical applications such as induction regulators.

A symmetric rotating magnetic field can be produced with as few as two polar wound coils driven at 90 degrees phasing. However, 3 sets of coils are nearly always used because it is compatible with a symmetric 3-phase AC sine current system.

The three coils are driven with each set driven 120 degrees in phase from the others. For the purpose of this example, the magnetic field is taken to be the linear function of the coil's current.

The result of adding three 120-degree phased sine waves on the axis of the motor is a single rotating vector which remains always constant in magnitude.

The rotor has a constant magnetic field. The N pole of the rotor will move toward the S pole of the magnetic field of the stator, and vice versa. This magneto-mechanical attraction creates a force which will drive the rotor to follow the rotating magnetic field in a synchronous manner.

Three-phase systems are used where the three currents are equal in magnitude and have a 120 degree phase difference. Three similar coils having mutual geometrical angles of 120 degrees will create the rotating magnetic field in this case.

The ability of the three phase system to create the rotating field utilized in electric motors is one of the main reasons why three phase systems dominate in the world electric power supply systems.

Rotating magnetic fields are also used in induction motors. Because magnets degrade with time, induction motors use short-circuited rotors (instead of a magnet) which follow the rotating magnetic field of a multi-coiled stator.

In these motors, the short circuited turns of the rotor develop eddy currents in the rotating field of the stator which in turn move the rotor by Lorentz force.

These types of motors are not usually synchronous, but instead necessarily involve a degree of 'slip' in order that the current may be produced due to the relative movement of the field and the rotor.

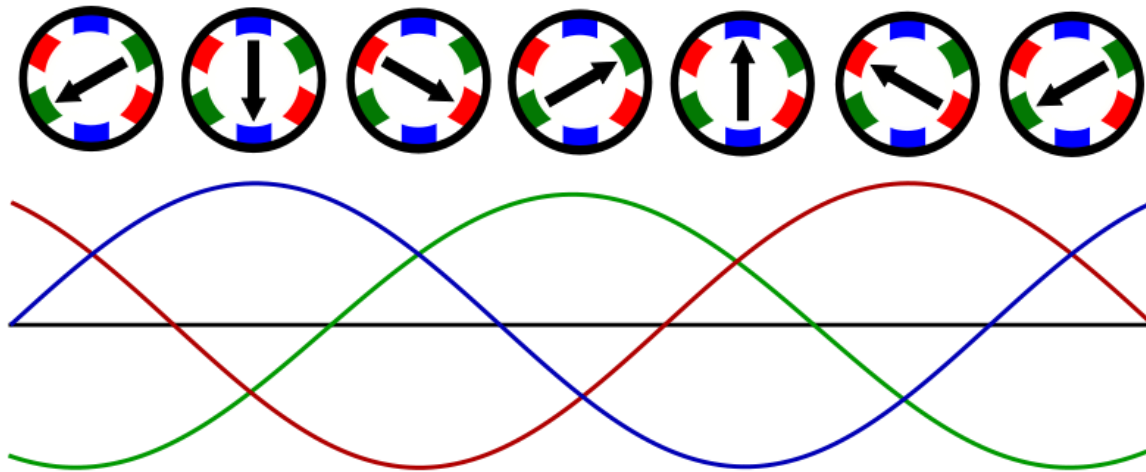


Figure 4.2 Three-phase rotating magnetic field as indicated by the arrows

$$\text{Rotational speed } N = \frac{f}{P}$$

$$f = NP$$

N is the rotational speed of the magnetic flux.

4.5 Reversal of rotating field

The windings in a 3 phase system, when activated by a 3 phase supply produce a rotating magnetic field in the rotor area of the system. Swapping phase Y with phase B re-orders the fluxes so that the flux rotates in the opposite direction.



Think about it!

Swapping B with R does exactly the same thing as does swapping Y with R. Think of it like a triangle with corners called Y, B and R.

If you swap any two corners and follow the points Y, B and R you'll go in an opposite direction. Swap two more corners and you're back to the original rotation.

This is what it looks like. The black arrow is the flux produced by the three phase windings:

Each phase has the same voltage in a sinewave, but 120 degrees out of phase. The question then becomes which phase leads the other. This is what determines the direction of the system.

The phases have a phase shift of 120 degrees - called electrical phase angle, meanwhile the windings on the system are also shifted by 120 deg - mechanical angle. In a such way, when the current passes through windings the rotating magnetic field is formed, which is the sum of all three vectors.

If you simply swap two wires, the magnetic field changes the direction of rotation. It is obvious that in **Figure 4.3**, swapping the yellow phase and blue phase will change direction of rotation.

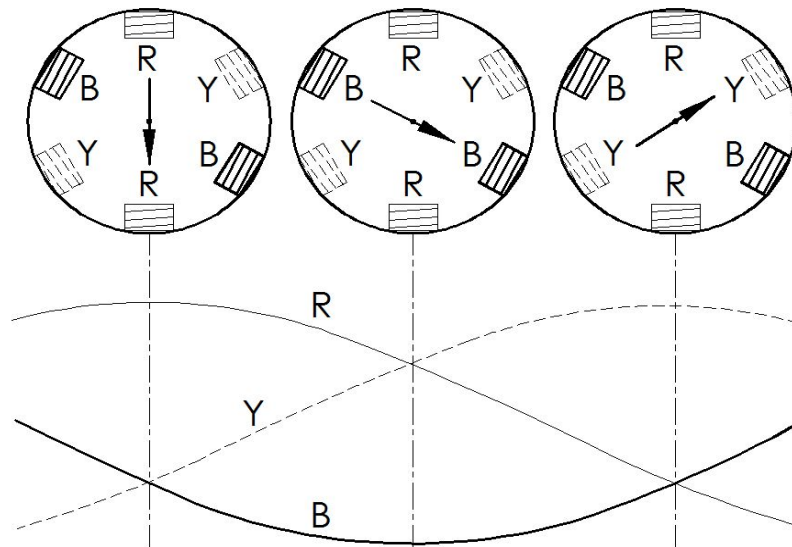


Figure 4.3

4.5.1 Hunting

Unloaded synchronous machine has zero degree load angle. On increasing the shaft load gradually load angle will increase. Let us consider that load P_1 is applied suddenly to unloaded machine shaft so machine will slow down momentarily.

Also load angle (δ) increases from zero degree and becomes δ_1 . During the first swing electrical power developed is equal to mechanical load P_1 . Equilibrium is not established so rotor swings further.

Load angle exceeds δ_1 and becomes δ_2 . Now the electrical power generated is greater than the previous one. Rotor attains synchronous speed. But it does not stay in synchronous speed and it will continue to increase beyond synchronous speed.

As a result of rotor acceleration above synchronous speed the load angle decreases. So once again no equilibrium is attained. Thus rotor swings or oscillates about new equilibrium position.

**Note:**

This phenomenon is known as hunting or phase swinging.

4.5.2 Causes of hunting

Some causes of hunting are:

- Sudden change in load.
- Sudden change in field current.
- A load containing harmonic torque.
- Fault in supply system.

4.5.3 Effects of hunting

Effects of hunting are:

- It may lead to loss of synchronism.
- Produces mechanical stresses.
- Increases machine losses and cause temperature rise.
- Cause greater surges in current and power flow.

4.5.4 Reduction of hunting

Two techniques should be used to reduce hunting. These are:

Use of a Damper Winding: It consists of low electrical resistance copper or aluminum brush embedded in slots of pole faces in salient pole machine.

Damper windings damp out hunting by producing torque opposite to slip of the rotor. The magnitude of the damping torque is proportional to the slip speed.

Use of Flywheel: The prime mover is provided with a large and heavy flywheel. This increases the inertia of prime mover and helps in maintaining the rotor speed constant.

4.6 Synchronous motor**4.6.1 Introduction**

A synchronous electric motor is an AC motor in which, at steady state, the rotation of the shaft is synchronized with the frequency of the supply current. The rotation period is exactly equal to an integral number of AC cycles.

**Note:**


Synchronous motors contain multiphase AC electromagnets on the stator of the motor that create a magnetic field which rotates in time with the oscillations of the line current.

The rotor with permanent magnets or electromagnets turns in step with the stator field at the same rate and as a result, provides the second synchronized rotating magnet field of any AC motor.

A synchronous motor is only considered doubly fed if it is supplied with independently excited multiphase AC electromagnets on both the rotor and stator.

4.6.2 Uses for synchronous motors

The synchronous motor and induction motor are the most widely used types of AC motor. The difference between the two types is that the synchronous motor rotates in exact synchronism with the line frequency.

	<p>Note: The synchronous motor does not rely on current induction to produce the rotor's magnetic field. By contrast, the induction motor requires "slip", the rotor must rotate slightly slower than the AC current alternations, to induce current in the rotor winding.</p>
---	---

Small synchronous motors are used in timing applications such as in synchronous clocks, timers in appliances, tape recorders and precision servomechanisms in which the motor must operate at a precise speed; speed accuracy is that of the power line frequency, which is carefully controlled in large interconnected grid systems.

Synchronous motors are available in sub-fractional self-excited sizes to high-horsepower industrial sizes. In the fractional horsepower range, most synchronous motors are used where precise constant speed is required.

These machines are commonly used in analog electric clocks, timers and other devices where correct time is required.

In high-horsepower industrial sizes, the synchronous motor provides two important functions:

- It is a highly efficient means of converting AC energy to work.
- It can operate at leading or unity power factor and thereby provide power-factor correction.

4.6.3 Construction

The principal components of a synchronous motor are the stator and the rotor. The stator of synchronous motor and stator of induction motor are similar in construction.

With the wound-rotor synchronous doubly fed electric machine as the exception, the stator frame contains wrapper plate. Circumferential ribs and key-bars are attached to the wrapper plate.

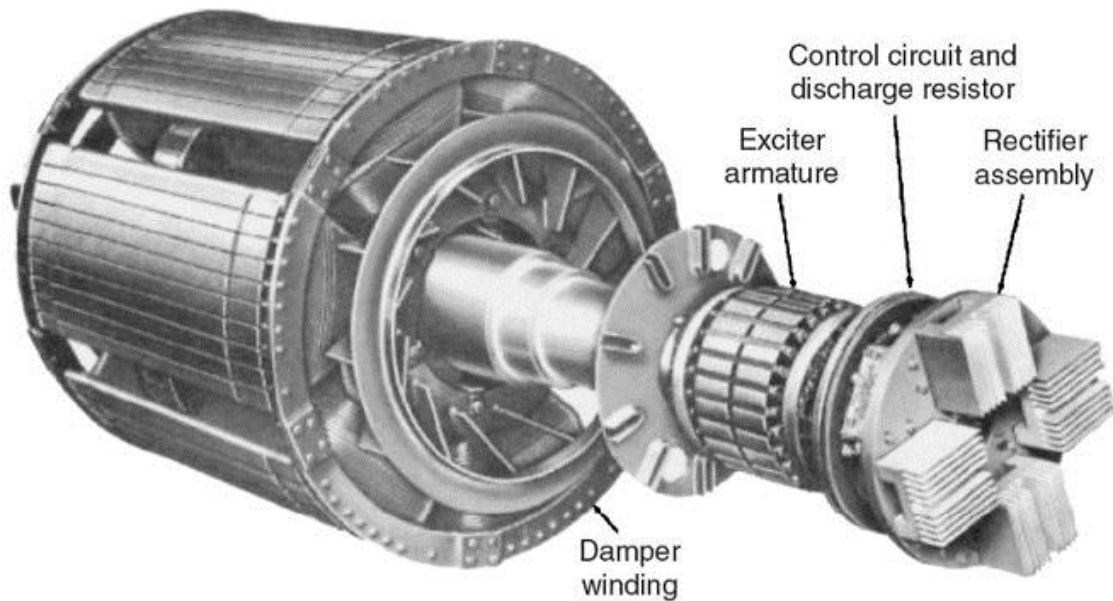


Figure 4.4 Synchronous motor rotor

To carry the weight of the machine, frame mounts and footings are required. When the field winding is excited by DC excitation, brushes and slip rings are required to connect to the excitation supply. The field winding can also be excited by a brushless exciter.

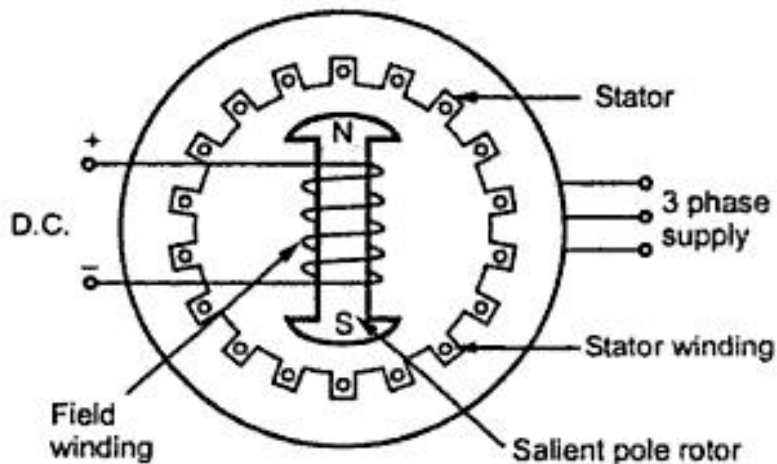


Figure 4.5 Synchronous motor

Cylindrical, round rotors, (also known as non-salient pole rotor) are used for up to six poles. In some machines or when a large number of poles are needed, a salient pole rotor is used. The construction of synchronous motor is similar to that of a synchronous alternator.

4.6.4 Starting up

Above a certain size, synchronous motors are not self-starting motors. This property is due to the inertia of the rotor. It cannot instantly follow the rotation of the magnetic field of the stator.

Since a synchronous motor produces no inherent average torque at standstill, it cannot accelerate to synchronous speed without some supplemental mechanism.

Large motors operating on commercial power frequency include a "squirrel cage" induction winding which provides sufficient torque for acceleration and which also serves to damp oscillations in motor speed in operation.

Once the rotor nears the synchronous speed, the field winding is excited, and the motor pulls into synchronization. Very large motor systems may include a "pony" motor that accelerates the unloaded synchronous machine before load is applied.



Note:

Motors that are electronically controlled can be accelerated from zero speed by changing the frequency of the stator current.

Very small synchronous motors are commonly used in line-powered electric mechanical clocks or timers that use the powerline frequency to run the gear mechanism at the correct speed.

Such small synchronous motors are able to start without assistance if the moment of inertia of the rotor and its mechanical load is sufficiently small [because the motor] will be accelerated from slip speed up to synchronous speed during an accelerating half cycle of the reluctance torque.

Single-phase synchronous motors such as in electric wall clocks can freely rotate in either direction unlike a shaded-pole type. See Shaded-pole synchronous motor for how consistent starting direction is obtained.

4.7 Induction motor

4.7.1 Introduction

The three phase induction motor is the most widely used electrical motor. Almost 80% of the mechanical power used by industries is provided by three phase induction motors because of its simple and rugged construction, low cost, good operating characteristics, absence of commutator and good speed regulation.

In three phase induction motor the power is transferred from stator to rotor winding through induction. The Induction motor is also called asynchronous motor as it runs at a speed other than the synchronous speed.

4.7.2 Construction

Like any other electrical motor induction motor also have two main parts namely rotor and stator.

Stator: As its name indicates stator is a stationary part of induction motor. A stator winding is placed in the stator of induction motor and the three phase supply is given to it.

Rotor: The rotor is a rotating part of induction motor. The rotor is connected to the mechanical load through the shaft.

The rotor of the three phase induction motor are further classified as:

- Squirrel cage rotor.
- Slip ring rotor or wound rotor or phase wound rotor.

Depending upon the type of rotor construction used the three phase induction motor are classified as:

- Squirrel cage induction motor,
- Slip ring induction motor or wound induction motor or phase wound induction motor.



Note:

The construction of stator for both the kinds of three phase induction motor remains the same.

The other parts, which are required to complete the induction motor, are:

- Shaft for transmitting the torque to the load. This shaft is made up of steel.
- Bearings for supporting the rotating shaft.
- One of the problems with electrical motor is the production of heat during its rotation. In order to overcome this problem we need fan for cooling.
- For receiving external electrical connection Terminal box is needed.
- There is a small distance between rotor and stator which usually varies from 0.4 mm to 4 mm. Such a distance is called air gap.

4.7.3 Construction of three-phase induction motor

Stator frame:

It is the outer most part of the three phase induction motor. Its main function is to support the stator core and the field winding.

It acts as a covering and it provide protection and mechanical strength to all the inner parts of the induction motor.

Stator core:

The main function of the stator core is to carry the alternating flux. In order to reduce the eddy current loss, the stator core is laminated.

These laminated types of structure are made up of stamping which is about 0.4 to 0.5 mm thick. All the stamping are stamped together to form stator core, which is then housed in stator frame.

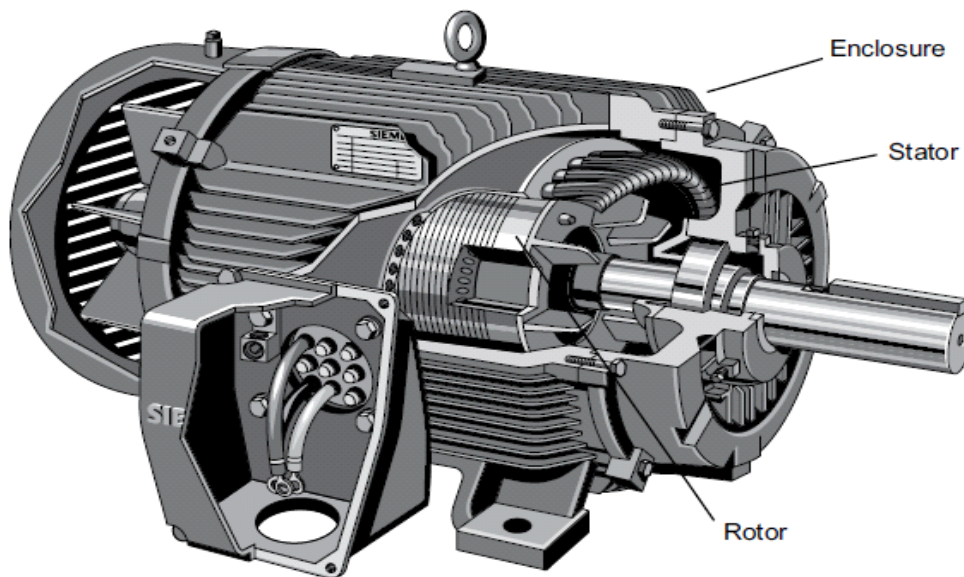


Figure 4.6 An induction motor

Field winding:

The slots on the periphery of stator core of the three phase induction motor carries three phase windings. This three phase winding is supplied by three phase ac supply.

The three phases of the winding are connected either in star or delta depending upon which type of starting method is used.



Note:

The squirrel cage motor is mostly started by star – delta stator and hence the stator of squirrel cage motor is delta connected.



Note:

The slip ring three phase induction motor are started by inserting resistances so, the stator winding of slip ring induction motor can be connected either in star or delta.

The winding wound on the stator of three phase induction motor is also called field winding and when this winding is excited by three phase AC supply it produces a rotating magnetic field.

4.7.4 Squirrel cage three phase induction motor

The rotor of the squirrel cage three phase induction motor is cylindrical in shape and have slots on its periphery.

The slots are not made parallel to each other but are bit skewed (skewing is not shown in the figure of squirrel cage rotor beside) as the skewing prevents magnetic locking of stator and rotor teeth and makes the working of motor more smooth and quieter.

The squirrel cage rotor consists of aluminium, brass or copper bars (copper bars rotor is shown in the figure beside). These bars are called rotor conductors and are placed in the slots on the periphery of the rotor.

The rotor conductors are permanently shorted by the copper or aluminium rings called the end rings. In order to provide mechanical strength these rotor conductors are braced to the end ring and hence form a complete closed circuit resembling like a cage and hence got its name as "squirrel cage induction motor".

The squirrel cage rotor winding is made symmetrical. As the bars are permanently shorted by end rings, the rotor resistance is very small and it is not possible to add external resistance as the bars are permanently shorted.

The absence of slip ring and brushes make the construction of Squirrel cage three phase induction motor very simple and robust and hence widely used three phase induction motor.

**Note:**

These motors have the advantage of adapting any number of pole pairs.

4.7.5 Slip ring or wound three phase induction motor

In this type of three phase induction motor the rotor is wound for the same number of poles as that of stator but it has less number of slots and has less turns per phase of a heavier conductor.


The rotor also carries star or delta winding similar to that of stator winding. The rotor consists of numbers of slots and rotor winding are placed inside these slots. The three end terminals are connected together to form star connection.

As its name indicates three phase slip ring induction motor consists of slip rings connected on same shaft as that of rotor. The three ends of three phase windings are permanently connected to these slip rings.

The external resistance can be easily connected through the brushes and slip rings and hence used for speed control and improving the starting torque of three phase induction motor. The brushes are used to carry current to and from the rotor winding.

These brushes are further connected to three phase star connected resistances. At starting, the resistance are connected in rotor circuit and is gradually cut out as the rotor pick up its speed.

When the motor is running the slip ring are shorted by connecting a metal collar, which connect all slip ring together and the brushes are also removed. This reduces wear and tear of the brushes.

	<p>Note: Due to presence of slip rings and brushes the rotor construction becomes somewhat complicated therefore it is less used as compared to squirrel cage induction motor.</p>
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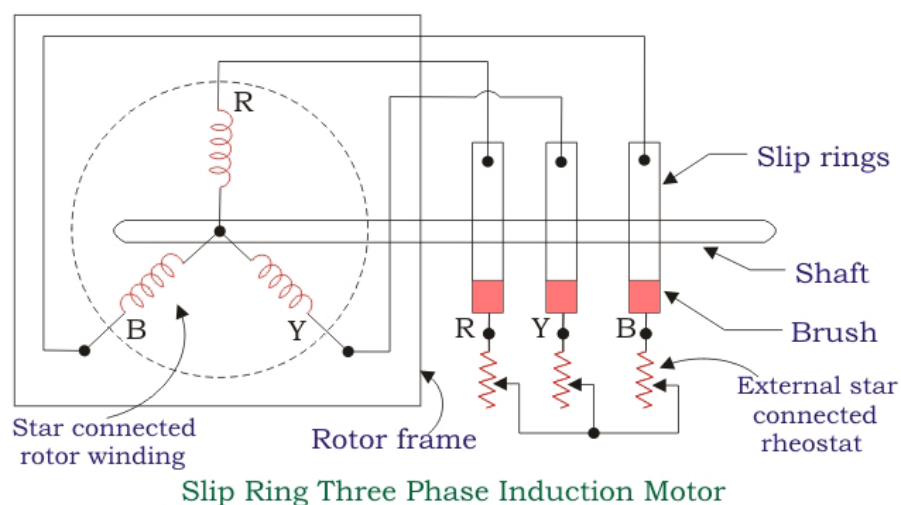


Figure 4.7

4.7.6 Slip

The stator winding is connected to the supply, and the poly-phase currents circulating through it produce a magnetic field which rotates at synchronous speed (speed equal to that of the rotating magnetic field).

If the rotor turned at synchronous speed, there would be no change in flux linkage, no induced current, and no torque. The small difference in speed that produces flux cutting and motor action is called the slip.

The slip full load for a squirrel-cage motor is typically 2% to 5%. Slip may also be described as the relative speed between the synchronous speed and the rotor speed.

Slip may be expressed in revolutions per minute, but is more commonly expressed in terms of the synchronous speed as either a percentage or as a per unit value.

Where:

s = per unit slip or percentage slip

N = synchronous speed of the field in revolutions per minute
 N_r = actual speed of the rotor in revolutions per minute
 n = synchronous speed of the field in revolutions per second
 n_r = actual speed of the rotor in revolutions per second



Important Note!

The rotor field created by the induced rotor current moves ahead at a speed relative to the rotor structure.

The magnetic line of the stator field cuts the rotor conductors and induces current in them; the rotor follows after the stator field (Figure 5.28). There is absolutely no physical electrical connection between the stator and the rotor of the induction motor.

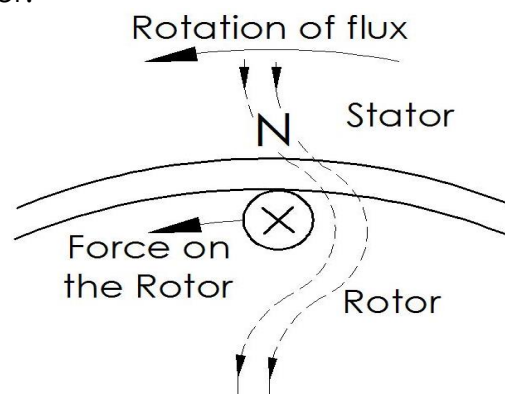


Figure 4.8 Force on rotor

Since the speed of the motor depends upon the frequency of the supply as well as the number of poles, the stator may be wound for a two-four-six- or eight-pole machine, depending upon the speed required.

The following table shows a few rotor speeds for the standard frequency of 50 Hz:

Number of poles	Calculation	Speed
2-pole	$50 = 1 \times n$	$n = 50$ rev/sec, or 3000 rev/min
4-pole	$50 = 2 \times n$	$n = 25$ rev/sec, or 1500 rev/min
12-pole	$50 = 6 \times n$	$n = 8 \frac{1}{3}$ rev/sec, or 500 rev/min

Table 4.1

4.7.7 Starting up

From the torque slip characteristic it is clear that at the slip equals to one we have some positive starting torque hence we can say that the three phase induction motor is self-starting machine, then why there is a need of starters for three phase induction motor?

The answer is very simple. If we look at the equivalent circuit of the three phase induction motor at the time of starting, we can see the motor behaves like an

electrical transformer with short circuited secondary winding, because at the time of starting, the rotor is stationary and the back emf due to the rotation is not developed yet hence the motor draws the high starting current.

So the reason of using the starter is clear here. We use starters in order to limit the high starting current. We use different starters for both the type of three phase induction motors.

Let us consider first squirrel cage type of induction motor.

In order to choose a particular type of starting method for the squirrel cage type of induction motor, we have three main considerations and these are:

- A particular type of starter is selected on the basis of power capacity of the power lines.
- The type of starter selected on the basis of the size and the design parameters of the motor.
- The third consideration is the type of load on the motor (i.e. the load may be heavy or light).

We classify starting methods for squirrel cage induction motor into two types on the basis of voltage.

The two types are:

- Full voltage starting method and
- reduced voltage method for starting squirrel cage induction motor. Now let us discuss each of these methods in detail.

Now we can directly write the expression for torque of the induction motor as:

$$T = \frac{1}{W_s} \times I_s^2 \frac{r}{s}$$

From the help of the above expression we write the ratio of starting torque to full load torque as:

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f} \right)^2 \times s_f$$

T_f as full load torque

I_f as per phase rotor current at full load

I_s as per phase rotor current at the time of starting

s_f as full load slip

s_s as starting slip

R_2 as rotor resistance

W_s as synchronous speed of the motor Now we can directly write the expression for torque of the induction motor as:

$$T = \frac{1}{W_s} \times I_s^2 \frac{r}{s}$$

From the help of the above expression we write the ratio of starting torque to full load torque as:

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \dots\dots(i)$$

Here we have assumed that the rotor resistance is constant and it does not vary with the frequency of the rotor current.

From the above equation we can have the expression for the starting torque in terms of the full load torque. Now at the time of starting the per phase voltage is reduced to xV_1 , the per phase starting current is also reduced to xI_s . On substituting the value of I_s as xI_s in equation 1.

We have:

$$\frac{T_s}{T_f} = \left(\frac{xI_s}{I_f}\right)^2 \times s_f$$

$$\frac{T_s}{T_f} = \left(\frac{I_s}{I_f}\right)^2 \times s_f \times x^2$$

T_s as starting torque



Worked Example 4.1

A three-phase, 66 V, star-connected motor has an output of 85 kW, with an efficiency of 90% and a power factor of 0,8.

Calculate:

1. The line current
2. If the motor windings were connected in delta, what would be the three-phase voltage supply suitable for the motor?

Solution:

Three-phase star-connected motor $V_L = 660 \text{ V}$ $P_{out} = 85 \text{ kW}$ $\eta = 0,9$

$$\cos \Phi = 0,8$$

$$P_{in} = \frac{85}{0,9}$$

$$= 94,444 \text{ kW}$$

$$P = \sqrt{3} IL VL \cos \Phi$$

$$94444 = \sqrt{3} IL(660)(0,8)$$

$$IL = 103,27 A$$



Worked Example 4.2

Two similar, three-phase, star-connected alternators are connected in parallel. Each machine has a synchronous reactance of $8,8 \Omega$ per phase and negligible resistance. The machines are adjusted to be in exact phase opposition relative to each other and the excitation of one alternator is adjusted to give an open-circuit voltage of $2\,700 V/\text{phase}$. The circulating current of $50 A$.

Calculate the following:

1. The open-circuit voltage of the other machine assuming it is less than that of the first machine
2. The terminal line voltage

Solution:

$$1. \quad X = 8,8 \Omega$$

$$EA = 2700 V/PH$$

$$IR = 50 A$$

$$IR = ER/2X$$

$$ER = IR \times (2X)$$

$$= 50 \times (2 \times 8,8)$$

$$= 880 V$$

$$ER = EA + EB$$

$$EB = EA - ER$$

$$= 2700 - 880$$

$$= 1820 V$$

$$\begin{aligned}
 2. \quad \text{Terminal voltage} &= EA - 0,5 ER \\
 &= 2700 (0,5 \times 880) \\
 &= 2260 \text{ V}
 \end{aligned}$$



Worked Example 4.3

A three-phase slip-ring induction motor gives a reading of 77 V across the slip-rings on open-circuit with normal stator voltage applied. The rotor is star-connected and has a standstill impedance of $0,8 + j 6 \Omega$ per phase.

Determine the rotor current when the machine is:

1. At standstill with the slip-rings joined to a star-connected starter with phase impedance of $7 + j 9 \Omega$.
2. Running normally with a 5,5% slip

Solution:

$$1. \quad VL = 77 \text{ V } Z_o = 0,8 + j6$$

$$E_o = \frac{77}{\sqrt{3}}$$

$$= 44,46 \text{ V}$$

$$Z_o = (0,8 + j6) + (7 + j9)$$

$$= 7,8 + j15$$

$$= 16,9 \angle 62,53$$

$$I_o = \frac{E_o}{Z_o}$$

$$= \frac{44,46}{16,9}$$

$$= 2,63 \text{ A}$$

$$2. \quad S = 5,5\% = 0,055$$

$$E_2 = s E_o$$

$$= 0,055 \times 44,46$$

$$= 2,45$$

$$X_2 = s X_0$$

$$= 0,055 \times 6$$

$$= 0,33$$

$$Z_2 = \sqrt{R^2 + X^2}$$

$$= \sqrt{(0,8)^2 + (0,33)^2}$$

$$= 0,87$$

$$I_2 = \frac{E_2}{Z_2}$$

$$= \frac{2,45}{0,87}$$

$$= 2,82 \text{ A}$$



Worked Example 4.4

If the phase voltage of a three phase star connected alternator is 360 V, what would the line voltages be when:

1. The phase is correctly connected.
2. The connection to the yellow phase is reversed.

Solution:

Correctly connected

$$V_{RY} = V_{RN} + V_{NY}$$

$$= 380 \angle 90^\circ + 380 \angle 150^\circ$$

$$= (0 + j 380) + (-329 + j 190)$$

$$= -329 + j 570$$

$$= 658,13 \angle 120^\circ$$

$$V_{RY} = V_{BR} = V_{YB} = 658,13$$

OR

$$380 \times \sqrt{3} = 658,18,54$$

With one phase reversed

$$= 380 \angle 0^\circ + 380 \angle -120^\circ$$

$$= (380 - j0) + (-190 - j 329,09)$$

$$= 190 - j329,09$$

$$= 380 < -60$$



Worked Example 4.5

A three-phase induction motor has 8 poles and is supplied from a 50 Hz supply.

Calculate:

1. The synchronous speed
2. The rotor speed when the slip is 8%
3. The rotor frequency when the rotor runs at 250 r/min

Solution:

$$1. \quad p = 8/2 = 4 \quad f = 50\text{Hz}$$

Synchronous speed : N_s

$$f = N_s \frac{p}{60}$$

$$N_s = f \times \frac{60}{4}$$

$$= 50 \times \frac{60}{4}$$

$$= 750 \text{ r/min}$$

$$2. \quad N_r = N_s - s N_s$$

$$= 750 - (0,08 \times 750)$$

$$= 690 \text{ r/min}$$

$$3. \quad f_r = p \frac{(N_s - N_r)}{60}$$

$$= 4 \frac{750 - 690}{60}$$

$$= 33,33 \text{ Hz}$$



Activity 4.1

A three-phase induction motor develops 55 kW when running at 80% efficiency at a power factor of 0,75 lagging.

Calculate the input power readings on each of the two watt-meters.

[68.750; 0.883; 35048.77; 68750; 35048.77; 51899.385; 16850.62]



Activity 4.2

A three phase, four-pole, 50 Hz induction motor, with a star-connected rotor, has a rotor resistance of 0,8 Ω per phase and at standstill the reactance is 2,8 Ω . The EMF between the slip-rings is 260 V. Full-load speed is 1 380 r/min.

Calculate:

1. The fractional slip
2. The EMF induced in each phase of the rotor
3. The rotor reactance per phase
4. The rotor current and power factor (if rings are short-circuited)
5. The rotor frequency

[25; 0.08; 12.01; 0.228; 0.96; 4]



Activity 4.3

1. With reference to induction motors, what is meant by the term *slip*?
2. Explain why slip is necessary for an induction motor to operate.
3. Name two methods used for finding the slip of an induction motor.
4. Is a single-phase induction motor self-starting? Give a reason for your answer.
5. Does an induction motor develop torque when running at synchronous speed?
6. Discuss the reason for your answer.



Activity 4.4

A three-phase, 50 Hz, eight pole induction motor has a slip of 0,05 per unit, when the output is 45 kW. The frictional loss is 375 W.

Calculate:

1. Rotor speed
2. Rotor copper loss

[750; 712.5; 608.14; 47763.2; 2388.16]



Activity 4.5

Calculate the efficiency and the output power of a three-phase 450 V induction motor, running on load with a frictional slip of 0,05 and drawing a current of 80 A at a power factor of 0,8. When running light at 450 V, the motor has an input current of 30 A and the power taken is 3 000 W. The resistance per phase of the stator winding is 0,8 Ω , delta-connected.

[0.8; 49883.06; 5120; 2238.15; 2280; 9638; 40245; 81]



Activity 4.6

A three-phase, six-pole star-connected alternator delivers 375 V between lines on open circuit, running at a speed of 1450 r/min. There are two conductors per slot and three slots per pole, per phase.

Assume the winding has a pitch factor of 0,8 and a distribution factor of 0,96 and assuming a sine wave form.

Calculate the following:

1. The frequency
2. Turns per phase
3. Useful flux per pole

[72.5; 36; 18; 48.7]



Activity 4.7

A three-phase, 500 V, star-connected motor has an output of 100 kW, with an efficiency of 80% and a power factor of 0,8.

Calculate the following:

1. The line current
2. If the motor windings were connected in delta, what would be the correct voltage suitable for a three-phase motor?

[125; 180.42; 312.5; 288.68; 380]



Activity 4.8

A three-phase 475 V star-connected motor has an output of 75 kW, with an efficiency of 85% and a power factor of 0,9.

Calculate:

1. The line current
2. If the motor windings are connected in delta, what will be the correct three-phase supply voltage suitable for the motor?

[119.16; 206.39; 274.25]



Activity 4.9

Two similar three-phase, star-connected alternators are operating in parallel. Each machine has a synchronous reactance of $6,5 \Omega$ per phase and negligible resistance, and is excited to generate an EMF of 2675 V per phase. The machines have a phase displacement of 30 electrical degrees relative to each other.

Calculate the:

1. Circulating current
2. Terminal voltage per phase
3. Power supplied from one machine to another

[184.68; 106.5; 2583.85; 825.540]



Activity 4.10

A star-connected, three-phase alternator, runs at a speed of 1 500 r/min, and has to generate a voltage of 800 V at 50 Hz on open circuit. The stator has two slots per pole per phase and four conductors per slot.

Assume all the conductors per phase to be series connected and coils to be full-pitched. $k_d = 0,96$

Calculate the:

1. Number of poles
2. Useful flux per pole

[4; 32; 461.88; 135]



Self-Check

I am able to:	Yes	No
• Describe the use, construction and working principle of the alternator		
• Describe the use, construction and working principle of the synchronous motor		
• Describe the use, construction and working principle of the induction motor		
• Describe parallel operation, hunting, slip, reversal and rotating field		
• Calculate starting torque, torque, power		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Module 5

Generation and Supply of AC Power

Learning Outcomes

On the completion of this module the student must be able to:

- Describe the effect that resistance and temperature has on an overhead line
- Describe the effect that inductance has on an overhead line
- Describe the effect that capacitance has on an overhead line
- Calculate losses in overhead lines... resistance, inductance and capacitance

5.1 Introduction



Electric power transmission is the bulk movement of electrical energy from a generating site, such as a power plant, to an electrical substation.

The interconnected lines which facilitate this movement are known as a transmission network. The combined transmission and distribution network is known as the power grid.



Note:

High-voltage overhead conductors are not covered by insulation. The conductor material is nearly always an aluminium alloy, made into several strands and possibly reinforced with steel strands.

Conductor sizes range from 12 mm² to 750 mm², with varying resistance and current-carrying capacity. Thicker wires would lead to a relatively small increase in capacity due to the skin effect, that causes most of the current to flow close to the surface of the wire.

Because of this current limitation, multiple parallel cables (called bundle conductors) are used when higher capacity is needed. Bundle conductors are also used at high voltages to reduce energy loss caused by corona discharge.

Today, transmission-level voltages are usually considered to be 110 kV and above. Lower voltages, such as 66 kV and 33 kV, are usually considered sub-transmission voltages, but are occasionally used on long lines with light loads.

Voltages less than 33 kV are usually used for distribution. Voltages above 765 kV are considered extra high voltage and require different designs compared to equipment used at lower voltages.

5.2 Losses in overhead lines

5.2.1 Resistance

The AC resistance of a conductor in a transmission line is based on the calculation of its DC resistance.

If DC current is flowing along a round cylindrical conductor, the current is uniformly distributed over its cross-section area and its DC resistance, R , is evaluated by:

$$R = \frac{\rho L}{A}$$

ρ is the resistivity of the conductor material.

L is the length of the conductor

$$\text{Cross-sectional area } A = \frac{\pi D^2}{4}$$

5.2.2 Frequency effect

The frequency of the AC voltage produces a second effect on the conductor resistance due to the non-uniform distribution of the current.

This phenomenon is known as skin effect. As frequency increases, the current tends to go toward the surface of the conductor and the current density decreases at the center.

Skin effect reduces the effective cross-section area used by the current, and thus, the effective resistance increases.

Also, although in small amount, a further resistance increase occurs when other current-carrying conductors are present in the immediate vicinity.

A skin correction factor k , obtained by differential equations and Bessel functions, is considered to re-evaluate the AC resistance. For 60 Hz, k is estimated around 1.02

5.2.3 Temperature Effect

The resistivity of any conductive material varies linearly over an operating temperature, and therefore, the resistance of any conductor suffers the same variations.

As temperature rises, the conductor resistance increases linearly, over normal operating temperatures, according to the following equation:

$$\frac{R_2}{R_1} = \frac{R_0 (1 + \rho_0 T_2)}{R_0 (1 + \rho_0 T_1)}$$

R_0 is the resistance at 0 degrees

R_1 is the resistance at T_1

R_2 is the resistance at T_2

ρ_0 is the temperature coefficient at 0 degrees


5.2.4 Current-Carrying Capacity

The current-carrying capacity is determined mostly by the conductor resistance and the heat dissipated from its surface. The heat generated in a conductor (Joule's effect) is dissipated from its surface area by convection and radiation.

5.2.5 Inductance and Inductive Reactance

A current-carrying conductor produces concentric magnetic flux lines around the conductor.

If the current varies with the time, the magnetic flux changes and a voltage is induced. Therefore, an inductance is present, defined as the ratio of the magnetic flux linkage and the current.

	<p>Note: The magnetic flux produced by the current in transmission line conductors produces a total inductance whose magnitude depends on the line configuration.</p>
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Inductance of a single phase line:

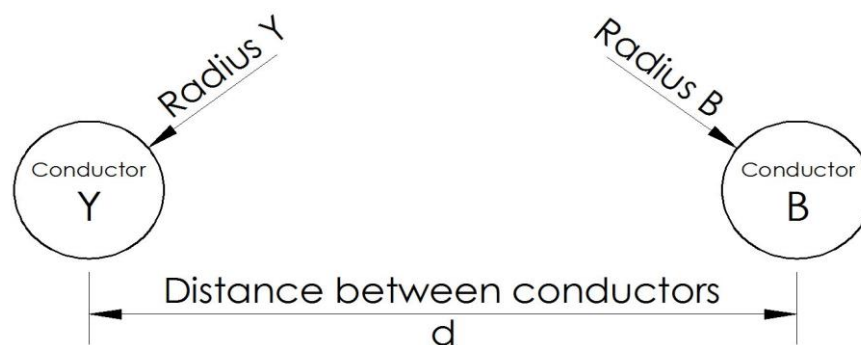


Figure 5.1 Two single-phase conductors spanning two poles


$$\text{Total inductance in conductor B only } L = 0.1 + 0.4 \log_e \frac{d}{r}$$

r is the radius of the conductor.

5.2.6 Bundle Conductor Effect

For transmission of power across long distances, high voltage transmission is employed.

Transmission higher than 132 kV poses some problems, such as the corona effect, which cause significant power loss and interference with communication circuits.

	<p>Note: In order to reduce this corona effect, it is preferable to use more than one conductor per phase, or bundled conductors.</p>
---	--

Bundle conductors consist of several parallel cables connected at intervals by spacers, often in a cylindrical configuration. The optimum number of conductors depends on the current rating, but typically higher-voltage lines also have higher current.

There is also some advantage due to lower corona loss:

- Bundled conductors reduce the voltage gradient in the vicinity of the line. This reduces the possibility of corona discharge.
- At extra high voltage, the electric field gradient at the surface of a single conductor is high enough to ionize air, which wastes power, generates unwanted audible noise and interferes with communication systems. Improvements in the transmission efficiency as loss due to corona effect is countered.
- Bundled conductor lines will have higher capacitance in comparison with single lines. Thus, they will have higher charging currents, which helps in improving power factor.
- When transmitting alternating current, bundle conductors also avoid the reduction in ampacity of a single large conductor due to the skin effect.
- A bundle conductor also has lower reactance, compared to a single conductor.
- Additionally, bundled conductors cool themselves more efficiently due to the increased surface area of the conductors, further reducing line losses.
- The increased GMR reduces line reactance and inductance.

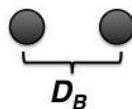


Figure 5.2 Two-conductor bundle with equal spacing

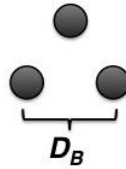


Figure 5.3 Three-conductor bundle with equal spacing



Note:

In addition to reducing corona losses and improving the skin effect, conductor bundling also reduces line inductance.

5.2.7 Inductance of a three-phase three-conductor line

Figure 5.3 shows three conductors evenly spaced:

$$\text{Total inductance in one conductor only } L_{\text{Phase}} = 0.05 + 0.2 \log_e \frac{d}{r}$$

If the triangle of conductors are not symmetrical, then an average distance d_e must be found:

$$\text{Average distance } d_e = \sqrt[3]{d_Y d_B d_R}$$

$$\text{Total inductance in one conductor only } L_{\text{Phase}} = 0.05 + 0.2 \log_e \frac{d_e}{r}$$

For three flat, equally spaced conductors, the average distance, d_e :

$$\text{Average distance } d_e = \sqrt[3]{d^3} = 1.26 d$$

5.2.8 Capacitance of a Three-Phase Line

For three equally spaced conductors, the total charge between any one of the conductors and the neutral plane will be equal to the phasor sum of two equal charging currents 120 degrees apart.

Between any conductor and the neutral plane:

$$\text{The total equivalent capacitance } C_N = \frac{1}{18 \log_e \left[\frac{d-r}{r} \right]}$$

If the triangle of conductors are not symmetrical, then an average capacitance per phase must be found:

$$\text{The total equivalent capacitance } C_{\text{Phase}} = \frac{1}{18 \log_e \left[\frac{d_e}{r} \right]}$$



Activity 5.1

A three-phase transmission line supplies a 2,45 MW star-connected load, having a power factor of 0,8 lagging at a line voltage of 36 kV.

The line has a resistance of 90 ohms per phase and an inductive reactance of 160 ohms per phase.

Calculate the:

1. Voltage at the sending end
2. Regulation
3. Efficiency of the line

Solution:

$$1. \quad \text{Load } P = 2,45 \text{ MW} = \frac{2,45 \text{ MW}}{3} \text{ per phase}$$

$$\cos \Phi = 0,8 \text{ lagging (sin } \Phi = 0,6)$$

$$V_r = \frac{36\,000}{\sqrt{3}} (\cos \Phi + j \sin \Phi)$$

$$= \frac{36\,000}{\sqrt{3}} (0,8 + j0,6)$$

$$= 16\,627,69 + j\,12\,470,77$$

$$I_p = \frac{2,45 \text{ MVV}/3}{36\,000/\sqrt{3}} = 39,29 \text{ A}$$

$$V_d = IZ = 39,29(90 + j\,160)$$

$$= 3536,1 + j\,6286,4$$

$$V_s = V_r + V_d$$

$$= 16\,627,69 + j\,12\,470,77 + 3536,1 + j\,6286,4$$

$$= 20\,163,79 + j\,18\,075,17$$

$$= 27539,24 \angle 42,9^\circ$$

$$V_s \text{ line voltage} = \sqrt{3} \times 27539,24 = 47,7 \text{ kV}$$

$$2. \quad \text{Reg} = \frac{V_s - V_r}{V_r}$$

$$= \frac{27539,24 - 36000/\sqrt{3}}{36000/\sqrt{3}}$$

OR

$$\frac{47700 - 36000}{36\,000}$$

$$= 0,325 \text{ pu} \qquad 0,325 \text{ pu}$$

$$\text{Output} = 2,45 \text{ MW} / 3 \text{ per phase} = 816,67 \text{ kW}$$

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

$$= (39,29)^2 \times 90$$

$$= 138,93 \text{ kW}$$

$$\text{Input} = \text{output} + \text{losses}$$

$$= 816,67 + 138,93$$

$$= 955,6 \text{ kW}$$

$$3. \quad \text{Efficiency} = \frac{\text{output}}{\text{Input}}$$

$$= \frac{816,67}{955,6}$$

$$= 0,85 \text{ (85\%)}$$



Activity 5.2

An overhead, single-phase transmission line delivers 2 400 kW at 36 kV. The power factor is 0,85 lagging. The total resistance of the line is 22 Ω and the total inductive reactance is 33 Ω .

Determine the following:

1. The sending line voltage
2. The per unit regulation
3. The transmission efficiency

Solution:

$$1. \quad R = 22 \text{ ohms}; X = 33 \text{ ohms}$$

$$P = 2400 \text{ kW}; V_r = 36 \text{ kV}; \cos \Phi = 0,85 = 31,79$$

$$I = \frac{P}{V} \cos \Phi$$

$$= \frac{2\,400\,000}{36\,000} \times 0,85$$

$$= 78,43 \text{ A}$$

$$\begin{aligned}
 V_s &= V \angle \Phi + IR + IX \angle 90 \\
 &= 36\,000 \angle 31,79 + 78,43 \times 33 \angle 90 \\
 &= 30\,599,45 + j18\,965,07 + 175,46 + j2588,19 \\
 &= 32324,91 + j21553,26 \\
 &= 38\,851,55 \angle 33,69 \text{ kV}
 \end{aligned}$$

$$\begin{aligned}
 2. \quad Reg &= V_s - \frac{V_r}{V_r} \\
 &= 38\,851,55 - \frac{36000}{3600} \\
 &= 0,079
 \end{aligned}$$

$$\begin{aligned}
 3. \quad \eta &= \frac{P_o}{P_i} + \text{Losses} \\
 \eta &= \frac{2400 \text{ kW} / 2400 \text{ kW} + (78,43)^2 \times 22}{1000} \\
 &= 94,66\%
 \end{aligned}$$



Activity 5.3

Calculate the inductance and capacitance per phase of a 28 km, three-phase overhead line having solid copper conductors of diameter 0,8 cm that are spaced on the corners of a triangle having sides of length 120 cm, 160 cm and 220 cm.

Solution:

$$\begin{aligned}
 d_1 &= 120 \times 10^{-2} \text{ m} & \text{dia.} &= 0,8 \text{ cm} \\
 d_2 &= 160 \times 10^{-2} \text{ m} & r &= 0,4 \times 10^{-2} \text{ m} \\
 d_3 &= 220 \times 10^{-2} \text{ m} & km &= 28 \\
 de &= \sqrt[3]{1,2 \times 1,6 \times 2,2} \\
 &= 1,62 \text{ m} \\
 L &= km [0,05 + 0,2 \log_e (de/r)] \text{ mH} \\
 &= 28 \left[0,05 + 0,2 \log_e \left(\frac{1,62}{0,004} \right) \right] \text{ mH}
 \end{aligned}$$

$$= 35,02 \text{ mH}$$

$$C = 28[1,18 \log e (1,62/0,004)]$$

$$= 0,259 \mu\text{f}$$



Activity 5.4

Calculate the total resistance, inductance and capacitance of a single-phase 36 km, overhead line with solid conductors of 1,8 cm diameter spaced 0,8 m between centres. Take resistivity of conductor material as $1,7 \mu\Omega \text{ cm}$.

Solution:

$$\begin{aligned} \text{loop resistance} &= \frac{\rho l}{a} \\ &= \frac{1,7 \times 72 \times 10^6}{10^6 \times \pi \times 0,9^2} \\ &= 4,81 \Omega \end{aligned}$$

$$\begin{aligned} \text{loop inductance} &= 72[0,05 + 0,2 \log e d/r] \text{mH} \\ &= 72[0,05 + 0,2 \log e (80/0,9)] \text{mH} \\ &= 68,22 \text{ mH} \end{aligned}$$

$$\begin{aligned} \text{Total capacitance} &= \frac{36}{36 \log e \left(\frac{d-r}{r} \right)} \\ &= \frac{36}{36 \log e \left(\frac{80-0,9}{0,9} \right)} \\ &= 0,23 \mu\text{F} \end{aligned}$$



Activity 5.1

Determine the total resistance, inductance and capacitance of a single-phase, 33 km, overhead line with solid conductors of 1,4 cm diameter and spaced 0,7 m between centres. Take resistivity of conductor material as $1,7 \mu\Omega \text{ cm}$ and ignore skin effect.

[7.29; 64.01; 0.2165]



Activity 5.2

Calculate the inductance and capacitance per phase, of 35 km of three phase overhead line, having solid copper conductors with a diameter of 1,5 cm.

When the overhead line is:

1. Spaced 50 cm between adjacent centres in flat regular spacing.
2. Spaced on the corners of a triangle having sides of length 55 cm : 85 cm : 110 cm.

[0.63; 32.76; 0.44; 0.8012; 34.45; 0.416]



Activity 5.3

Calculate the inductance per phase, of a 200 km, three phase transmission line, having an equilateral conductor spacing of 10 m and a conductor diameter of 30 mm.

[270.01]



Activity 5.4

A single-phase overhead transmission line delivers 2350 kW at 28 kV. The power factor is 0,8 lagging. The total resistance of the line is 15Ω and the total inductive reactance is 20Ω .

Calculate:

1. The sending end voltage.
2. The per unit regulation.
3. The transmission efficiency.

[104.91; $1573.65 + j2098.2$; $30526.67 < 38.25$; 0.09; 93.4]



Activity 5.5

Calculate the inductance and capacitance per phase of a 35 km, three phase overhead line having solid copper conductors of diameter 0,6 cm that are spaced on the corners of a triangle having sides of length 125 cm, 165 cm and 235 cm.

[1.69; 46.09; 0.307]



Activity 5.6

An overhead, single phase transmission line delivers 2200 kW at 31 kV. The power factor is 0,85 lagging. The total resistance of the line is 22Ω and the total inductive reactance is 30Ω .

Calculate the following:

1. The sending line voltage.
2. The per unit regulation.
3. The transmission efficiency.

[83.49; 33902<33.83; 0.094; 93.4; 2.02; 11.092]



Activity 5.7

1. Explain why the voltage at a power station is stepped up to very high values and give the advantages of stepping up the voltage.
2. With electrical transmission, what is the corona effect?
3. What do bundle conductors consist of?
4. What is the current-carrying capacity and what is it determined by?



Activity 5.8

A load of 3175 kVA at 27 kV and a power factor of 0,8 lagging is supplied by a three-phase transmission line having a resistance of $5,8 \Omega$ per phase and an inductive reactance of $8,8 \Omega$ per phase.

Determine:

1. The sending and end line-voltage.
2. The percentage regulation.
3. The efficiency of the line.

[No ans.]



Activity 5.9

A three-phase transmission line supplies a 870 kW star-connected load with a power factor of 0,8 lagging, at a line voltage of 36 kV. The line has a resistance of 45Ω per phase and an inductive reactance of 75Ω per phase.

Calculate the voltage at the sending end and the percentage regulation.

[No ans.]



Self-Check

I am able to:

- | | Yes | No |
|--|-----|----|
| • Describe the effect that resistance and temperature has on an overhead line | | |
| • Describe the effect that inductance has on an overhead line | | |
| • Describe the effect that capacitance has on an overhead line | | |
| • Calculate losses in overhead lines... resistance, inductance and capacitance | | |

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

Module 6

Measuring Power in Balanced and Unbalanced Systems

Learning Outcomes

On the completion of this module the student must be able to:

- Describe Measuring three-phase power by three Wattmeter method
- Describe Measuring three-phase power by two Wattmeter method
- Describe Measuring three-phase power by one Wattmeter method
- Describe Measuring single-phase and three-phase power with instrument transformers
- Calculate power

6.1 Introduction



This module describes how to measure three-phase power by one, two and three Wattmeter methods. It also describes measuring single-phase and three-phase power with instrument transformers. Examples showing how to calculate power are given.

6.2 Measuring three-phase power by three Wattmeter method

The circuit diagram is shown in **Figure 6.1**:

Here, it is applied to three phase four wire systems, current coil of all the three wattmeter's marked as one, two and three are connected to respective phases marked as one, two and three.

Pressure coils of all the three wattmeter are connected to common point at neutral line. Clearly each wattmeter will give reading as product of phase current and line voltage which is phase power.

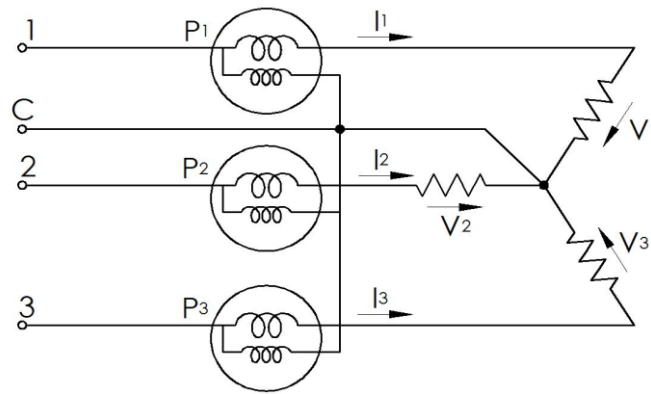


Figure 6.1 Star connected three-phase four-wire system

The resultant sum of all the readings of wattmeter will give the total power of the circuit. Mathematically we can

$$P = P_1 + P_2 + P_3 = V_1 I_1 + V_2 I_2 + V_3 I_3$$

6.3 Measuring three-phase power by two Wattmeter method

In this method we have two types of connections (a) Star connection of loads (b) Delta connection of loads. **Figure 6.2** shows the star connection.

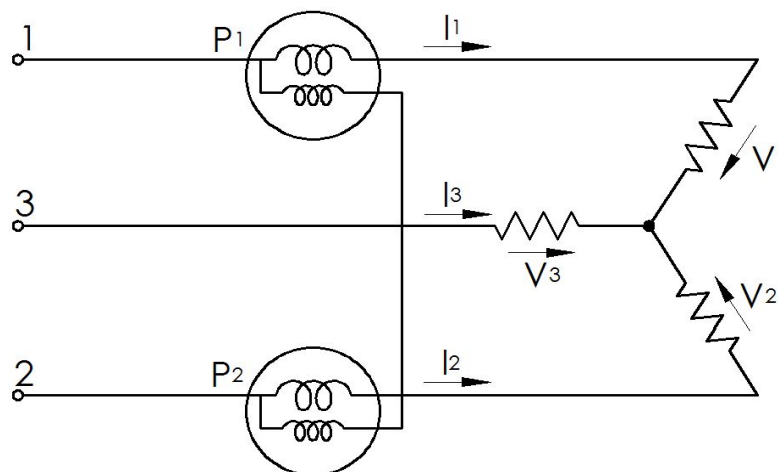


Figure 6.2 Star connected three-phase three-wire system

For star connected load clearly the reading of wattmeter one is product phase current and voltage difference ($V_2 - V_3$). Similarly the reading of wattmeter two is the product of phase current and the voltage difference ($V_1 - V_3$).

Thus the total power of the circuit is sum of the reading of both the wattmeters. Mathematically we can write

$$P = P_1 + P_2 = I_1(V_1 + V_2) + I_2(V_2 - V_3)$$

but we have $I_1 + I_2 + I_3 = 0$, hence putting the value of $I_1 + I_2 = -I_3$.

When the load is delta connected as shown in **Figure 6.3**, we get total power as $V_1 I_1 + V_2 I_2 + V_3 I_3$.

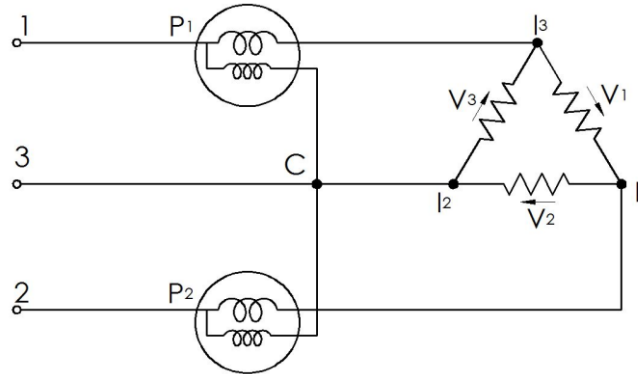


Figure 6.3 Delta connected three-phase three-wire system

The reading of wattmeter one can be written as

$$P_1 = -V_3 (I_1 - I_3)$$

and reading of wattmeter two is

$$P_2 = -V_2 (I_2 - I_1)$$

$$\text{Total power is } P = P_1 + P_2 = V_2 I_2 + V_3 I_3 - I_1 (V_2 + V_3)$$

but $V_1 + V_2 + V_3 = 0$,

hence expression for total power will reduce to $V_1 I_1 + V_2 I_2 + V_3 I_3$.

6.4 Measuring three-phase power by one Wattmeter method

Limitation of this method is that it cannot be applied on an unbalanced load. So under this condition we have $I_1 = I_2 = I_3 = I$ and $V_1 = V_2 = V_3 = V$.

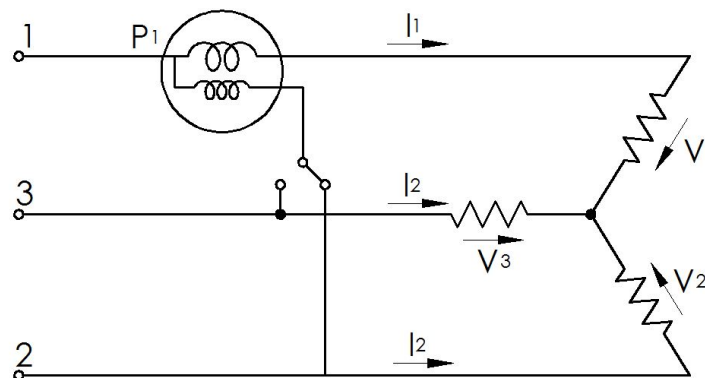


Figure 6.4 Star connected three-phase three-wire system

Two switches are given which are marked as 1-3 and 1-2, by closing the switch 1-3 we get reading of wattmeter as

$$P_1 = V_{13} I_1 \cos(30 - \phi) = \sqrt{3} \times VI \cos(30 - \phi)$$

Similarly the reading of wattmeter when switch 1-2 is closed is

$$P_2 = V_{12} I_1 \cos(30 + \phi) = \sqrt{3} \times VI \cos(30 + \phi)$$

$$\text{Total power is } P_1 + P_2 = 3VI \cos \phi$$


6.5 Instrument transformers in a single-phase circuit

Figure 6.5 shows an instrument load connected through instrument transformers to a single-phase, high-voltage line.

The instruments include a voltmeter (22-6), an ammeter, and a wattmeter. The potential transformer is rated at 4,600 to 115 volts; the current transformer is rated at 50 to 5 amperes.

The potential coils of the volt meter and the wattmeter are connected in parallel across the low-voltage output of the potential transformer. Therefore, the voltage across the potential coils of each of these instruments is the same.

The current coils of the ammeter and the watt meter are connected in series across the secondary output of the current transformer. As a result, the current in the current coils of both instruments is the same.

	<p>Note: The secondary of each instrument transformer is grounded to provide protection from high-voltage hazards.</p>
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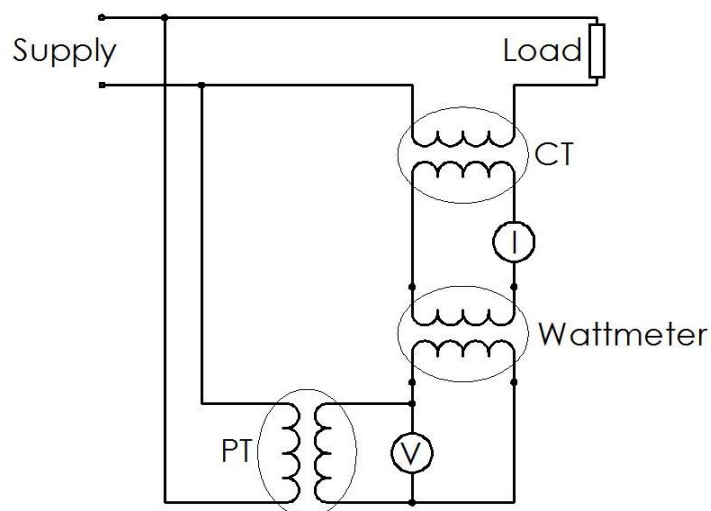


Figure 6.5 Instrument transformers in a single-phase circuit

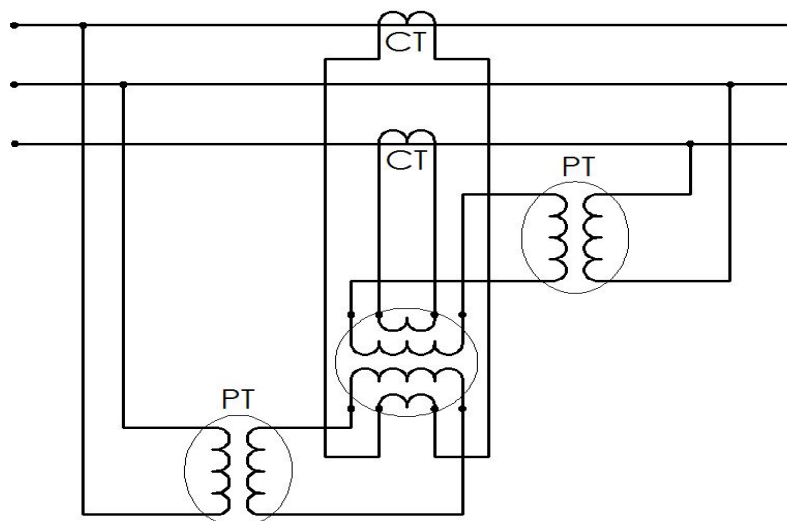


Figure 6.6 Instrument transformers in a three-phase circuit



Activity 6.1

Two wattmeters are used to measure the input power to a balanced three-phase load, which has a unity power factor. Each meter indicates 17,5 kW. The power factor drops to 0,8 lagging but the power remains unchanged.

Calculate the readings on the wattmeters.

Solution:

$$P_1 = 17,5$$

$$P_2 = 17,5 \cos \phi = 0,8 (36,87^\circ)$$

$$\text{Total power} = P_1 + P_2 = 35 \text{ kW}$$

$$\tan \phi = \sqrt{3}(P_2 - P_1)/P_2 + P_1$$

$$\tan 36,87^\circ / \sqrt{3} = P_2 - P_1 / P_2 + P_1$$

$$0,75 / \sqrt{3} = P_2 - P_1 / P_2 + P_1$$

$$P_2 - P_1 = 0,433(P_2 + P_1)$$

$$= 0,433(35)$$

$$= 15,16 \text{ kW}$$

$$\text{Per Meter} = 7,58 \text{ kW}$$

$$\text{Readings: } P1 = 17,5 - 7,58$$

$$= 9,92$$

$$P2 = 17,5 + 7,58$$

$$= 25,08 \text{ kW}$$



Activity 6.2

Three identical coils are connected in star across a three-phase, 370 V, 50 Hz supply. The readings on two wattmeters connected to measure the total power are 2,5 kW and 1,8 kW respectively.

Calculate:

1. The power factor
2. The line current

Solution:

$$V = 370 \text{ V } f = 50 \text{ Hz } W1 = 2,5 \text{ W } W2 = 1,8$$

$$\tan \Phi = \sqrt{3}(W1 - W2)/W1 + W2$$

$$= \sqrt{3}(2,5 - 1,8)/(2,5 + 1,8)$$

$$= 0,281$$

$$\therefore \Phi = 15,7^\circ$$

$$\therefore \cos \Phi = \cos 15,7^\circ = 0,96$$

$$I_L = PT/\sqrt{3} V_L \cos \Phi$$

$$= (4,3 \times 10^3)/\sqrt{3} \times 370 \times 0,96$$

$$= 6,99 \text{ A}$$



Activity 6.3

The input power to a 3 350 V three-phase delta connected induction motor is 180 kW. The power factor of the motor is 0,85 lagging.

Calculate the:

1. Line and phase currents
2. Input power readings on the two watt-meters
3. kVA rating of the motor

Solution:

$$1. \quad PT = \sqrt{3} V_L I_L \cos\Phi$$

$$I_L = \frac{180\,000}{\sqrt{3} \times 3350} \times 0,85$$

$$= 36,5A$$

$$I_P = \frac{I_L}{\sqrt{3}} = 36,5/\sqrt{3} = 63,2 A$$

$$2. \quad W1 = V_L I_L \cos(-30 + \Phi) \quad \Phi = 31,79$$

$$= 3350 \times 36,5 \cos(30 + 31,79)$$

$$= 3350 \times 36,5 \cos(61,79)$$

$$= 57,8 kW$$

$$W2 = V_L I_L \cos(30 - \Phi)$$

$$= 3350 \times 36,5 \cos(30 - 31,79)$$

$$= 122,22 kW$$

$$3. \quad kVA = \frac{\sqrt{3} V_L I_L}{1000}$$

$$= \frac{\sqrt{3} \times 3350 \times 36,5}{1000}$$

$$= 211,79 kW$$



Activity 6.4

Each branch of a three-phase star-connected load consists of a coil of resistance $5,5 \Omega$ and reactance $6,5 \Omega$. The load is supplied at a line voltage of $400 V$, $50 Hz$. The power supplied to the load is measured by the two-wattmeter method.

Calculate their separate readings.

Solution:

$$Z = 5,5 + j 6,5 = 8,51 \angle 49,76^\circ$$

$$V_L = 400 \text{ V}$$

$$\Phi = 49,76^\circ \text{ lag}$$

$$V_p = 400/\sqrt{3}$$

$$= 230,9$$

$$I_P = V_P/Z_P$$

$$= 230,9 \angle 0^\circ / 8,51 \angle 49,76^\circ$$

$$= 27,03 \angle -49,76^\circ$$

$$I_L = I_P = 27,03 \angle -49,76^\circ$$

$$P_2 + P_1 = \sqrt{3} V_L I_L \cos \Phi$$

$$= \sqrt{3} \times 400 \times 27,03 \cos 49,76$$

$$= 12,097 \text{ kW}$$

$$\tan \Phi = \sqrt{3}(P_2 - P_1)/P_2 + P_1$$

$$P_2 - P_1 = \tan 49,76^\circ \times 12,097/\sqrt{3}$$

$$= 8,25 \text{ kW}$$

$$2 P_1 = 3,85$$

$$P_1 = 1,92 \text{ kW}$$

$$P_2 = 12,097 - 1,92$$

$$= 10,18 \text{ kW}$$



Activity 6.1

1. Draw a neat labelled sketch showing how the two-wattmeter method can be used to measure power in a three-phase network.
2. Draw a neat labelled sketch showing how the two-wattmeter method is used to measure power in a star connected three-phase three-wire system.
3. Draw a neat labelled sketch showing how the two-wattmeter method is used to measure power in a delta connected three-phase three-wire

system.

4. Measuring three-phase power by one Wattmeter method has one limitation, what is the limitation?



Activity 6.2

Two wattmeters are connected to measure the input to a balanced three-phase circuit. The readings are 3 300 W and 720 W respectively.

Find the power factor of the circuit when:

- Both the readings are positive.
- The latter reading is obtained after reversing the connections to the current coil of one instrument.

[47.98; 0.67; 2.7; 0.347]



Activity 6.3

A three-phase induction motor develops 55 kW when running at 80% efficiency at a power factor of 0,75 lagging.

Calculate the input power readings on each of the two watt-meterse.

[68.750; 35048.77; 51899.385; 16850.62]



Activity 6.4

Each branch of a three-phase star connected load consists of a coil of resistance 5Ω and reactance 6Ω . The load is supplied at a line voltage of 400 V, 50 Hz. The power supplied to the load measured by the two wattmeter method. Calculate their separate readings.


[242.49; 29.56<-50.19; 13.112; 11.092]





Activity 6.5


A wattmeter measures the AC power delivered to a load as 250 W. The supply voltage is 115 V and the load is known to have a phase angle of 33 degrees. Calculate the load current.

[2.59]

	<h3>Activity 6.6</h3>
<p>A wattmeter measures the AC power delivered to a load as 100 W, and an ammeter and voltmeter monitor the load current as 1.5 A and 100 V. Calculate the phase angle between the load current and voltage.</p>	
<p>[100; 0.667; 48.2]</p>	

	<h3>Activity 6.7</h3>
<p>Find the power drawn by a three-phase induction motor if the readings on the two wattmeter's are 860W and 240 W.</p>	
<p>[1100]</p>	

	<h3>Activity 6.8</h3>
<p>Two watt-meters are used to measure the input power to a balanced three-phase load with unity power factor. Each meter indicates 18,5 kW.</p> <p>Calculate the readings on the watt-meters, if the power factor drops to 0,7 lagging but the power remains the same.</p>	
<p>[No ans.]</p>	

	<h3>Self-Check</h3>		
I am able to:	Yes	No	
• Describe Measuring three-phase power by three Wattmeter method	<input type="checkbox"/>	<input type="checkbox"/>	
• Describe Measuring three-phase power by two Wattmeter method	<input type="checkbox"/>	<input type="checkbox"/>	
• Describe Measuring three-phase power by one Wattmeter method	<input type="checkbox"/>	<input type="checkbox"/>	
• Describe Measuring single-phase and three-phase power with instrument transformers	<input type="checkbox"/>	<input type="checkbox"/>	
• Calculate power	<input type="checkbox"/>	<input type="checkbox"/>	
<p>If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.</p>			

Module 7

Switchgear and Protective Devices and Control

Learning Outcomes

On the completion of this module the student must be able to:

- Describe the use and operation of an earth leakage relay
- Describe the use and operation of an attracted armature relay
- Describe the use and operation of an electromagnetic relay
- Describe the use and operation of a Bucholz relay
- Describe the use and operation of Diode protection

7.1 Introduction



This module describes the use and operation of an earth leakage relay, attracted armature relay, electromagnetic relay, Bucholz relay and diode protection.

7.2 Protective relays

Any system of protection must comply with certain requirements.

They are:

- It must be sensitive enough to detect a fault in the early stages.
- It must be able to isolate a faulty machine or apparatus from the remainder of the system.
- It must be absolutely reliable in operation and as simple and robust as possible.
- It must be able to discriminate between fault currents in the section being protected.
- Fault currents in other sections, i.e. there must be a minimum disruption when a fault occurs.

7.2.1 Earth leakage relay

The working principle of voltage ELCB is quite simple. One terminal of the relay coil is connected to the metal body of the equipment to be protected against earth leakage and other terminal is connected to the earth directly.

If any insulation failure occurs or live phase wire touches the metal body, of the equipment, there must be a voltage difference appears across the terminal of the coil connected to the equipment body and earth. This voltage difference produces a current to flow the relay coil.

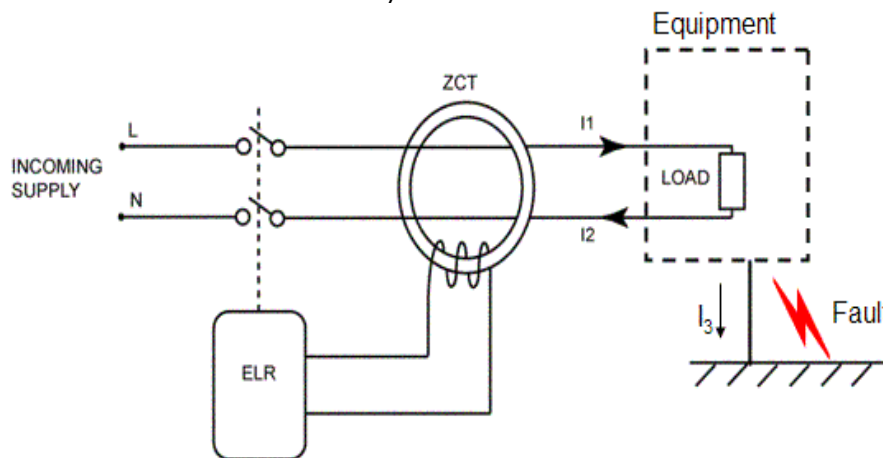



Figure 7.1

If the voltage difference crosses, a predetermined limit, the current through the relay becomes sufficient to actuate the relay for tripping the associated circuit breaker to disconnect the power supply to the equipment.

	<p>Note: The typicality of this device is, it can detect and protect only that equipment or installation with which it is attached. It cannot detect any leakage of insulation in other installation of the system.</p>
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7.2.2 The attracted armature relay

Figure 7.2 shows a diagram of an attracted armature relay.

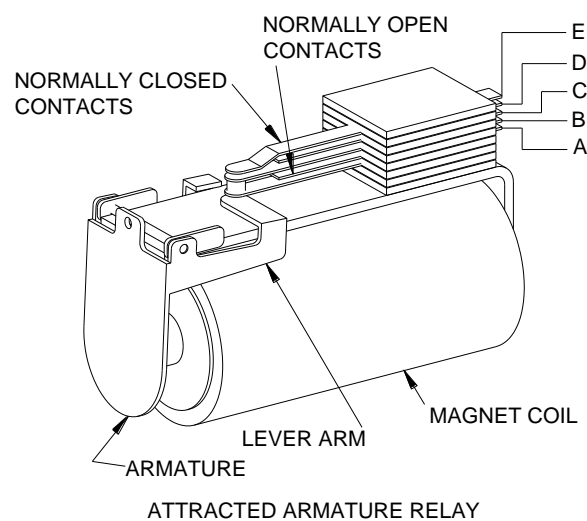


Figure 7.2 Attracted Armature Relay

The attracted armature relay operates by the movement of the armature into the magnetic field generated by the coil.

When the coil is energized, the armature is attracted and the contact points close.

7.2.3 The electromagnetic relay

Figure 7.3 shows a diagram of the electromagnetic relay.

The relay may be used to protect any size of feeder by choosing an appropriate C/T ratio. The relay operating current can be altered either by adjusting the air gap or by having tapings on the relay coil.

When the latter method is used, a special tapping plug bridge is incorporated in the relay which prevents the C/T secondary being open circuited whilst the tapping is changed.

Otherwise the un-cancelled primary flux generated by the feeder current may cause such a high flux density and secondary induced E.M.F. so as to seriously damage the C/T.

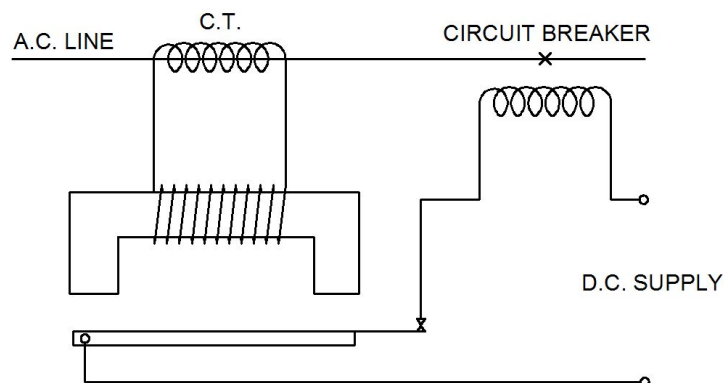


Figure 7.3 Electromagnetic relay

7.2.4 Buchholz relay

Transformer protection.

Rapid gas evolution:

The rate of gas evolution that will instantaneously cause the alarm to activate.

Medium gas evolution:

A gas evolution rate that causes displacement of oil that operates a relay which activates the alarm.

Slow gas evolution:

A gradual collection of gasses over days or weeks accumulate.

Allowance must be made for the different faults that manifest themselves with the operation of a transformer. These possible faults have produced a list of **principles** that are used in transformer protection.

They are:

- The tank must be earthed.
- Gas detection apparatus must be in place.
- Current detection must be possible.
- Over fluxing.
- Overheating.
- Over current protection.
- Unrestricted earth fault.
- Restricted earth fault.

Figure 7.4 shows a Bucholtz relay that will operate under the following conditions.

- Low oil level.
- Slow gas leak.
- Internal explosion.

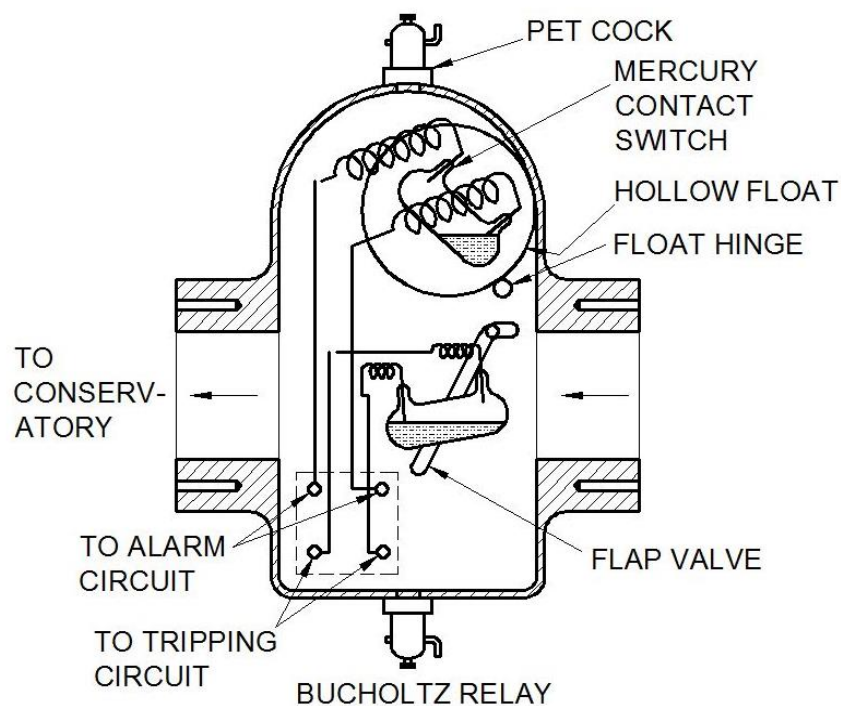


Figure 7.4 Bucholz relay

The color of the gas in the site glass of the Bucholtz relay for the following faults are:

- Burst insulation = white or yellow gas
- Breakdown of oil = Black or gray gas

7.3 High inductive circuits

If a switch is suddenly opened that is providing current to an inductor. Since inductors have the property

$$V = L \, di/dt,$$

it is not possible to turn off the current suddenly, since that would imply an infinite voltage across the inductor's terminals.

What happens instead is that the voltage across the inductor suddenly rises and keeps rising until it forces current to flow. Electronic devices controlling inductive loads can be easily damaged, especially the component that "breaks down" in order to satisfy the inductor's craving for continuity of current.

The switch is initially closed, and current I is flowing through the inductor. When the switch is opened, the inductor "tries" to keep current flowing from A to B, as it had been.

That means that terminal B goes positive relative to terminal A. In a case like this it may go 1000 volts positive before the switch contact "blows over". This shortens the life of the switch and also generates impulsive interference that may affect other circuits nearby.



Note:

If the switch happens to be a transistor, it would be an understatement to say that its life is shortened; its life is ended.

Diode protection:

The best solution is to put a diode across the inductor. The diode must be able to handle the initial diode current, which equals the steady current that had been flowing through the inductor. something like a 1N4004 is fine for many cases.

- When the switch is on, the diode is back-biased (from the dc drop across the inductor's winding resistance).
- At turn-off the diode goes into conduction, putting the switch terminal a diode drop above the positive supply voltage.

The only disadvantage of this protection circuit is that it lengthens the decay of current through the inductor, since the rate of change of inductor current is proportional to the voltage across it.

For applications where the current must decay quickly (high-speed impact printers, high-speed relays, etc.), it may be better to put a resistor across the inductor, choosing its value so that $V_{\text{supply}} + IR$ is less than the maximum allowed voltage across the switch.

For fastest decay with a given maximum voltage, a zener could be used instead, giving a ramp-down of current rather than an exponential decay.



Activity 7.1

1. Discuss five requirements that a protective system is based on.
2. Discuss the working principle of an earth leakage relay.
3. Make a neat diagram of an earth leakage relay.
4. Discuss the working principle of the attracted armature relay.
5. Discuss the working principle of the electromagnetic relay.
6. Name the eight points on the list of principles that are used in transformer protection.
7. Discuss the working principle of the Bucholtz relay.
8. What is the reason why it is not possible to turn off the switch suddenly that is providing current to an inductor, and what would happen if this was done?



Self-Check

I am able to:

- | | Yes | No |
|---|-----|----|
| • Describe the use and operation of an earth leakage relay | | |
| • Describe the use and operation of an attracted armature relay | | |
| • Describe the use and operation of an electromagnetic relay | | |
| • Describe the use and operation of a Bucholz relay | | |
| • Describe the use and operation of Diode protection | | |

If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.

Module 8

Installation and Care of Electrical Equipment

Learning Outcomes

On the completion of this module the student must be able to:

- Describe the installation process of a transformer
- Describe the inspection management of a transformer
- Describe the maintenance processes of a transformer
- Describe the characteristics of copper
- Describe the characteristics of aluminium
- Describe dielectric materials

8.1 Introduction



This module describes the installation process, inspection management and maintenance processes of a transformer. It also describes the characteristics of copper, aluminium and dielectric materials.

8.2 Installation of a transformer

Before your transformer is scheduled to be shipped to its designated site, it's important that you coordinate with the manufacturer what acceptance tests should be carried out.

The transformer's suitability tests:

- Standard transformer tests performed for each unit include the following:
 - Ratio, for voltage relationship
 - Polarity for single- and 3-phase units (because single-phase transformers are sometimes connected in parallel and sometimes in a 3-phase bank)
 - Phase relationship for 3-phase units (important when two or more transformers are operated in parallel)
 - Excitation current, which relates to efficiency and verifies that core design is correct
 - No-load core loss, which also relates to efficiency and correct core design

- Resistance, for calculating winding temperature and [I.sup.2]R component of winding losses (usually not required on 600V class units)
- Impedance (via short circuit testing), which provides information needed for breaker and/or fuse sizing and interrupting rating and for coordinating relaying schemes
- Load loss, which again directly relates to the transformer's efficiency
- Regulation, which determines voltage drop when load is applied
- Applied and induced potentials, which verify dielectric strength

**Note:**

There are additional tests that may be applicable, depending upon how and where the transformer will be used.

The additional tests that can be conducted include the following:

- Impulse (where lightning and switching surges are prevalent)
- Sound (important for applications in residential and office areas and that can be used as comparison with future sound tests to reveal any core problems)
- Temperature rise of the coils, which helps ensure that design limits will not be exceeded
- Corona for medium voltage (MV) and high-voltage (HV) units, which helps determine if the insulation system is functioning properly
- Insulation resistance (megohmmeter testing), which determines dryness of insulation and is often done after delivery to serve as a benchmark for comparison against future readings
- Insulation power factor, which is done at initial installation and every few years thereafter to help determine the aging process of the insulation

8.2.1 Site considerations**Positioning the transformer:**

When planning the installation, you should select a location that complies with all safety codes yet does not interfere with the normal movement of personnel, equipment, and material.

Foundations:

Foundation preparation usually includes an evaluation of soil characteristics and concrete work. For transformers placed outside that are 2000kVA and above, you may wish to have the soil examined.

**Note:**

A civil engineer should be consulted for approving the foundations.

Structural support:

When placed inside or on top of a building, you must consider structural capabilities because a transformer represents a highly concentrated load. For

new buildings, you should work with the structural engineers so that the transformer's placement is included in the building plans.

Installing transformers in existing structures may require an analysis of the building for structural support capability since the original structural information may not be available.

Preliminary inspection upon receipt of transformer:

When received, a transformer should be inspected for damage during shipment. Examination should be made before removing it from the railroad car or truck, and, if any damage is evident or any indication of rough handling is visible, a claim should be filed with the carrier at once and the manufacturer notified.

Handle and lift with care:

Transformers are designed with provisions for lifting, jacking, and/or rolling. These provisions will vary depending upon the weight, size, and mechanical configuration of the unit.



Note:

Transformers should be maintained in an upright position when being moved.

Making connections that work:

When you start making the connections between the transformer's terminals and the incoming and outgoing conductors, carefully follow the instructions given on the nameplate or on the connection diagram.



Note:

Check all of the tap jumpers for proper location and for tightness. Re-tighten all cable retaining bolts after the first 30 days of service.

Before working on the connections make sure all safety precautions have been taken. As appropriate, you should make arrangements to adequately support the incoming/outgoing connecting cables to ensure that there is no mechanical stress imposed on transformer bushings and connections.

Controlling sound level:

When testing a transformer for sound level, you should recognize that all transformers, when energized, produce an audible noise. Although there are no moving parts in a transformer, the core does generate sound.

Grounding:

Grounding is necessary to remove static charges that may accumulate and also is needed as a protection should the transformer windings accidentally come in contact with the core or enclosure (or tank for wet types).

8.2.2 Final inspection and testing:

Once the transformer has been located on its permanent site, a thorough final inspection should be made before any assembly is accomplished and the unit is energized.

Before energizing the unit, it's very important that you alert all personnel installing the transformer that lethal voltages will be present inside the transformer enclosure as well as at all connection points.



Note:

The installation of conductors should be performed only by personnel qualified and experienced in high-voltage equipment.

For this test, apply a low-voltage (240V or 480V) to the high-voltage winding and measure the output at the low-voltage winding. However, for low-voltage (600V and below) transformers, this is not practical.

All windings should be checked for continuity:

You should arrange for an insulation resistance test to be carried out to make certain that no windings are grounded.

You will find it beneficial to carry out this testing for future comparative purposes, and also for determining the suitability of the transformer for energizing or application of a high potential test.

When operating in parallel:

When transformers are installed for parallel operation, their rated voltages, impedances, and turn ratios ideally should be the same and their phasor relationships identical.

Applying the load:

Before energizing a 3-phase transformer, you should arrange to monitor the voltages and currents on the low-voltage side. Then, without connecting the load, energize the transformer.

Connect the load and energize the transformer:

While monitoring the voltages and currents, gradually increase the load in a stepped or gradual application until full load is reached. If you cannot gradually increase the load, then full load may be applied.

After installation:

you should check the output voltage of the transformer. This should be done at some safe access point near or at the load. Never attempt to check the output voltage at the transformer. Dangerous high voltage will be present within the transformer enclosure.

When changing taps:

the same changes must be made for all phases. Consult the transformer diagrammatic nameplate for information on what tap must be used to correct for extra high or extra low incoming line voltage.

The same adjustment should be made to compensate for voltage drop in the output due to long cable runs.

When the load-side voltage is low, tap connections below 100% of line voltage must be used to raise the load voltage. If the load-side voltage is high, tap connections above 100% of line voltage must be used to lower the load voltage.

8.3 Care of equipment**8.3.1 Inspection of transformers**

The following periodic tests and inspections are recommended for routine maintenance of the medium power transformers.

Gauge readings:

One month after initial energization and annually thereafter.

Cooling fans:

Inspect annually.

Check the cooling fans (if any) by setting the fan “auto/manual” control switch to the “manual” position. The fans should rotate at full speed within approximately five seconds.

Control wiring:

Inspect annually.

Control wiring should be checked to insure that wire insulation is in good condition. The control cabinet and associated conduit should be inspected to ensure that weather seals are intact.

Paint finish:

Inspect annually.

Inspect the paint finish for damage or weathering that exposes the primer coat or bare metal. Repair any paint damage that might be found.

Fluid dielectric test:

Test annually.

Sample the insulating fluid as described below. The dielectric strength of the insulating fluid should measure at least 26 kV.

Bushings and surge arrester insulations:

Inspect annually.

Bushing and surge arrester insulators should be clean. If the surfaces are excessively dirty, they should be cleaned while the transformer is not energized.

Bushing terminals:

Inspect one month after energization and annually thereafter.

If the transformer is energized and under load, measure bushing terminal temperatures using an infrared scanner.

Excessive bushing terminal temperature indicates a loose or dirty connection. If the transformer is not energized, use a torque measuring device to make sure terminal connections

Gaskets:

Check annually

Visually check all gaskets for cracking or other signs of deterioration. Replace as necessary.

When replacing a gasket carefully clean mating surfaces to remove any rust, dirt, transformer fluid, old gasket material, or other contamination that might prevent a good seal.

Use an appropriate gasket cement when installing new gaskets.

8.3.2 Maintenance of transformers

Monthly maintenance:

- The oil level in oil cap under silica gel breather must be checked in one-month interval. If it is found the transformer oil inside the cup comes below the specified level, the oil is to be topped-up to the specified level.
- Breathing holes in silica gel breather should also be checked monthly and properly cleaned if required, for proper breathing action.
- If the transformer has oil filled bushing, the oil level inside the bushing must be visually checked using the oil gage attached to those bushing.

Daily maintenance:

- Reading of MOG (Magnetic Oil Gage) of main tank and conservator tank.
- Check color of silica gel in breather.
- Leakage of oil from any part of a transformer. If oil leakage is found, take required action to plug the leakage. If silica gel becomes pinkish, it should be replaced.

Annual maintenance:

- The auto, remote, manual function of cooling system that means, oil pumps, air fans, and other items engaged in cooling system of transformer, along with their control circuit to be checked in the interval of one year. In the case of trouble, investigate control circuit and physical condition of pumps and fans.
- All the bushings of the transformer to be cleaned by soft cotton cloths yearly. During cleaning the bushing should be checked for cracking.

- Oil condition of OLTC to be examined in every year. For that, oil sample to be taken from drain valve of diverter tank, and this collected oil sample to be tested for dielectric strength (BDV) and moisture content (PPM). If BDV is low and PPM for moisture is found high compared to recommended values, the oil inside the OLTC to be replaced or filtered.
- Mechanical inspection of Buchholz relays to be carried out on yearly basis.
- All marshalling boxes to be cleaned from inside at least once in a year. All illumination, space heaters, to be checked whether they are functioning properly or not. If not, required maintenance action to be taken. All the terminal connections of control and relay wiring to be checked and tighten at least once in a year.
- All the relays, alarms and control switches along with their circuit, in R&C panel (Relay and Control Panel) and RTCC (Remote Tap Changer Control Panel) to be cleaned by appropriate cleaning agent.
- The pockets for OTI, WTI (Oil Temperature Indicator & Winding Temperature Indicator) on the transformer top cover to be checked and if required oil to be replenished.
- The proper function of Pressure Release Device and Buchholz relay must be checked annually.
- Insulation resistance and polarization index of transformer must be checked with battery operated megger of 5 KV range.
- Resistive value of earth connection and riser must be measured annually with clamp on earth resistance meter.
- DGA or Dissolve Gas Analysis of transformer Oil should be performed.

8.4 Materials used in electrical systems

8.4.1 Copper

Electrical conductivity:

Electrical conductivity is a measure of how well a material transports an electric charge. This is an essential property in electrical wiring systems.



Note:

Copper has the highest electrical conductivity rating of all non-precious metals: the electrical conductivity of copper = 58.5 S/m at 20 °C.

Tensile strength:

Tensile strength measures the force required to pull an object such as rope, wire, or a structural beam to the point where it breaks. The tensile strength of a material is the maximum amount of tensile stress it can take before breaking.



Note:

Copper's higher tensile strength (200–250 N/mm² annealed)

Corrosion resistance:

Corrosion is the unwanted breakdown and weakening of a material due to chemical reactions. Copper generally resists corrosion from moisture, humidity, industrial pollution, and other atmospheric influences.

Coefficient of thermal expansion:

Metals and other solid materials expand upon heating and contract upon cooling. This is an undesirable occurrence in electrical systems.

**Note:**

Copper has a low coefficient of thermal expansion for an electrical conducting material.

Thermal conductivity:

Thermal conductivity is the ability of a material to conduct heat. In electrical systems, high thermal conductivity is important for dissipating waste heat, particularly at terminations and connections.

**Note:**

Copper has a 60% higher thermal conductivity rating than aluminium.

8.4.2 Aluminium**Electrical conductivity:**

Aluminium has a high electrical conductivity rating, but lower than copper. The electrical conductivity of aluminium = 36.9 S/m at 20 °C.

Tensile strength:

Aluminium has a lower tensile strength than copper although aluminium is used in overhead cables because it is light. Aluminium has a tensile strength of 100 N/mm² for typical conductor alloys.

Corrosion resistance:

Aluminium resists corrosion. Only the outer skin of the material becomes corroded due to the presence of oxygen in the atmosphere. This corroded outer skin then protects the rest of the material from further corrosion.

Coefficient of thermal expansion:

Metals and other solid materials expand upon heating and contract upon cooling. This is an undesirable occurrence in electrical systems.

**Note:**

Aluminium, an alternate common conductor, expands nearly one third more than copper under increasing temperatures.

Thermal conductivity:


Thermal conductivity is the ability of a material to conduct heat.

Aluminium has a 60% lower thermal conductivity rating than copper.

8.4.3 Dielectric materials

A dielectric material is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material as they do in a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization.


Because of dielectric polarization, positive charges are displaced toward the field and negative charges shift in the opposite direction. This creates an internal electric field that reduces the overall field within the dielectric itself.

	<p>Note:</p> <p>If a dielectric is composed of weakly bonded molecules, those molecules not only become polarized, but also reorient so that their symmetry axes align to the field.</p>
---	---

Dielectric materials used:

Dielectric materials can be solids, liquids, or gases. In addition, a high vacuum can also be a useful, nearly lossless dielectric even though its relative dielectric constant is only unity.


Solid dielectrics are perhaps the most commonly used dielectrics in electrical engineering, and many solids are very good insulators. Some examples include porcelain, glass, and most plastics.


	<p>Note:</p> <p>Air, nitrogen and sulphur hexafluoride are the three most commonly used gaseous dielectrics.</p>
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- Industrial coatings such as parylene provide a dielectric barrier between the substrate and its environment.
- Mineral oil is used extensively inside electrical transformers as a fluid dielectric and to assist in cooling. Dielectric fluids with higher dielectric constants, such as electrical grade castor oil, are often used in high voltage capacitors to help prevent corona discharge and increase capacitance.
- Because dielectrics resist the flow of electricity, the surface of a dielectric may retain stranded excess electrical charges. This may occur accidentally when the dielectric is rubbed (the tribo-electric effect). This can be useful, as in a Van de Graaff generator or electrophorus, or it can be potentially destructive as in the case of electrostatic discharge.
- Specially processed dielectrics, called electrets (which should not be confused with ferroelectrics), may retain excess internal charge or "frozen

in" polarization. Electrets have a semi-permanent electric field, and are the electrostatic equivalent to magnets. Electrets have numerous practical applications in the home and industry.

- Some dielectrics can generate a potential difference when subjected to mechanical stress, or (equivalently) change physical shape if an external voltage is applied across the material. This property is called piezoelectricity. Piezoelectric materials are another class of very useful dielectrics.
- Some ionic crystals and polymer dielectrics exhibit a spontaneous dipole moment, which can be reversed by an externally applied electric field. This behaviour is called the ferroelectric effect. These materials are analogous to the way ferromagnetic materials behave within an externally applied magnetic field. Ferroelectric materials often have very high dielectric constants, making them quite useful for capacitors.

	Activity 8.1
<ol style="list-style-type: none"> 1. When installing a new transformer. State 5 checks to be carried out before the transformer leaves the supplier. 2. When a new transformer arrives on site. Name 5 checks to be performed before it is lifted or moved from the transport. 3. Discuss three precautions when lifting a new transformer onto its foundations. 4. Name four maintenance checks to be carried out on a weekly basis. 5. Name four maintenance checks to be carried out on annually. 6. Discuss 5 characteristics of copper. 7. Discuss two advantages of using aluminium above copper. 8. Discuss four disadvantages of using aluminium above copper. 9. Name two solid dielectric materials used in industry. 10. Explain the function of the solid dielectric material used in a capacitor. 	

	Self-Check	
I am able to:	Yes	No
• Describe the installation process of a transformer		
• Describe the inspection management of a transformer		
• Describe the maintenance processes of a transformer		
• Describe the characteristics of copper		
• Describe the characteristics of aluminium		
• Describe dielectric materials		
If you have answered 'no' to any of the outcomes listed above, then speak to your facilitator for guidance and further development.		

Past Examination Papers



**higher education
& training**

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

AUGUST 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080085)

22 July 2015 (Y-Paper)

13:00 – 16:00

Calculators may be used.

This question paper consists of 5 pages and 1 formula sheet of 2 pages.

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N5
TIME: 3 HOURS
MARKS: 100**

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
 2. Read ALL the questions carefully
 3. Number the answers according to the numbering system used in this question paper.
 4. Write neatly and legibly.
-

QUESTION 1:

1.1 Name **THREE** methods used for improving poor commutation in a DC generator (3)

1.2 A 40 kW, 475 V, 1 000 r/min DC shunt motor has a full-load efficiency of 90 %. The armature circuit has a resistance of $0,24 \Omega$ and a total voltage drop of 3 V at the brushes. The field current is 1,6 A.

Calculate:

1.2.1 The full-load line current. (3)

1.2.2 The full-load shaft torque in Nm. (3)

1.2.3 The total resistance of the motor starter. to limit the armature starting current to 1,3 times of the full load current. (5)

1.3 A DC motor draws an armature current of 180A at 50 V. The resistance of the armature circuit is $0,4 \Omega$. The motor has 6 poles and the armature is lap-connected with 1 800 conductors. The flux per pole is 0,05 Wb.

Calculate:

1.3.1 The speed. (3)

1.3.2 The gross torque developed by the armature. (3)

[20]

QUESTION 2:

2.1 Define the RMS or effective value of an alternating current. (3)

2.2 The following ordinates were taken during a half cycle of a symmetrical alternating current wave. The current varies in a linear manner between successive points:

Phase angle degrees :	0	30	60	90	120	150	180
Current in amperes :	0	6,5	18,5	25	23	18,5	0

Without plotting the graph, determine the following:

2.2.1 The mean value (5)

2.2.2 The RMS value. (3)

2.3 An impedance of $Z_1 = 4 - j6 \Omega$ is connected in parallel with another impedance of $Z_2 = 5 + j10 \Omega$. This circuit is connected in series to an (11)

impedance of $Z_3 = 3 + j7 \Omega$. The combination is then connected in parallel to an impedance of $Z_4 = 4 + j8 \Omega$. The current flowing through Z_1 is 12L 0 A. Calculate the supply voltage and total current.

[22]

QUESTION 3:

3.1 List THREE types of losses that occur in transformers. (3)

3.2 Explain *mutual induction* as applicable to transformers. (3)

3.3 A 950 kVA, 45 kV/15 kV single-phase transformer with a resistance voltage drop of 1,8 percent and a reactance voltage drop of 5 % is connected in parallel with a 1 400 kVA, 45 kV/15 kV single-phase transformer with a resistance voltage drop of 4% and a reactance voltage drop of 8 % . (9)

Determine the kVA loading and operating power factor of each transformer when the total load is 2 000 kVA at a power factor of 0,8 lagging.

3.4 A three-phase 475 V star-connected motor has an output of 75 kW, with an efficiency of 85 % and a power factor of 0,9.

Calculate:

3.4.1 The line current (3)

3.4.2 If the motor windings are connected in delta, what will be the correct three-phase supply voltage suitable for the motor? (2)

[20]

QUESTION 4:

4.1 State FIVE advantages of induction motors

4.2 An single-phase overhead transmission line delivers 2 350 kW at 28 kV (5)
The power factor is 0,8 lagging. The total resistance of the line is 15 Ω and the total inductive reactance is 20 Ω .

Calculate:

4.2.1 The sending end voltage. (5)

4.2.2 The per unit regulation. (2)

4.2.3 The transmission efficiency. (3)

4.3 A three-phase induction motor develops 55 kW when running at 80 % efficiency at a power factor of 0, 75 lagging. (5)

Calculate the input power readings on each of the two watt-meters.

[20]

QUESTION 5:

5.1 Define *regulation of an alternator*. (3)

5.2 Determine the number of stator conductors per slot for a three-phase 50 hertz alternator if the winding is star-connected and has to give a line voltage of 45 kV when the machine is on an open-circuit. The flux per pole is 0,25 wb. Assume full-pitch coils and the stator to have 3 slots per pole per phase. The speed is 1 000 r/pm and the distribution factor is 0,96. (6)

5.3 Two similar single- phase, alternators are connected in parallel. Each machine has a synchronous impedance of $0,6 + j 5,5 \Omega$ and generates an open circuit EMF of 1 900 V. The machines have a phase displacement of 30 electrical degrees relative to each other.

Calculate:

5.3.1 The circulating current. (4)

5.3.2 The terminal voltage. (2)

5.3.3 The power supplied from one machine to the other. Assume that there is no external load. (3)

[18]

TOTAL: 100

ELECTROTECHNICS N5

FORMULA SHEET

Armature ampere-turns/pole

$$= \frac{1}{2} \cdot \frac{I_a}{C} \cdot \frac{Z}{2P}$$

$$E = V \pm I_a R_a$$

$$E = \frac{2pNZ\Phi}{60c}$$

$$T = 0,318 \frac{I_a}{c} ZP\Phi$$

$$k = n \sqrt{\frac{R_1}{r_m}}$$

$$r_1 = R_1 \left[\frac{k-1}{k} \right]$$

$$r_1 = R_s \frac{1-y}{1-y^m}$$

$$R_1 = bR_1 (k-1) \times \frac{1-b^n}{1-b} + r_m$$

$$y = \frac{I_2}{I_1}$$

$$r_1 = bR_1 (k-1)$$

$$\frac{E_1}{E_2} = \frac{K\Phi_1 N_1}{K\Phi_2 N_2}$$

$$\frac{T_1}{T_2} = \frac{K\Phi_1 I_{a1}}{K\Phi_2 I_{a2}}$$

$$I_{ave1} = \frac{i_1 + i_2 + i_3 + \dots + i_n}{n}$$

$$I_{rms1wk} = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2 + \dots + i_n^2}{n}}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$f = \frac{1}{2\pi L} \sqrt{\frac{L}{C} - R^2}$$

$$P = \sqrt{3} I_L V_L \cos \phi$$

$$P_1 = V_L I_L \cos (30 - \phi)$$

$$P_2 = V_L I_L \cos (30 + \phi)$$

$$\tan \phi = \frac{\sqrt{3} (P_2 - P_1)}{(P_2 + P_1)}$$

% Voltage regulation

$$= I_1 \frac{(R_e \cos \phi \pm X_e \sin \phi)}{V_1} \times \frac{100}{1}$$

$$Z_e = \sqrt{R_e^2 + X_e^2}$$

$$\% Z_e = \frac{I Z_e}{V} \times \frac{100}{1}$$

$$S_1 = S \frac{Z_2}{Z_1 + Z_2}$$

$$E = 2,222 k_d k_p Z \Phi f$$

$$I_r = \frac{E_r}{Z_r}$$

$$E_o = V_p \frac{Z_r}{Z_s}$$

$$\cos \phi_r = \frac{R}{Z_r}$$

$$s = \frac{2\pi T(n_s - n_r)}{2\pi T n_s}$$

$$L = 0,05 + 0,2 \text{ Lin } \frac{d}{r}$$

$$C = \frac{1}{36 \text{ Lin } \frac{d-r}{r}}$$

$$C = \frac{1}{18 \text{ Lin } \frac{de}{r}}$$

% Regulation

$$= \frac{V_s - V_R}{V_R} \times \frac{100}{1} = \frac{V_s - V_R}{V_R} \times \frac{100}{1} = \frac{V_s - V_R}{V_R} \times \frac{100}{1}$$

Marking Guidelines



**higher education
& training**

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

AUGUST 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080074)

**22 July 2015 (Y-Paper)
13:00 – 16:00**

QUESTION 1

1.1 Increase the brush-contact resistance. ✓

Shift the brushes forward in the generator. ✓

Use commutating poles. (interpoles) ✓ (3)

1.2.1 $V = 475 \text{ V}$ $P = 40 \text{ kW}$. $N = 1\,000 \text{ rpm}$ $\eta = 90\% = 0.9$

$R_a = 0,24$ $I_f = 1,6 \text{ A}$ $V_b = 3 \text{ V}$

Input = $\frac{\text{Output}}{\eta} = \frac{40}{0,9} = 44,444 \text{ kW}$ ✓

$I_L = \frac{P}{V} = \frac{44444}{475}$ ✓
 $= 93,57 \text{ A}$ ✓ (3)

1.2.2 Output = $\frac{2 \pi N T}{60}$

$40\,000 = \frac{2 \pi 1\,000 T}{60}$ ✓

$T = \frac{40\,000 \times 60}{2 \pi 1\,000}$ ✓

$= 381,97 \text{ Nm}$ ✓ (3)

1.2.3 Starting current = 1,3 (full. Load) = $1,3 \times 93,57 = 121,64 \text{ A}$ ✓

$I_a = I - I_f = 121,64 - 1,6 = 120,04 \text{ A}$ ✓

$V = E + V_b + V_a$ (at start) $E = 0$ $V_a = I_a (R_a + x)$

$475 = 0 + 3 + 120,04 (0,24 + x)$ ✓

$x = \frac{475 - 31,81}{120,04}$ ✓

$= 3,69 \Omega$ ✓ (5)

1.3 1.3.1 $I_a = 180 \text{ A}$ $V = 550$ $R_a = 0,4 \text{ ohms}$
 Lap-connected - $c = 6$ $Z = 1\,800$ Flux/pole = $0,05 \text{ Wb}$

$$\begin{aligned} E &= V - (I_a \times R_a) \\ &= 550 - (180 \times 0,4) \\ &= 550 - 72 \\ &= 478 \text{ V} \checkmark \end{aligned}$$

$$\frac{2 \pi NT}{60} = E I_a = \frac{2 Z}{c} \times \frac{N_p}{60} \times \phi \times I_a$$

$$478 = 2 \times \frac{1\,800}{6} \times \frac{N \times 3}{60} \times 0,05$$

$$478 = 1,5 N$$

$$N = 318,67 \text{ r/min (5,31 rps)} \checkmark \quad (3)$$

1.3.2 $P = E I_a$
 $= 478 \times 180$
 $= 86\,040 \text{ W} \checkmark$

$$\frac{2 \pi NT}{60} = 86\,040$$

$$\begin{aligned} T &= \frac{60 \times 86\,040}{2 \pi \times 318,67} \checkmark \\ &= 2\,578,28 \text{ N.m.} \checkmark \end{aligned}$$

(3)
 [20]

QUESTION 2

2.1 The effective value of an alternating current is that value of alternating current, which produces the same amount of heat energy ✓, at the same rate as a direct-current ✓ would, if passed through an identical resistance ✓ (3)

2.2 2.2.1

$$i_1 = \frac{0 + 6,5}{2} = 3,25 \text{ A} \checkmark$$

$$i_2 = \frac{6,5 + 18,5}{2} = 12,5 \text{ A} \checkmark$$

$$i_3 = \frac{18,5 + 25}{2} = 21,75 \text{ A} \checkmark$$

$$i_4 = \frac{25 + 23}{2} = 24 \text{ A} \checkmark$$

$$i_5 = \frac{23 + 18,5}{2} = 20,75 \text{ A} \checkmark$$

$$i_6 = \frac{18,5 + 0}{2} = 9,25 \text{ A} \checkmark \quad (6 \times 0,5)$$

(3)

$$I_{\text{ave}} = \frac{i_1 + i_2 + i_3 + i_4 + i_5 + i_6}{n}$$

$$= \frac{3,25 + 12,5 + 21,75 + 24 + 20,75 + 9,25}{6 \checkmark}$$

$$= \frac{91,5}{6}$$

$$= 15,25 \checkmark$$

(2)
[5]

2.2.2

$$I_{\text{rms}} = \sqrt{\frac{(i_1)^2 + (i_2)^2 + (i_3)^2 + (i_4)^2 + (i_5)^2 + (i_6)^2}{n}}$$

$$= \sqrt{\frac{(3,25)^2 + (12,5)^2 + (21,75)^2 + (24)^2 + (20,75)^2 + (9,25)^2}{6 \checkmark}}$$

$$= \frac{\sqrt{1732}}{6 \checkmark}$$

$$= 16,99 \text{ A} \checkmark$$

(3)

$$\begin{aligned}
 2.3 \quad Z1 &= 4 - j6 &= 7,21 < -56,3 \Omega \\
 Z2 &= 5 + j10 &= 11,18 < 63,43 \Omega \\
 Z3 &= 3 + j7 &= 7,6 < 66,8 \Omega \\
 Z4 &= 4 + j8 &= 8,94 < 63,43 \Omega \\
 Z1 + Z2 &= 9 + j4 &= 9,84 < 23,96
 \end{aligned}$$

$$\begin{aligned}
 ZP &= \frac{Z1 \times Z2}{Z1 + Z2} \\
 &= \frac{7,21 < -56,3 \times 11,18 < 63,43}{9,84 < 23,96} \\
 &= 8,19 < -16,83 \text{ ohm } \checkmark
 \end{aligned}$$

$$\begin{aligned}
 VP1 &= I1 Z1 \\
 &= 12 < 0 \times 7,21 < -56,3 \\
 &= 86,52 < -56,3 \text{ V } \checkmark \quad (48 - 71,98)
 \end{aligned}$$

$$\begin{aligned}
 I2 &= \frac{VP}{Z2} &= \frac{86,52 < -56,3}{11,18 < 63,43} \checkmark \\
 &= 7,74 < -119,73 \checkmark \quad (-3,84 - j6,72)
 \end{aligned}$$

$$\begin{aligned}
 I3 &= I1 + I2 &= (12 + j0) + (-3,84 - j6,72) \\
 &= 8,16 - j6,72 \\
 &= 10,57 < -39,47 \checkmark
 \end{aligned}$$

$$\begin{aligned}
 V3 &= I3 \times Z3 &= 10,57 < -39,47 \times 7,6 < 66,8 \\
 &= 80,33 < 27,33 \text{ V } \checkmark \quad (71,36 + j36,88)
 \end{aligned}$$

$$\begin{aligned}
 VT &= VP + V3 &= (48 - 71,98) + (71,36 + j36,88) \checkmark \\
 &= 119,36 - j35,1 \\
 &= 124,41 < -16,39 \checkmark
 \end{aligned}$$

$$I4 = \frac{VT}{Z4} = \frac{124,41 < -16,39}{8,94 < 63,43} = 13,92 < -79,82 \checkmark$$

$$\begin{aligned}
 IT &= I1 + I2 + I4 &= 12 < 0 + 7,74 < -119,73 + 13,92 < -79,82 \\
 &= 12 + j0 + (-3,84 - j6,72) + 2,46 - j13,7 \checkmark \\
 &= 10,62 - j20,42 \\
 &= 23,02 < -62,52 \text{ A } \checkmark
 \end{aligned}$$

(11)
[22]

QUESTION 3

- 3.1 Constant losses (core losses) ✓
 Variable losses (copper losses) ✓
 Eddy current losses ✓ (3)

- 3.2 When an alternating voltage is applied to the primary winding, ✓ an alternating flux is set up in the core, which links with the secondary winding ✓ and induces an EMF of the same frequency in the secondary winding. ✓ (3)

- 3.3 Single-phase transformer 30kV/10kV
 Two transformers: 950 kVA 1 400 kVA
 ST = 2 000 kVA

$$\cos \Phi = 0,8$$

$$\Phi = 36,87 \text{ lagging} \quad ST = 2000 < -36,87$$

$$Z_1 = \frac{1\,400}{950} (1,8 + j5) = 2,65 + j7,37 = 7,82 < 70,2 \quad \checkmark$$

$$Z_2 = 4 + j8 = 8,94 < 63,43 \quad \checkmark$$

$$Z_1 + Z_2 = 6,65 + j15,37 = 16,75 < 66,6 \quad \checkmark$$

$$S_1 = ST \times \frac{Z_2}{Z_1 + Z_2} = \frac{2\,000 < -36,87 \times 8,94 < 63,43}{16,75 < 66,6} \quad \checkmark$$

$$= 1\,067,46 < -40,04 \quad \checkmark$$

$$\cos \Phi = 0,77 \text{ lagging} \quad \checkmark$$

$$S_2 = ST \times \frac{Z_1}{Z_1 + Z_2} = \frac{2\,000 < -36,87 \times 7,82 < 70,2}{16,75 < 66,6} \quad \checkmark$$

$$= 933,73 < -33,27 \quad \checkmark$$

$$\cos \Phi = 0,84 \text{ lagging} \quad \checkmark \quad (9)$$

- 3.4.1 Three phase motor (star)

$$V_L = 475 \quad \text{Output } P = 75 \text{ kW} \quad \text{efficiency} = 85\% = 0,85 \quad \cos \Phi = 0,9$$

$$\text{Input } P = 75 / 0,85 = 88,235 \text{ kW} \quad \checkmark$$

$$P = \sqrt{3} I_L V_L \cos \Phi$$

$$88235 = \sqrt{3} I_L (475) (0,9) \quad \checkmark$$

$$I_L = 119,16 \text{ A} \quad \checkmark \quad (3)$$

3.4.2 For delta connected motor winding :

$$\begin{aligned} I_L &= \sqrt{3} I_p \\ &= \sqrt{3} \times 119,16 \\ &= 206,39 \text{ A } \checkmark \end{aligned}$$

$$\begin{aligned} P &= \sqrt{3} I_L V_L \cos \Phi \\ 88235 &= \sqrt{3} (206,39) (V_L) (0,9) \end{aligned}$$

$$V_L = 274,25 \text{ V } \checkmark$$

(2)
[20]

QUESTION 4

- 4.1 Induction motors start up from rest without needing any starting motor. \checkmark
 They are robust. \checkmark
 Their friction losses are low. \checkmark
 Their efficiency is good \checkmark
 Their cost is low \checkmark

(5)

4.2 4.2.1 $P = I V \cos \Phi$

$$2\,350\,000 = I \times 28\,000 \times 0,8$$

$$I = 104,91 \text{ A } \checkmark$$

$$\text{Volt drop} = IR + jIX$$

$$= 104,91 (15 + j 20)$$

$$= 1573,65 + j 2098,2 \checkmark$$

$$V_s = V_r (\cos \Phi + j \sin \Phi) + V_{\text{drop}}$$

$$= 28\,000 (0,8 + j 0,6) + 1\,573,65 + j 2\,098,2$$

$$= 22\,400 + j 16\,800 + 1\,573,65 + j 2\,098,2 \checkmark$$

$$= 23\,973,65 + j 18\,898,2 \checkmark$$

$$= 30\,526,67 \angle 38,25^\circ \checkmark$$

(5)

4.2.2 $\text{Reg.} = \frac{V_s - V_r}{V_r}$

$$= \frac{30\,526,67 - 28\,000}{28\,000} \checkmark = 0,09 \text{ pu } \checkmark$$

(2)

$$\begin{aligned}
 4.2.3 \quad \text{Losses} &= I^2 R = (104,91)^2 \times 15 = 165,092 \text{ kW} \checkmark \\
 \eta &= \frac{\text{Output}}{\text{Output} + \text{Losses}} \\
 &= \frac{2350}{2350 + 165,092} \checkmark \\
 &= 0,934 \text{ (93,4\%)} \checkmark \quad (3)
 \end{aligned}$$

$$4.3 \quad P = 55 \text{ kW} \quad \text{eff.} = 80\% = 0,8 \quad \cos \Phi = 0,75 \quad \Phi = 41,41$$

$$\text{Input } P = \frac{55\,000}{0,8} = 68,750 \text{ kW} \checkmark$$

$$P_1 + P_2 = 68\,750 \text{ watts} \quad \dots\dots\dots \text{eqn 1}$$

$$\tan \Phi = \tan 41,41 = 0,883$$

$$\tan \Phi = \frac{\sqrt{3}(P_2 - P_1)}{P_2 + P_1}$$

$$0,883 = \frac{\sqrt{3}(P_2 - P_1)}{68\,750} \checkmark$$

$$P_2 - P_1 = 35\,048,77 \checkmark$$

$$P_1 + P_2 = 68\,750 \text{ watts} \quad \dots\dots\dots \text{eqn 1}$$

$$P_2 - P_1 = 35\,048,77 \dots\dots\dots \text{eqn 2}$$

$$(1 + 2): \quad 2P_2 = 103\,798,77$$

$$P_2 = 51\,899,385 \checkmark$$

Substitute P_2 IN eqn. 1

$$P_1 + 51\,899,385 = 68\,750$$

$$P_1 = 16\,850,62 \text{ W} \checkmark$$

(5)
[20]

QUESTION 5

5.1 Regulation can be defined as the change in terminal voltage ✓ between no-load and full-load conditions ✓ while the speed and field current remain constant. ✓ (3)

$$5.2 \quad E_o = \frac{45\,000}{\sqrt{3}} = 25\,980,76 \text{ V (phase value)} \checkmark$$

$$E_o = 2,22 \text{ kd. kp. } \Phi f Z / \text{ph}$$

$$25980,76 = 2,22 (0,96) (1) (0,25) (50) Z / \text{ph}$$

$$Z_{\text{ph}} = 975,25 \text{ V } \checkmark$$

$$\begin{aligned} ZT &= 975,25 \times 3 = 2\,925,75 \text{ (for 3 phases)} \checkmark \\ f &= \frac{n p}{60} \end{aligned}$$

$$50 = \frac{1\,000 \times p}{60}$$

$$p = 3 \text{ (pole pairs)} \checkmark$$

$$\begin{aligned} \text{poles} &= 6 \\ 3 &= \text{slots/pole/phase} \end{aligned}$$

$$3 = \frac{\text{slots}}{6 \times 3}$$

$$\text{slots} = 18 \times 3 = 54 \checkmark$$

$$\begin{aligned} Z / \text{slot} &= \frac{ZT}{\text{slots}} = \frac{2\,925,75}{54} = 54,18 \\ &= 54,18 \text{ conductors } \checkmark \end{aligned} \quad (6)$$

Past Examination Papers



**higher education
& training**

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

APRIL 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080085)

7 April 2015 (Y-Paper)

13:00 – 16:00

Calculators may be used.

This question paper consists of 5 pages and a formula sheet of 2 pages.

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N5
TIME: 3 HOURS
MARKS: 100**

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
 2. Read ALL the questions carefully
 3. Number the answers according to the numbering system used in this question paper.
 4. Write neatly and legibly.
-

QUESTION 1:

- 1.1 Briefly explain why the terminal voltage of a DC shunt excited generator drops, as the current supplied by the machine is increased. (2)
- 1.2 What is the function of the commutating poles and compensating windings in a DC machine? (2)
- 1.3 An eight pole DC motor has a wave connected armature with 800 conductors. The brushes are displaced through five angular degrees from the geometrical axis. The armature current is 270 A.

Calculate the following:

- 1.3.1 The demagnetising and cross-magnetising ampere turns per pole. (4)
- 1.3.2 The additional field current required neutralising this demagnetization if the field winding has 1600 turns/pole. (2)
- 1.4 A 535 V shunt motor draws an armature current of 40 A while running at 550 r/min. The armature circuit has a resistance of 5Ω . If the magnetic flux is decreased by 30 % and the torque developed by, the armature increases by 40%.

Calculate the following :

- 1.4.1 The armature current: (3)
- 1.4.2 The speed (7)

[20]

QUESTION 2:

- 2.1 Two circuits are connected in parallel to a 300 V, 50 Hz supply. The total current taken by the combination is 25 A, at unity power factor. Circuit A consists of a $8,8 \Omega$ resistor and a $200 \mu f$ capacitor connected in series. Circuit B consists of a resistor and an inductive reactance in series.

Calculate for circuit B :

- 2.1.1 The current (4)
- 2.1.2 The power factor (2)
- 2.1.3 The impedance (2)
- 2.1.4 The reactance (1)

- 2.1.5 The resistance (1)
- 2.2 A constant voltage at a frequency of 2,5 MHz is applied across a circuit consisting of an inductor in series with a variable capacitor. When the capacitor is set to 370 pf, the current is at its maximum value. When the capacitance is reduced to 340 pf, the current is 0,707 of its maximum value. (10)
- Find the inductance and the resistance of the inductor. [20]

QUESTION 3:

- 3.1 A three phase delta connected load, each phase of which has an inductive reactance of 75Ω and a resistance of 50Ω , is supplied from the secondary of a three phase star connected transformer, which has a phase voltage of 260 V.
- Calculate the following:
- 3.1.1 The potential difference across each phase of the load. (2)
- 3.1.2 The current in each phase of the load. (2)
- 3.1.3 The current in the transformer secondary windings. (1)
- 3.1.4 Total power drawn from the supply and its power factor (3)
- 3.2 A 15 kVA, 3500/700 volt single-phase transformer, operating at no-load, has resistances and leakage reactance as follows: (4)
- Primary winding: Resistance $7,5 \Omega$, reactance 15Ω
 Secondary' winding: Resistance $0,5 \Omega$, reactance $0,65 \Omega$
- Determine the approximate value of the secondary voltage at full-load, with a power factor of 0,8 (lagging), when the primary supply voltage is 3 500 V.
- 3.3 A three-phase, 500 V, star-connected motor has an output of 100 kW, with an efficiency of 80 % and a power factor of 0,8.
- Calculate the following:
- 3.2.1 The line current (2)
- 3.2.2 If the motor windings were connected in delta, what would be the correct voltage suitable for a three-phase motor? (2)
- 3.4 If the phase voltage of a three phase star connected alternator is 360 V, what would the line voltages be when:

3.4.1 The phase is correctly connected. (2)

3.4.2 The connection to the yellow phase is reversed. (2)

[20]

QUESTION 4:

4.1 Calculate the inductance and capacitance per phase of a 35 km , three phase overhead line having solid copper conductors of diameter 0,6 cm that are spaced on the corners of a triangle having sides of length 125 cm, 165 cm and 235 cm. (6)

4.2 An overhead, single phase transmission line delivers 2 200 kW at 31 kV. The power factor is 0,85 lagging. The total resistance of the line is 22 Ω and the total inductive reactance is 30 Ω . (4)

Calculate the following:

4.2.1 The sending line voltage (4)

4.2.2 The per unit regulation (2)

4.2.3 The transmission efficiency (2)

4.3 Each branch of a three-phase star connected load consists of a coil of resistance 5 Ω and reactance 6 Ω . The load is supplied at a line voltage of 400V, 50 Hz. The power supplied to the load measured by the two wattmeter method. (6)

Calculate their separate readings.

[20]

QUESTION 5:

5.1 A three-phase star-connected alternator supplies a 650 kW, 3,8 kV delta connected induction motor, with an efficiency of 85 % and a full-load power factor of 0,8. (7)

Calculate the KVA output of the alternator and the value of the current in the alternator and motor windings.

5.2 A three-phase, 50 Hz induction motor has 4 poles and runs at a speed of 1 000 r/min when the total torque developed by the rotor is 170 Nm.

Calculate the following:

5.2.1 The total input power to the rotor (4)

5.2.2 The rotor copper loss in watts (3)

- 5.5 Determine the number of stator conductors per slot for a three-phase, 50 Hz, alternator, if the winding is star-connected and has to supply a line voltage of 20 kV, when the machine is on an open circuit. The flux per pole is 0,4 wb. Assume full-pitch coils and the stator to have three slots per pole per phase. The speed is 375 r/ min and the distribution factor is 0,96. (6)

[20]

TOTAL: 100

ELECTROTECHNICS N5

FORMULA SHEET

Armature ampere-turns/pole

$$= \frac{1}{2} \cdot \frac{I_a}{C} \cdot \frac{Z}{2P}$$

$$E = V \pm I_a R_a$$

$$E = \frac{2pNZ\Phi}{60c}$$

$$T = 0,318 \frac{I_a}{c} ZP\Phi$$

$$k = n \sqrt{\frac{R_1}{r_m}}$$

$$r_1 = R_1 \left[\frac{k-1}{k} \right]$$

$$r_1 = R_s \frac{1-y}{1-y^m}$$

$$R_1 = bR_1 (k-1) \times \frac{1-b^n}{1-b} + r_m$$

$$y = \frac{I_2}{I_1}$$

$$r_1 = bR_1 (k-1)$$

$$\frac{E_1}{E_2} = \frac{K\Phi_1 N_1}{K\Phi_2 N_2}$$

$$\frac{T_1}{T_2} = \frac{K\Phi_1 I_{a1}}{K\Phi_2 I_{a2}}$$

$$I_{ave1} = \frac{i_1 + i_2 + i_3 + \dots + i_n}{n}$$

$$I_{rms1wk} = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2 + \dots + i_n^2}{n}}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$f = \frac{1}{2\pi L} \sqrt{\frac{L}{C} - R^2}$$

$$P = \sqrt{3} I_L V_L \cos \phi$$

$$P_1 = V_L I_L \cos (30 - \phi)$$

$$P_2 = V_L I_L \cos (30 + \phi)$$

$$\tan \phi = \frac{\sqrt{3} (P_2 - P_1)}{(P_2 + P_1)}$$

% Voltage regulation

$$= I_1 \frac{(R_e \cos \phi \pm X_e \sin \phi)}{v_1} \times \frac{100}{1}$$

$$Z_e = \sqrt{R_e^2 + X_e^2}$$

$$\% Z_e = \frac{I Z_e}{V} \times \frac{100}{1}$$

$$S_1 = S \frac{Z_2}{Z_1 + Z_2}$$

$$E = 2,222 k_d k_p Z \Phi f$$

$$I_r = \frac{E_r}{Z_r}$$

$$E_o = V_p \frac{Z_r}{Z_s}$$

$$\cos \phi_r = \frac{R}{Z_r}$$

$$s = \frac{2\pi T(n_s - n_r)}{2\pi T n_s}$$

$$L = 0,05 + 0,2 \text{ Lin } \frac{d}{r}$$

$$C = \frac{1}{36 \text{ Lin } \frac{d-r}{r}}$$

$$C = \frac{1}{18 \text{ Lin } \frac{de}{r}}$$

% Regulation

$$= \frac{V_s - V_R}{V_R} \times \frac{100}{1} = \frac{V_s - V_R}{V_R} \times \frac{100}{1} = \frac{V_s - V_R}{V_R} \times \frac{100}{1}$$

Marking Guidelines



higher education
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Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

APRIL 2015

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080074)

7 April 2015 (Y-Paper)
13:00 – 16:00

QUESTION 1

- 1.1 Due to the resistance loss in the armature circuit, ✓ the shunt current also decreases causing a further terminal voltage drop. ✓ (2)
- 1.2 Commutating poles improve commutation. ✓ (1)
- Compensating windings minimize armature reaction. ✓ (1)
- 1.3 1.3.1 $p = 4$ $c = 2$ $Z = 800$ mech deg. = 5° and Elect deg = $p \times 5 = 20^\circ$ $I_a = 270$ A Field winding = 1600 t/p
- Demag At/p = $0.5 \times I_a / c \times Z / 2p \times (4\theta / 360)$
 $= 0.5 \times 270 / 2 \times 800 / 8 \times (4 \times 20 / 360)$ ✓ = 1500 At/p ✓
- Cross-mag At / p = $0.5 \times 270 / 2 \times 800 / 8 \times [1 - (4 \times 20 / 360)]$ ✓
 $= 5250$ At ✓ (2)
- 1.3.2 MMF = $N I$ ✓
 $I = 1500 / 1600$
 $= 0.94$ A ✓ (2)
- 1.4 1.4.1 $V = 535$ V $I_a = 40$ A $N_1 = 550$ rpm $R_a = 0.5 \Omega$ $\phi_1 = 100\%$ (1)
 $\phi_2 = 70\%$ (0,7) $T_1 = 100\%$ (1) $T_2 = 140\%$ (1,4) (2)
- $T \propto I_a \phi$
 $T_1 / T_2 = I_{a1} \phi_1 / I_{a2} \phi_2$ ✓
 $I_{a2} = T_2 I_{a1} \phi_1 / T_1 \phi_2$
 $= 1.4 \times 40 \times 1 / 1 \times 0.7$ ✓
 $= 80$ A ✓ (3)
- 1.4.2 $E_1 = V - I_a R_a$
 $= 535 - (40 \times 0.5)$ ✓
 $= 515$ V ✓
- $E_2 = V - I_{a2} R_a$
 $= 535 - (80 \times 0.5)$ ✓
 $= 495$ V ✓
- $E_1 / E_2 = N_1 \phi_1 / N_2 \phi_2$
 $N_2 = E_2 N_1 \phi_1 / E_1 \phi_2$ ✓
 $= 495 \times 550 \times 1 / 515 \times 0.7$ ✓
 $= 755.2$ r/pm ✓ (7)
- [20]

QUESTION 2

$$\begin{aligned}
 2.1.1 \quad Z_A &= R - jX_C \\
 &= 8,8 - j(1/2\pi fc) \\
 &= 8,8 - j(1/2\pi 50 \times 200 \times 10^{-6}) \\
 &= 8,8 - j15,92 \\
 &= 18,19 \angle -61,07^\circ \quad \checkmark \\
 \\
 \quad \quad \quad I_A &= V / Z_A \\
 &= 300 \angle 0^\circ / 18,19 \angle -61,07^\circ \\
 &= 16,49 \angle 61,07^\circ \text{ A} \quad \checkmark \\
 \\
 \quad \quad \quad I_B &= I_T - I_A \\
 &= 25 \angle j0^\circ - 16,49 \angle 61,07^\circ \\
 &= 25 + j0 - (7,98 + j14,43) \quad \checkmark \\
 &= 17,02 - j14,43 \\
 &= 22,31 \angle -40,29^\circ \text{ A} \quad \checkmark \quad (4) \\
 \\
 2.1.2 \quad \cos \phi &= \cos 40,29^\circ \quad \checkmark \\
 &= 0,76 \text{ Lagging} \quad \checkmark \quad (2) \\
 \\
 2.1.3 \quad Z_B &= V_B / I_B \\
 &= 300 \angle 0^\circ / 22,31 \angle -40,29^\circ \quad \checkmark \\
 Z_B &= 13,45 \angle 40,29^\circ = (10,26 + j8,7) \quad (2) \\
 \\
 2.1.4 \quad X_L &= 8,7 \Omega \quad \checkmark \quad (\text{from } Z_B = 10,26 + j8,7) \quad (1) \\
 \\
 2.1.5 \quad R &= 10,26 \Omega \quad \checkmark \quad (\text{from } Z_B = 10,26 + j8,7) \quad (1)
 \end{aligned}$$

$$\begin{aligned}
 2.2 \quad C_1 &= 370 \times 10^{-12} \text{ for } (I_{\max}) \\
 C_2 &= 340 \times 10^{-12} \text{ for } I_2 = 0,707 I_m \\
 \\
 X_{C1} &= 1 / 2\pi fc \\
 &= 10^{12} / 2\pi \times 2,5 \times 10^6 \times 370 = 172,06 \Omega \quad \checkmark \\
 \\
 X_{L1} &= X_{C1} = 172,06 \quad \text{resonance} \quad \checkmark \\
 \\
 X_{L1} &= 2\pi fL \\
 L &= X_L / 2\pi f = 172,06 / 2\pi \times 10^6 \times 2,5 = 10,95 \mu\text{H} \quad \checkmark \\
 \\
 X_{C2} &= 1 / 2\pi fC_2 = 10^{12} / 2\pi \times 10^6 \times 340 \times 2,5 = 187,24 \Omega \quad \checkmark \\
 \\
 \text{Increase in } X_C &= 187,24 - 172,06 = 15,18 \Omega \quad \checkmark \\
 \\
 I_1 &= V / Z_1 \quad Z_1 = R \text{ (resonance)} \quad \checkmark
 \end{aligned}$$

$$I_2 = 0,707 I_1 \quad = 0,707 V / Z_1 \quad = V / Z_2$$

$$Z_2 = \sqrt{R^2 + (15,18)^2} \quad \checkmark$$

$$0,707 V / Z_1 = V / Z_2$$

$$0,707 V / R = V / \sqrt{R^2 + (15,18)^2} \quad \checkmark$$

$$(0,707 V)^2 / R^2 = V^2 / R^2 + (15,18)^2$$

$$[R^2 + (15,18)^2] / R^2 = V^2 / (0,707V)^2$$

$$[R^2 + (15,18)^2] / R^2 = 1 / 0,707^2$$

$$R^2 + (15,18)^2 = R^2 / 0,707^2 \quad \checkmark$$

$$0,707^2 R^2 + (0,707^2)(15,18^2) = R^2$$

$$R^2 - 0,707^2 R^2 = (0,707^2)(15,18^2)$$

$$R^2 (1 - 0,707^2) = (0,707^2)(15,18^2)$$

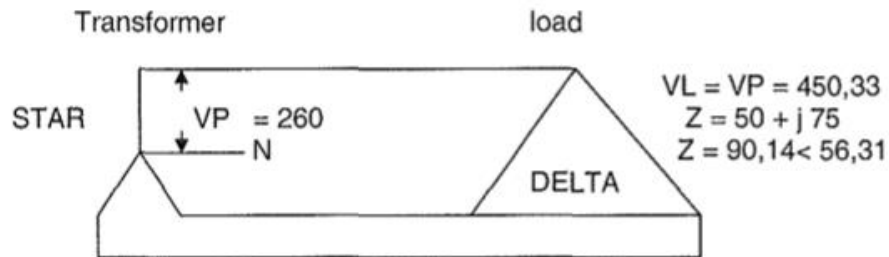
$$R^2 = (0,707^2)(15,18^2) / (1 - 0,707^2)$$

$$R = 15,18 \Omega \quad \checkmark$$

(10)
[20]

QUESTION 3

3.1



3.1.1

$$V_L = \sqrt{3} V_P = \sqrt{3} \times 260 = 450,33 \text{ V} \quad \checkmark \quad (2)$$

$$= V_P = 450,33 \quad \checkmark$$

3.1.2

$$I_P(\text{load}) = V_P / Z_P$$

$$= 450,33 \angle 0 / 90,14 \angle -56,31 \quad \checkmark$$

$$= 5 \angle -56,31 \quad \checkmark \quad (2)$$

3.1.3

$$I_L = \sqrt{3} \times 5 = 8,66 \text{ A} \quad \checkmark \quad (1)$$

3.1.4

$$P = \sqrt{3} I_L V_L \cos \phi$$

$$= \sqrt{3} \times 8,66 \times 450,33 \times 0,55 \quad \checkmark$$

$$= 3,72 \text{ kW} \quad \checkmark \quad (2)$$

$$\cos \phi = \cos 56,31$$

$$\text{pf} = 0,55 \quad \checkmark \quad (1)$$

3.2 Single ph Trf. 15 kVA

$$V_1 / V_2 = 3500 / 700 = N_1 / N_2$$

$$R_1 = 7,5 \Omega \quad R_2 = 0,5 \Omega \quad X_1 = 15 \Omega \quad X_2 = 0,65 \Omega \quad V_1 = 3500 \text{ V} \quad \cos \phi = 0,8$$

$$I_1 = VA / V_1$$

$$= 15000 / 3500$$

$$= 4,29 \text{ A}$$

$$R_e = R_1 + R_2 (N_1 / N_2)^2$$

$$= 7,5 + 0,5(5)^2$$

$$= 20 \Omega \quad \checkmark$$

$$X_e = X_1 + X_2 (N_1 / N_2)^2$$

$$= 15 + 0,65(5)^2$$

$$= 31,25 \Omega$$

$$Z_e = \sqrt{(R_e)^2 + (X_e)^2}$$

$$= \sqrt{(20)^2 + (31,25)^2}$$

$$= 37,1 \quad \text{OR} \quad 20 + j 31,25 = 37,1 \angle 57,38 \quad \checkmark$$

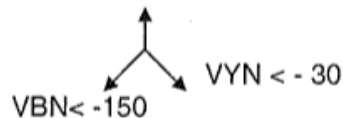
$$\begin{aligned} \text{REG.} &= I_1 (R_e \cos \phi + X_e \sin \phi) / V_1 \\ &= 4,29 [(20)(0,8) + (31,25)(0,6)] / 3500 \\ &= 4,29 [16 + 18,75] / 3500 \\ &= 0,043 \text{ per unit } \checkmark \end{aligned}$$

$$\begin{aligned} \text{FULL } V_2 &= \text{NO LOAD } V_2 - \text{CHANGE} \\ &= (700) - (N/L \ V_2 \times \text{reg}) \\ &= 700 - (700 \times 0,043) \\ &= 700 - 30,1 \\ &= 669,9 \text{ V } \checkmark \end{aligned} \quad (4)$$

3.3 3.3.1 3 PH. Star con motor $V_L = 500\text{V}$ $P_{\text{out}} = 100 \text{ kW}$ $\eta = 0,8$
 $\text{COS } \phi = 0,8$
 $P_{\text{in}} = 100 / 0,8$
 $= 125 \text{ kW}$
 $P = \sqrt{3} I_L V_L \text{COS } \phi$
 $125\ 000 = \sqrt{3} I_L (500) (0,8) \checkmark$
 $I_L = 180,42 \text{ A } \checkmark$

FOR DELTA CON. MOTOR WINDING :
 $I_L = \sqrt{3} I_P = \sqrt{3} 180,42 = 312,5 \checkmark$
 $P = \sqrt{3} I_L V_L \text{COS } \phi$
 $125000 = \sqrt{3} \times 312,5 \times V \times 0,8$
 $V_L = 288,68 \text{ V } \checkmark$

$$V_{RN} < 90$$



$$V_p = 380$$

3.4 3.4.1 Correctly connected

$$\begin{aligned} V_{RY} &= V_{RN} + V_{NY} && \text{OR} \\ &= 380 \angle 90 + 380 \angle 150 && 380 \times \sqrt{3} = 658,18,54 \\ &= (0 + j 380) + (-329 + j 190) \checkmark \\ &= -329 + j 570 \\ &= 658,13 \angle 120 \\ V_{RY} &= V_{BR} = V_{YB} = 658,13 \checkmark \end{aligned}$$

With one phase reversed

$$\begin{aligned} VRY &= 380 \angle 0^\circ + 380 \angle -120^\circ \\ &= (380 - j0) + (-190 - j329,09) \quad \checkmark \\ &= 190 - j329,09 \\ &= 380 \angle -60^\circ \quad \checkmark \end{aligned}$$

(8)
[20]

QUESTION 4

4.1 $d_1 = 125 \times 10^{-2}$ $d_2 = 165 \times 10^{-2}$ $d_3 = 235 \times 10^{-2}$ $\text{dia} = 0,6 \text{ cm}$ $r = 0,3 \times 10^{-2} \text{ m}$

$$\begin{aligned} d_e &= \sqrt[3]{1,25 \times 1,65 \times 2,35} \quad \checkmark \\ &= 1,69 \text{ m} \quad \checkmark \end{aligned}$$

$$L = \text{km} [0,05 + 0,2 \log_e (d_e/r)] \text{ mH}$$

$$= 35 [0,05 + 0,2 \log_e (1,69 / 0,003)] \text{ mH} \quad \checkmark$$

$$= 46,09 \text{ mH} \quad \checkmark$$

$$\begin{aligned} C &= 35 [1 / 18 \log_e (1,69 / 0,003)] \quad \checkmark \\ &= 0,307 \mu\text{f} \quad \checkmark \end{aligned}$$

(6)

4.2 4.2.1 $R = 22 \text{ ohms}$ $X = 30 \text{ ohms}$
 $P = 2200 \text{ kW}$ $V_r = 31 \text{ kV}$ $\text{Cos } \phi = 0,85 = 31,79$

$$\begin{aligned} I &= P / V \text{ Cos } \phi \\ &= 2200000 / 31000 \times 0,85 \\ &= 83,49 \text{ A} \quad \checkmark \end{aligned}$$

$$V_s = V \angle \phi + IR + IX \angle 90^\circ$$

$$= 31000 \angle 31,87^\circ + 83,49 \times 22 + 83,49 \times j30$$

$$30 \angle 90^\circ \quad \checkmark$$

$$2504,7$$

$$= 26326,7 + j16367,8 + 1836,78 + j$$

$$= 28163,48 + j18872,5 \quad \checkmark$$

$$= 33902,1 \angle 33,83^\circ \text{ kV} \quad \checkmark \quad (4)$$

4.2.2 $\text{Reg} = V_s - V_r / V_r$
 $= 33902 - 31000 / 31000 \quad \checkmark$
 $= 0,094 \quad \checkmark \quad (2)$

$$\begin{aligned}\eta &= P_o / P_o + \text{Losses} \\ \eta &= 2200 / \frac{2200 + 83,49^2 \times 22}{1000} \checkmark \\ &= 93,4 \% \quad \checkmark\end{aligned}\quad (2)$$

$$\begin{aligned}4.3 \quad Z &= 5 + j6 = 7,81 \angle 50,19 \quad V_L = 400V \quad \phi = 50,19 \text{ lag} \\ V_p &= 400 / \sqrt{3} \\ &= 242,49 V \quad \checkmark \\ I_P &= V_P / Z_P \\ &= 230,9 \angle 0 / 7,81 \angle 50,19 \\ &= 29,56 \angle -50,19 \quad \checkmark\end{aligned}$$

$$I_L = I_P = 29,56 \angle -50,19 \quad \checkmark$$

$$\begin{aligned}P_2 + P_1 &= \sqrt{3} V_L I_L \cos \phi \\ &= \sqrt{3} \times 400 \times 29,56 \cos 50,19 \\ &= 13,112 \text{ kW} \quad \dots\dots\dots (1)\end{aligned}$$

$$\begin{aligned}\tan \phi &= \sqrt{3} (P_2 - P_1) / P_2 + P_1 \\ P_2 - P_1 &= \tan 50,19 \times 13,112 / \sqrt{3} \quad \checkmark \\ &= 9,08 \text{ kW} \quad \dots\dots\dots (2)\end{aligned}$$

$$2 P_1 = 4,03 \quad \dots\dots\dots (1 - 2)$$

$$P_1 = 2,02 \text{ kW} \quad \checkmark$$

$$\begin{aligned}P_2 &= 13,112 - 2,02 \\ &= 11,092 \text{ kW} \quad \checkmark\end{aligned}$$

(6)
[20]**QUESTION 5**

$$5.1 \quad P_o = 650 \text{ kW} \quad V = 3800 V \quad \eta = 85 \% (0,85) \quad \cos \phi = 0,8$$

$$\begin{aligned}P_{in} &= P_{out} / \eta \\ &= 650000 / 0,85 \quad \checkmark \\ &= 764705,88 \text{ W} \quad \checkmark\end{aligned}$$

$$\begin{aligned}I_L &= P_{in} / \sqrt{3} V_L \cos \phi \\ &= 764705,88 / \sqrt{3} \times 3800 \times 0,8 \quad \checkmark \\ &= 145,23 \text{ A}\end{aligned}$$

$$I(\text{alt}) = 145,23 \text{ A} \quad \checkmark$$

$$\begin{aligned}I(\text{motor}) &= I_L / \sqrt{3} \\ &= 145,23 / \sqrt{3} \\ &= 83,85 \text{ A} \quad \checkmark\end{aligned}$$

$$\begin{aligned}S &= \sqrt{3} V_L I_L \\ &= \sqrt{3} \times 3800 \times 145,23 \quad \checkmark \\ &= 955873,81 \text{ VA} \\ &= 955,87 \text{ KVA} \quad \checkmark\end{aligned}\quad (7)$$

5.2 5.2.1 $f = 50 \text{ Hz}$ $p = 4/2 = 2$ $N_r = 1000 \text{ rpm}$ $T = 170 \text{ Nm}$

$$\begin{aligned} f &= N_s / 60 \\ \therefore N_s &= 60 \times f / p \quad \checkmark \\ &= 60 \times 50 / 2 \\ &= 1500 \text{ rpm} \quad \checkmark \end{aligned}$$

Rotor input

$$\begin{aligned} P &= 2 \pi N_s T / 60 \\ &= 2 \pi \times 1500 \times 170 / 60 \quad \checkmark \\ &= 26703,5 \text{ W} \\ &= 26,7 \text{ kW} \quad \checkmark \end{aligned} \tag{4}$$

5.2.2 Rotor Cu Loss = $S \times$ Rotor input

$$\begin{aligned} S &= N_s - N_r / N_s &= 1500 - 1000 / 1500 \quad \checkmark \\ & &= 0,33 \quad \checkmark \end{aligned}$$

$$\begin{aligned} \text{Rotor Cu Loss} & &= 0,33 \times 26703,5 \\ & &= 8812,2 \text{ W} \quad \checkmark \end{aligned} \tag{3}$$

5.3 $f = 50 \text{ Hz}$ $\phi = 0,3 \text{ wb}$ $k_d = 0,96$ $N = 360 \text{ rpm}$

$$\begin{aligned} V_L & &= \sqrt{3} V_p \\ V_p & &= 20 / \sqrt{3} \\ & &= 11,557 \text{ kV} \quad \checkmark \end{aligned}$$

$$\begin{aligned} V_p & &= 2 k_f k_d k_p \phi f X \\ X & &= V_p / 2 k_f k_d \phi f \\ & &= 11547 / 2 \times 1,11 \times 0,96 \times 1 \times 0,3 \times 50 \quad \checkmark \\ & &= 361,2 \text{ conductors / ph (say 362)} \end{aligned}$$

$$\begin{aligned} f & &= N_p / 60 \\ p & &= 60 f / N \\ & &= 60 \times 50 / 375 \\ & &= 8 \text{ pole pairs} \\ & &= 16 \text{ poles} \quad \checkmark \end{aligned}$$

$$\begin{aligned} \text{Slots / phase} & &= 60 \text{ slots / phase} \quad \checkmark \\ 3 \times 20 \text{ slots / phase} & & \end{aligned}$$

$$\begin{aligned} \text{Cond / Slot} & &= (\text{cond. / ph}) / (\text{slots / ph}) \\ & &= 362 / 60 \\ & &= 6,03 \quad \checkmark \end{aligned}$$

(6)
[20]

TOTAL: 100

Past Examination Papers



**higher education
& training**

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

NOVEMBER 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080085)

**18 November 2014 (Y-Paper)
13:00 – 16:00**

This question paper consists of 5 pages and a formula sheet of 2 pages.

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N5
TIME: 3 HOURS
MARKS: 100**

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
 2. Read ALL the questions carefully
 3. Number the answers correctly according to the numbering system used in this question paper.
 4. Keep subsections of questions together.
 5. Write neatly and legibly.
-

QUESTION 1:

- 1.1 State TWO characteristics of DC motors. (2)
- 1.2 1.2.1 Calculate the number of series turns per pole, required on a compound generator, for it to maintain a constant voltage at 630 V, between no-load and full-load of 450 kW. With no series winding, it was found that the shunt current has to be 6 A on no-load and 7,5 A on full-load, to maintain the voltage constant at 630 V. Number of turns per pole on the shunt winding is 2 400. (5)
- 1.2.2 If the series coils were wound with 8 turns/pole and had a total resistance of 0,06 Ω . (5)
- Calculate the value of the diverter resistance required to give level-compounding.
- 1.3 A 30,5 kW, 440 V, eight -pole DC motor has a wave-wound armature with 1 200 conductors , and the commutator has 150 segments. The full-load efficiency is 85 % and the shunt current is 1,5 A. The brushes are shifted backwards through 1,4 segments from the geometric neutral. (8)

Calculate the demagnetising and cross-magnetising ampere-turns per pole.

[20]**QUESTION 2:**

- 2.1 A coil dissipates 1 800 W and draws a current of 20 A when it is connected to a 280 V, 50 Hz alternating current supply. When another coil is connected in parallel with it, the total supply current is 55 A, at a power factor of 0,85. (14)
- Calculate the current and power factor when the coils are connected in series across the same supply.
- 2.2 A circuit, with a resistance of 8,5 Ω , an inductance of 0,7 H and a variable capacitance in series, is connected across a 180 V, 50 Hz supply.
- 2.2.1 The capacitance to give resonance. (2)
- 2.2.2 The voltages across the inductance and the capacitance. (4)

[20]**QUESTION 3:**

- 3.1 A 310 kVA transformer has 660 turns on the primary and 220 turns on the secondary. The primary and secondary resistances are 0,8 Ω and 0,06 Ω and the leakage reactance are 1,7 Ω and 0,07 Ω respectively. The supply

voltage is 2 700 V.

Calculate:

- 3.1.1 The equivalent impedance referred to the primary circuit. (3)
- 3.1.2 Voltage regulation for power factor of 0,8 lagging, and the secondary terminal voltage on full load. (7)
- 3.1.3 Voltage regulation for power factor of 0,8 leading and secondary terminal voltage on full load. (4)
- 3.2 A three phase transformer has 510 turns on the primary and 30 turns on the secondary winding. The supply voltage is 2 600 V.
- Calculate the secondary line voltage on no-load when the transformer is connected in:
- 3.2.1 star- delta (3)
- 3.2.2 delta-star (3)
- [20]**

QUESTION 4:

- 4.1 Determine the total resistance, inductance and capacitance of a single-phase 33 km, overhead line with solid conductors of 1,4 cm diameter and spaced 0,7 between centres. Take resistivity of conductor material as $1,7 \mu\Omega \text{ cm}$ and ignore skin effect. (6)
- 4.2 Calculate the inductance and capacitance per phase, of 35 km of three phase overhead line, having solid copper conductors with a diameter of 1,5 cm.
- When the overhead line is:
- 4.2.1 spaced 50 cm between adjacent centres in flat regular spacing. (6)
- 4.2.2 spaced on the corners of a triangle having sides of length 55 cm: 85 cm: 110 cm. (6)
- 4.3 Calculate the inductance per phase of a 200 km, three phase transmission line, having an equilateral conductor spacing of 10 m and a conductor diameter of 30 mm. (2)

[20]

QUESTION 5:

- 5.1 A three phase, four-pole, 50 Hz induction motor, with a star-connected rotor, has a rotor resistance of $0,8 \Omega$ per phase and at standstill the reactance is $2,8 \Omega$. The EMF between the slip-rings is 260 V. Full-load speed is 1 380 r/min.

Calculate

- 5.1.1 the fractional slip (3)
- 5.1.2 the EMF induced in each phase of the rotor (2)
- 5.1.3 the rotor reactance per phase (1)
- 5.1.4 the rotor current and power factor (if rings are short-circuited) (3)
- 5.1.5 the rotor frequency (1)
- 5.2 With reference to induction motors what is meant by the term *slip*? (4)

Explain why slip is necessary for an induction motor to operate.

- 5.3 A three-phase, 50 Hz, eight pole induction motor has a slip of 0,05 per unit, when the output is 45 kW. The frictional loss is 375 W.

Calculate:

- 5.3.1 Rotor speed (2)
- 5.3.2 Rotor copper loss (4)
- [20]**

TOTAL: 100

ELECTROTECHNICS N5

FORMULA SHEET

Armature ampere-turns/pole

$$= \frac{1}{2} \cdot \frac{I_a}{C} \cdot \frac{Z}{2P}$$

$$E = V \pm I_a R_a$$

$$E = \frac{2pNZ\Phi}{60c}$$

$$T = 0,318 \frac{I_a}{c} ZP\Phi$$

$$k = n \sqrt{\frac{R_1}{r_m}}$$

$$r_1 = R_1 \left[\frac{k-1}{k} \right]$$

$$r_1 = R_s \frac{1-y}{1-y^m}$$

$$R_1 = bR_1 (k-1) \times \frac{1-b^n}{1-b} + r_m$$

$$y = \frac{I_2}{I_1}$$

$$r_1 = bR_1 (k-1)$$

$$\frac{E_1}{E_2} = \frac{K\Phi_1 N_1}{K\Phi_2 N_2}$$

$$\frac{T_1}{T_2} = \frac{K\Phi_1 I_{a1}}{K\Phi_2 I_{a2}}$$

$$I_{ave} = \frac{i_1 + i_2 + i_3 + \dots + i_n}{n}$$

$$I_{rms} = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2 + \dots + i_n^2}{n}}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$f = \frac{1}{2\pi L} \sqrt{\frac{L}{C} - R^2}$$

$$P = \sqrt{3} I_L V_L \cos \phi$$

$$P_1 = V_L I_L \cos (30 - \phi)$$

$$P_2 = V_L I_L \cos (30 + \phi)$$

$$\tan \phi = \frac{\sqrt{3} (P_2 - P_1)}{(P_2 + P_1)}$$

% Voltage regulation

$$= I_1 \frac{(R_e \cos \phi \pm X_e \sin \phi)}{v_1} \times \frac{100}{1}$$

$$Z_e = \sqrt{R_e^2 + X_e^2}$$

$$\% Z_e = \frac{I Z_e}{V} \times \frac{100}{1}$$

$$S_1 = S \frac{Z_2}{Z_1 + Z_2}$$

$$E = 2,222 k_d k_p Z \Phi f$$

$$I_r = \frac{E_r}{Z_r}$$

$$E_o = V_p \frac{Z_r}{Z_s}$$

$$\cos \phi_r = \frac{R}{Z_r}$$

$$s = \frac{2\pi T (n_s - n_r)}{2\pi T n_s}$$

$$L = 0,05 + 0,2 \text{ Lin } \frac{d}{r}$$

$$C = \frac{1}{36 \text{ Lin } \frac{d-r}{r}}$$

$$C = \frac{1}{18 \text{ Lin } \frac{de}{r}}$$

% Regulation

$$= \frac{V_s - V_R}{V_R} \times \frac{100}{1}$$

Marking Guidelines



higher education
& training

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

NOVEMBER 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080074)

18 November 2014 (Y-Paper)
13:00 – 16:00

QUESTION 1

- 1.1
- Fixed poles in the field winding.
 - No rotating magnetic flux.
 - Great mass due to heavy wound armature. (Any 2 x 1) (2)

1.2.1 Ampere turns required on no load = $6 \times 2400 = 14400$ ✓

Ampere turns required on full load = $7,5 \times 2400 = 18000$ ✓
 Ampere turns required on series field on full load = $18000 - 14400$

= 3600 ✓

Full load line current $I_L = P/V$

= $\frac{450 \times 10^3}{630}$
 = $714,29 \text{ A}$ ✓

Constant field current

$I_f = 6 \text{ A}$
 $I_a = I_L + I_f$
 = $720,29 \text{ A}$ ✓

Turns required on series field = $\frac{3600}{720,29}$

= 5 ✓ (6)

1.2.2 With series winding of 8 t/p and resistance of $0,06 \Omega$

Ampere turns required = 3600

With 6 turns, series field current $I_f = 3600/6$
 = 450 A ✓

Current through diverter $R_x = 720,29 - 450$

= 270 A ✓

Voltage across diverter = voltage across series field

$\frac{(I_x)(R_x)}{R_x} = I_f(\text{series}) \times R(\text{series})$
 = $\frac{450 \times 0,06}{264,29}$ ✓

= $0,102 \Omega$ ✓ (4)

$$1.3 \quad P_i = \frac{30500}{0,85}$$

$$= 35882,35 \text{ W} \quad \checkmark$$

$$I_L = \frac{35882,35}{440} \quad \checkmark$$

$$= 81,55 \text{ A}$$

$$I_a = 81,55 - 1,5$$

$$= 80,05 \text{ A} \quad \checkmark$$

$$\text{Total At/p} = I_a Z / 4 p c$$

$$= \frac{80,05 \times 1200}{4 \times 4 \times 2}$$

$$= 3001,88 \quad \checkmark$$

$$\theta = \frac{360^\circ}{\text{segments}} \times \text{shift} \times p$$

$$= 360/150 \times 1,4 \times 4$$

$$= 13,44 \quad \checkmark$$

$$\text{Demag At/p} = \text{At/p} \times \frac{4 \theta}{360}$$

$$= 3001,88 \times \frac{4 \times 13,44}{360} \quad \checkmark$$

$$= 448,28 \quad \checkmark$$

$$\text{Cross- mag At/p} = \text{At/p} - \text{Demag At/p}$$

$$= 3001,88 - 448,28$$

$$= 2553,6 \quad \checkmark$$

(8)
[20]

QUESTION 2

$$\begin{aligned}
 2.1 \quad P &= I V \cos \phi \\
 1800 &= 20 \times 280 \cos \phi \\
 \cos \phi &= 0,321 \text{ lagging } \checkmark \\
 P &= I^2 R \\
 R &= P/I^2 = 1800/20^2 = 4,5 \Omega \quad \checkmark \\
 \cos \phi &= R/Z \\
 Z_1 &= R/\cos \phi \\
 &= 4,5 / 0,321 = 14 \Omega \\
 Z_1 &= 14 < 71,28 \quad \checkmark \\
 &\text{OR} \\
 Z_1 &= V/I = \frac{280 < 0}{20 < -71,28} \\
 &= 14 < 71,28 \\
 &= 4,49 + j 13,26 \\
 \text{PARALLEL} \\
 I_1 &= 20 < -71,28 = 6,41 - j 18,94 \\
 I_T &= 55 < -31,79 = 46,75 - j 29 \quad \checkmark \\
 I_2 &= I_T - I_1 \quad \checkmark \\
 &= (46,75 - j 29) - (6,41 - j 18,94) \\
 &= 46,75 - j 29 - 6,41 + j 18,94 \quad \checkmark \\
 &= 40,34 - j 10,06 \\
 &= 41,58 < -14 \text{ A} \quad \checkmark \\
 Z_2 &= V/I_2 = \frac{280 < 0}{41,58 < -14} \quad \checkmark \\
 &= 6,73 < 14 \quad \checkmark \\
 &= 6,53 + j 1,63 \Omega \\
 \text{SERIES} \\
 Z_T &= Z_1 + Z_2 \quad \checkmark \\
 &= 4,49 + j 13,26 + 6,53 + j 1,63 \\
 &= 11,02 + j 14,89 \\
 &= 18,52 < 53,5 \Omega \quad \checkmark \\
 I &= V/Z_T = \frac{280 < 0}{18,52 < 53,5} \quad \checkmark \\
 &= 15,12 < -53,5 \text{ A} \\
 \cos \phi &= \cos 53,5 = 0,595 \text{ lagging} \quad \checkmark \\
 I &= 15,12 \text{ A} \quad \checkmark
 \end{aligned}$$

(14)

$$2.2 \quad 2.2.1 \quad 2\pi fL = 1/2\pi fC$$

$$C = 1 / (2 \times \pi \times 50)^2 \times 0,7 \quad \checkmark$$

$$= 14,47 \mu F \quad \checkmark \quad (2)$$

$$2.2.2 \quad I = V / R$$

$$= 180 / 8,5$$

$$= 21,18 A \quad \checkmark$$

$$V_L = 2 \times \pi \times 50 \times 0,7 \times 21,18 \quad \checkmark$$

$$= 4657,73 V \quad \checkmark$$

$$VC = VL = 4657,73 V \quad \checkmark \quad (4)$$

[20]

QUESTION 3

$$3.1.1 \quad R_e = 0,8 + 0,06 (660/220)^2$$

$$= 1,34 \Omega \quad \checkmark$$

$$X_e = 1,7 + 0,07 (660/220)^2$$

$$= 2,33 \Omega \quad \checkmark$$

$$Z_e = \sqrt{(1,34)^2 + (2,33)^2}$$

$$= 2,69 \Omega \quad \checkmark \quad (3)$$

$$3.1.2 \quad \cos \phi_2 = 0,8 \quad \sin \phi_2 = 0,6 \quad \checkmark$$

$$I_1 (\text{ FULL LOAD }) = \frac{VA}{V} = \frac{310000}{2700} = 114,81 A \quad \checkmark$$

$$V \text{ reg. (Pf. 0,8 lagging) } = \frac{I_1 (R_e \cos \phi_2 + X_e \sin \phi_2)}{V_1}$$

$$= \frac{114,81 (1,34 \times 0,8 + 2,33 \times 0,6)}{2700} \quad \checkmark$$

$$= 0,105 \text{ p.u.} \quad \checkmark$$

$$V_2 (\text{ no load }) = 2700 \times 220/660 = 900 V \quad \checkmark$$

Decrease of V_2 (bet. no load and full load)

$$= 900 \times 0,105 = 94,5 V$$

$$\checkmark$$

$$V_2 (\text{ full load }) = 900 - 94,5 = 805,5 V \quad \checkmark \quad (7)$$

$$\begin{aligned}
 3.1.3 \quad V_{reg.} (Pf. 0,8 \text{ leading}) &= I_1 (R_e \cos \phi_2 - X_e \sin \phi_2) \\
 &= 114,81 \left(\frac{1,34 \times 0,8}{2700} - 2,33 \times 0,6 \right) \\
 &= 0,0139 \text{ p.u.}
 \end{aligned}$$

Increase of V_2 (bet. no load and full load)

$$= 900 \times 0,0139 = 12,51 \text{ V}$$

$$V_2 \text{ (full load)} = 900 + 12,51 = 912,51 \text{ V} \quad (4)$$

$$\begin{aligned}
 3.2 \quad 3.2.1 \quad V_{ph 1} &= \frac{V_L}{\sqrt{3}} \\
 &= \frac{2600}{1,732} = 1501,11 \text{ V}
 \end{aligned}$$

$$\begin{aligned}
 V_{ph 2} &= V_{ph 1} \times \frac{N_2}{N_1} \\
 &= 1501,11 \times \frac{30}{510} \\
 &= 88,3 \text{ V}
 \end{aligned}$$

= secondary line voltage (3)

$$\begin{aligned}
 3.2.2 \quad V_{ph 1} &= 2600 \\
 V_{ph 2} &= 2600 \times \frac{N_2}{N_1} = 2600 \times \frac{30}{510} \\
 &= 152,94 \text{ V}
 \end{aligned}$$

$$\begin{aligned}
 V_L 2 &= 252 \text{ V} \times \sqrt{3} \\
 &= 264,9 \text{ V}
 \end{aligned}$$

(3)
[20]

QUESTION 4

$$\begin{aligned}
 4.1 \quad \text{Loop resistance} &= \frac{\rho l}{a} \\
 &= \frac{1,7 \times 66 \times 10^5}{10^6 \times \pi \times 0,7^2}
 \end{aligned}$$

$$= 7,29 \Omega$$

$$\text{Loop inductance} = 66 [0,05 + 0,2 \log_e d/r] \text{ mH}$$

$$= 66 [0,05 + 0,2 \log_e (70/0,7)] \text{ mH}$$

$$= 64,01 \text{ mH}$$

$$\text{Total capacitance} = \frac{33}{36 \log_e \left(\frac{d-r}{r} \right)}$$

$$\begin{aligned}
 &= \frac{33}{36 \log_e \left(\frac{70 - 0,7}{0,7} \right)} \\
 &= 0,2165 \mu \text{F}
 \end{aligned}$$

(6)

4.2 4.2.1

$$\begin{aligned}
 de &= \sqrt[3]{d \times d \times 2d} \\
 &= \sqrt[3]{50 \times 50 \times 100} \text{ cm} \quad \checkmark \\
 &= 63 \times 10^{-2} \text{ m} \quad \checkmark \\
 L &= Km [0,05 + 0,2 \log e (de/r)] \\
 &= 35 [0,05 + 0,2 \log e (0,63 / 0,75 \times 10^{-2})] \quad \checkmark \\
 &= 32,76 \text{ mH per phase} \quad \checkmark \\
 C &= Km [1/ 18 \log e (de/r)] \\
 C &= 35 [1/ 18 \log e (0,63 / 0,75 \times 10^{-2})] \quad \checkmark \\
 &= 0,44 \mu F \quad \checkmark
 \end{aligned}$$

(6)

4.2.2

$$\begin{aligned}
 de &= \sqrt[3]{d1 \times d2 \times d3} \\
 &= \sqrt[3]{55 \times 85 \times 110} \quad \checkmark \\
 &= 80,12 \times 10^{-2} \text{ m} \quad \checkmark \\
 L &= Km [0,05 + 0,2 \log e (de/r)] \\
 &= 35 [0,05 + 0,2 \log e \frac{(80,12 \times 10^{-2})}{0,75 \times 10^{-2}}] \quad \checkmark \\
 &= 34,45 \text{ mH per phase} \quad \checkmark \\
 C &= Km [1/ 18 \log e (de/r)] \\
 &= 35 [1/ 18 \log e \frac{(80,12 \times 10^{-2})}{0,75 \times 10^{-2}}] \quad \checkmark \\
 &= 0,416 \mu F \text{ per phase} \quad \checkmark
 \end{aligned}$$

(6)

4.3

$$K_m = 200 \quad 3 \text{ ph.} \quad d = 10 \text{ m} \quad r = 15 \times 10^{-3} \text{ m}$$

$$L = K_m [0,05 + 0,2 \log_e (d/r)] \text{ mH}$$

$$= 200 [0,05 + 0,2 \log_e (10 / 15 \times 10^{-3})] \text{ mH} \quad \checkmark$$

$$= 270,01 \text{ mH} \quad \checkmark \quad (2)$$

[20]

QUESTION 5

$$5.1 \quad 5.1.1 \quad \text{Syn. speed} = f/p = 50/2 = 25 \text{ r/s} \quad \checkmark$$

$$S = \frac{\text{Syn. speed} - \text{Actual speed}}{\text{Syn. Speed}} \quad \checkmark$$

$$= \frac{25 - 23}{25}$$

$$= 0,08 \quad \checkmark \quad (3)$$

$$5.1.2 \quad E_2 = 260 / \sqrt{3} = 150,11 \text{ V} \quad \checkmark$$

$$SE_2 = 0,08 \times 150,11$$

$$= 12,01 \text{ V} \quad \checkmark \quad (2)$$

$$5.1.3 \quad SX_2 = 0,08 \times 2,8$$

$$= 0,228 \Omega \quad \checkmark \quad (1)$$

$$5.1.4 \quad I_{\text{rotor}} = \frac{SE_2}{Z_r}$$

$$Z_r = 0,8 + j0,228$$

$$= 0,83 \angle 15,91^\circ \quad \checkmark$$

$$I_r = \frac{12,01 \angle 0^\circ}{0,83 \angle 15,91^\circ}$$

$$= 14,47 \angle -15,91^\circ \quad \checkmark$$

$$\cos \phi = 0,96 \text{ lagging} \quad \checkmark \quad (3)$$

$$5.1.5 \quad \text{Rotor frequency} = Sf$$

$$= 0,08 \times 50$$

$$= 4 \text{ Hz} \quad \checkmark \quad (1)$$

- 5.2 The difference between the synchronous speed (N_s) ✓ and the actual speed (N) of the rotor is known as slip. ✓
 For an induction motor to develop torque, EMF and current must be induced in the rotor. ✓
 This will only occur when there is a relative speed difference between the rotating magnetic field and the rotor (i.e. The motor has to have a slip) ✓
 Hence an induction motor must have slip to develop torque. (4)

5.3 5.3.1 $f_1 = \frac{n_1 p}{60}$
 $50 = \frac{n_1 \times 4}{60}$
 $n_1 = 750 \text{ r/min}$ ✓
 $n_2 = n_1 - s n_1$
 $= 750 - 0,05 (750)$
 $= 712,5 \text{ r/min}$ ✓ (2)

5.3.2 Gross P = $\frac{2 \pi \times n_2 \times T}{60}$
 $45375 = \frac{2 \pi \times 712,5 \times T}{60}$ ✓
 $T = 608,14 \text{ Nm}$ ✓
 Rotor input = $\frac{2 \pi \times n_1 \times T}{60}$
 $= \frac{2 \pi \times 750 \times 608,14}{60}$
 $= 47763,2 \text{ W}$ ✓
 Rotor cu. Loss = $s \times \text{rotor input}$
 $= 0,05 \times 47763,2$
 $= 2388,16 \text{ W}$ ✓ (4)
 [20]

TOTAL: 100

Past Examination Papers



higher education
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Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

AUGUST 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080085)

28 July 2014 (Y-Paper)

13:00 – 16:00

Calculators may be used.

This question paper consists of 6 pages and 2 formula sheets.

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N5
TIME: 3 HOURS
MARKS: 100**

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
 2. Read ALL the questions carefully
 3. Number the answers according to the numbering system used in this question paper.
 4. Write neatly and legibly.
-

QUESTION 1:

1.1 Briefly explain how you would change the direction of rotation of a DC motor. (2)

1.2 A DC motor can be self-regulating due to back EMF. (4)

Briefly discuss this statement.

1.3 An eight-pole generator has a lap-connected armature with 640 conductors. The ratio of the pole arc per pole pitch is 0,8. (4)

Calculate the ampere-turns per pole of a compensating winding to give uniform air gap density when the total armature current is 960 A.

1.4 An 88 kW, 540 V shunt generator has 1 800 turns on each pole of its field winding. On no-load a current of 9A in the field winding produces a terminal voltage of 540 V, but on full-load the shunt current has to be increased to 12 A for the same terminal voltage at the same speed. (8)

Calculate the number of series field turns per pole required for level compounding.

1.5 Name the practical applications of lap and wave windings in DC machines. (2)

[20]

QUESTION 2:

2.1 The following ordinates were taken during a half cycle of a symmetrical alternating current wave. The current varies in a linear manner between successive points:

Phase angle degrees :	0	30	60	90	120	150	180
Current in amperes :	0	12,6	24,4	31	29	24,4	0

Determine the following without plotting the graph,:

2.1.1 The mean value (5)

2.1.2 The RMS value (3)

2.2 A resonant circuit comprising of a coil of inductance 650 μH and a resistance of 60 ohms in parallel with a variable capacitor, is connected in series with a resistor of 9 900 ohms. The supply across this circuit is 80 V, with a frequency of 1, 5 MHz.

Calculate the:

2.2.1 Value of the capacitor at resonance (4)

- 2.2.2 Impedance of the parallel circuit (2)
- 2.2.3 Current in each branch (4)
- [18]**

QUESTION 3:

- 3.1 Name FOUR methods of reducing leakage flux in transformers. (4)

- 3.2 Two single-phase transformers are connected in parallel to a load of 900 A, at a power factor of 0,8 lagging.

Test data:

Open-circuit: 12 000/2 800,V for each transformer

Short-circuit with high voltage winding short-circuited:

Transformer A: secondary input 400 V, 450 A, 30 kW

Transformer B: secondary input 250 V, 450 A, 35 kW

Calculate the:

- 3.2.1 Voltage secondary (10)
- 3.2.2 Output and power factor of transformer A (3)
- 3.2.3 Output and power factor of transformer B (3)
- [20]**

QUESTION 4:

- 4.1 The input power to a 3 350 V three-phase delta connected induction motor is 180 kW. The power factor of the motor is 0, 85 lagging.

Calculate the:

- 4.1.1 Line and phase currents (2)
- 4.1.2 Input power readings on the TWO watt-meters (5)
- 4.1.3 kVA rating of the motor (2)
- 4.2 A three-phase transmission line supplies a 2,45, MW star-connected load, having a power factor of 0,8 lagging at a line voltage of 36 kV.

The line has a resistance of 90 ohms per phase and an inductive reactance of 160 ohms per phase.

Calculate the:

- 4.2.1 Voltage at the sending end (6)
- 4.2.2 Regulation (5)
- 4.2.3 Efficiency of the line (2)
- [22]**

QUESTION 5:

- 5.1 Does an induction motor develop torque when running at synchronous speed? (4)

Discuss the reason for your answer.

- 5.2 Two similar three-phase, star-connected alternators are operating in parallel. Each machine has a synchronous reactance of $6,5 \Omega$ per phase and negligible resistance, and is excited to generate an EMF of 2 675 V per phase. The machines have a phase displacement of 30 electrical degrees relative to each other.

Calculate the:

- 5.2.1 Circulating current (5)
- 5.2.2 Terminal voltage per phase (2)
- 5.2.3 Power supplied from ONE machine to another. (3)

- 5.3 A star-connected, three-phase alternator, runs at a speed of 1 500 r/min, and has to generate a voltage of 800 V at 50 Hz on open circuit. The stator has two slots per pole per phase and four conductors per slot.

Assume all the conductors per phase to be series connected and coils to be full-pitched. $k_d = 0,96$.

Calculate the:

- 5.3.1 Number of poles (2)
- 5.3.2 Useful flux per pole (4)
- [20]**

TOTAL: 100

ELECTROTECHNICS N5

FORMULA SHEET

Armature ampere-turns/pole

$$= \frac{1}{2} \cdot \frac{I_a}{C} \cdot \frac{Z}{2P}$$

$$E = V \pm I_a R_a$$

$$E = \frac{2pNZ\Phi}{60c}$$

$$T = 0,318 \frac{I_a}{c} ZP\Phi$$

$$k = n \sqrt{\frac{R_1}{r_m}}$$

$$r_1 = R_1 \left[\frac{k-1}{k} \right]$$

$$r_1 = R_s \frac{1-y}{1-y^m}$$

$$R_1 = bR_1 (k-1) \times \frac{1-b^n}{1-b} + r_m$$

$$y = \frac{I_2}{I_1}$$

$$r_1 = bR_1 (k-1)$$

$$\frac{E_1}{E_2} = \frac{K\Phi_1 N_1}{K\Phi_2 N_2}$$

$$\frac{T_1}{T_2} = \frac{K\Phi_1 I_{a1}}{K\Phi_2 I_{a2}}$$

$$I_{ave} = \frac{i_1 + i_2 + i_3 + \dots + i_n}{n}$$

$$I_{rms} = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2 + \dots + i_n^2}{n}}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$f = \frac{1}{2\pi L} \sqrt{\frac{L}{C} - R^2}$$

$$P = \sqrt{3} I_L V_L \cos \phi$$

$$P_1 = V_L I_L \cos (30 - \phi)$$

$$P_2 = V_L I_L \cos (30 + \phi)$$

$$\tan \phi = \frac{\sqrt{3} (P_2 - P_1)}{(P_2 + P_1)}$$

% Voltage regulation

$$= I_1 \frac{(R_e \cos \phi \pm X_e \sin \phi)}{v_1} \times \frac{100}{1}$$

$$Z_e = \sqrt{R_e^2 + X_e^2}$$

$$\% Z_e = \frac{I Z_e}{V} \times \frac{100}{1}$$

$$S_1 = S \frac{Z_2}{Z_1 + Z_2}$$

$$E = 2,222 k_d k_p Z \Phi f$$

$$I_r = \frac{E_r}{Z_r}$$

$$E_o = V_p \frac{Z_r}{Z_s}$$

$$\cos \phi_r = \frac{R}{Z_r}$$

$$s = \frac{2\pi T (n_s - n_r)}{2\pi T n_s}$$

$$L = 0,05 + 0,2 \text{ Lin } \frac{d}{r}$$

$$C = \frac{1}{36 \text{ Lin } \frac{d-r}{r}}$$

$$C = \frac{1}{18 \text{ Lin } \frac{de}{r}}$$

% Regulation

$$= \frac{V_s - V_R}{V_R} \times \frac{100}{1}$$

Marking Guidelines



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Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

AUGUST 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080074)

28 July 2014 (Y-Paper)
13:00 – 16:00

QUESTION 1

1.1 Can be changed by reversing either the field ✓ or armature connections. ✓ (2)

1.2 The voltage which is generated due to the moving of the armature conductors through the magnetic field flux is called the back EMF. ✓ This voltage is in opposition to the applied voltage by which it is generated. The motor will speed up until the necessary back EMF is built up because a low back EMF will cause a high armature current which will supply the extra driving torque to speed up the armature. ✓ Any change in the back EMF will result in speed change. ✓ The back EMF acts like a governor and therefore the motor is self-regulating. ✓ (4)

1.3 Pole = 6 $p = 3$
 $c = 2p = 2 \times 4 = 8$ ✓ $Z = 640$

$$\frac{\text{Pole arc}}{\text{Pole pitch}} = 0,8$$

$$I = 960 \text{ A}$$

$$\text{At/p} = \frac{IZ}{2c \ 2p} \times \frac{\text{Pole arc}}{\text{Pole pitch}} \checkmark$$

$$= \frac{960 \times 640}{2 \times 8 \times 2 \times 4} \times 0,8 \checkmark$$

$$= 3\ 840 \text{ At} \checkmark \quad (4)$$

1.4 $I = \frac{88\ 000}{540} = 162,96 \text{ A} \checkmark$

$$\text{At/p for full load} = 12\text{A} \times 1\ 800 \text{ t/p} \checkmark = 21\ 600 \text{ At/p} \checkmark$$

$$\text{t/p for no load} = 9\text{A} \times 1\ 800 \text{ t/p} \checkmark = 16\ 200 \text{ At/p} \checkmark$$

$$\text{At/p for series winding} = 21\ 600 - 16\ 200 \checkmark$$

$$= 5\ 400 \text{ At/p} \checkmark$$

$$\text{No. of series t/p} = 5\ 400 / 162,96$$

$$= 33,14 \checkmark$$

Say 34

(8)

Lap-wound - for low voltage and high current ✓

(1)

1.5 Wave-wound - for high voltage and low current. ✓

(1)

[20]

QUESTION 2

$$\begin{aligned}
 2.1 \quad 2.1.1 \quad i_1 &= 0 + 12,6 / 2 = 6,3A \\
 i_2 &= 12,6 + 24,4 / 2 = 18,5 \checkmark \\
 i_3 &= 24,4 + 31 / 2 = 27,7 \\
 i_4 &= 31 + 29 / 2 = 30 \checkmark \\
 i_5 &= 29 + 24,4 / 2 = 26,7 \\
 i_6 &= 24,4 + 0 / 2 = 12,2 \checkmark
 \end{aligned}$$

$$\begin{aligned}
 I_{ave} &= i_1 + i_2 + i_3 + i_4 + i_5 + i_6 / n \checkmark \\
 &= 6,3 + 18,5 + 27,7 + 30 + 26,7 + 12,2 / 6 \\
 &= 121,4 / 6 \\
 &= 20,23 A \checkmark
 \end{aligned} \tag{5}$$

$$\begin{aligned}
 2.1.2 \quad I_{rms} &= \sqrt{i_1^2 + i_2^2 + i_3^2 + i_4^2 + i_5^2 + i_6^2 / n} \checkmark \\
 &= \sqrt{6,3^2 + 18,5^2 + 27,7^2 + 30^2 + 26,7^2 + 12,2^2 / n} \checkmark \\
 &= \sqrt{2910,96 / 6} \\
 &= 22,03 A \checkmark
 \end{aligned} \tag{3}$$

$$\begin{aligned}
 2.2 \quad 2.2.1 \quad X_L &= 2 \pi f L \\
 &= 2 \pi \times 1,5 \times 10^6 \times 650 \times 10^{-6} = 6126,11 \Omega \checkmark
 \end{aligned}$$

$$f(\text{res}) = 1 / 2 \pi \sqrt{LC}$$

$$1,5 \times 10^6 = 1 / 2 \pi \sqrt{650 \times 10^{-6} \times C} \checkmark$$

$$\begin{aligned}
 \frac{\sqrt{650 \times 10^{-6} \times C}}{650 \times 10^{-6} \times C} &= 1 / \sqrt{2 \pi \times 10^6 \times 1,5} \\
 &= (1 / 2 \pi \times 10^6 \times 1,5)^2 \checkmark
 \end{aligned}$$

$$\begin{aligned}
 C &= 1,73 \times 10^{-11} \\
 &= 17,3 \times 10^{-12} F \checkmark
 \end{aligned} \tag{4}$$

$$\begin{aligned}
 2.2.2 \quad Z_{\text{parallel}} &= L / CR \\
 &= \frac{650 \times 10^{-6}}{17,3 \times 10^{-12} \times 60} \checkmark \\
 &= 626,204 k \Omega \checkmark
 \end{aligned} \tag{2}$$

$$\begin{aligned}
 2.2.3 \quad I &= V/ZT \\
 &= 80 / 9900 + 626204 \\
 &= 80 / 636104 \\
 &= 0,126 \text{ mA } \checkmark
 \end{aligned}$$

$$\text{pd across coil} = 0,126 \times 10^{-3} \times 626204 = 78,9 \text{ V } \checkmark$$

$$\begin{aligned}
 I_{\text{coil}} &= 78,9 / \sqrt{(60)^2 + (6126,11)^2} \\
 &= 12,88 \text{ mA } \checkmark
 \end{aligned}$$

$$\begin{aligned}
 I_{\text{cap}} &= 2 \pi \times 1,5 \times 10^6 \times 1,73 \times 10^{-12} \times 78,9 \\
 &= 0,129 \text{ mA } \checkmark
 \end{aligned}$$

(4)
[18]**QUESTION 3**

- 3.1 Making the transformer window long and narrow. \checkmark
 Arranging the primary and secondary windings concentrically. \checkmark
 Sandwiching the primary and secondary windings. \checkmark
 Using shell-type construction. \checkmark

(4)

$$\begin{aligned}
 3.2 \quad 3.2.1 \quad S &= 2800 < 0 \times 900 < -36,87 \\
 &= 2520 < -36,87 \quad \text{kVA } \checkmark
 \end{aligned}$$

TRF A

$$P = I V \cos \phi$$

$$\begin{aligned}
 30\,000 &= 450 \times 400 \times \cos \phi \\
 \cos \phi &= 0,167
 \end{aligned}$$

$$\phi = 80,39 \checkmark$$

$$I_A = 450 < -80,39$$

$$Z_A = V/I = \frac{400 < 0}{450 < -80,39} = 0,889 < 80,39 \checkmark$$

$$= 0,148 + j 0,88$$

TRF.B

$$P = I V \cos \phi$$

$$35\,000 = 450 \times 250 \times \cos \phi$$

$$\cos \phi = 0,3,1$$

$$\phi = 71,94$$

$$I_B = 450 \angle -71,94 \checkmark$$

$$\begin{aligned} Z_B &= V/I = \frac{250 \angle 0}{450 \angle -71,94} = 0,556 \angle 71,94 \checkmark \\ &= 0,17 + j0,53 \end{aligned}$$

$$\begin{aligned} Z_A + Z_B &= 0,148 + j0,88 + 0,17 + j0,53 \\ &= 0,318 + j1,4 \\ &= 1,44 \angle 77,2 \checkmark \end{aligned}$$

$$Z_T = \frac{Z_A \times Z_B}{Z_A + Z_B} = \frac{0,889 \angle 80,39 \times 0,556 \angle 71,94}{1,44 \angle 77,2}$$

$$= 0,343 \angle 75,13 \checkmark$$

$$\begin{aligned} V_D &= I_L \times Z_T \\ &= 900 \angle -36,87 \times 0,343 \angle 75,13 \\ &= 308,7 \angle 38,26 \checkmark \\ &= 242,39 + j191,16 \end{aligned}$$

$$\begin{aligned} V_S &= V(\text{NO LOAD}) - V_D \\ &= 2800 \angle 0 - 308,7 \angle 38,26 \checkmark \\ &= (2800 + j0) - (242,39 + j191,16) = 2800 + j0 - 242,39 \\ &\quad - j191,16 \\ &= 2557,61 - j191,16 \\ &= 2564,74 \angle -4,27 \checkmark \end{aligned} \tag{10}$$

$$\begin{aligned} 3.2.2 \quad S &= V_S \times I(\text{LOAD}) \\ &= 2564,74 \angle -4,27 \times 900 \angle -36,87 \\ &= 2308,27 \angle -41,14 \text{ kVA} \checkmark \end{aligned}$$

$$\begin{aligned} S_A &= \frac{S \times Z_B}{Z_A + Z_B} = \frac{2308,27 \angle -41,14 \times 0,556 \angle 71,94}{1,44 \angle 77,2} \\ &= 891,25 \angle -46,4 \text{ kVA} \checkmark \end{aligned}$$

$$\cos \phi = 0,69 \text{ lagging} \checkmark \tag{3}$$

$$3.2.3 \quad S_B = \frac{S \times Z_A}{Z_A + Z_B} = \frac{2308,27 \angle -41,14 \times 0,889 \angle 80,39}{1,44 \angle 77,2} \checkmark$$

$$= 1425 \angle -37,95 \text{ kVA} \checkmark$$

$$\cos \phi = 0,789 \text{ lagging} \checkmark \tag{3}$$

[20]

QUESTION 4

$$\begin{aligned}
 4.1 \quad 4.1.1 \quad P_T &= \sqrt{3} V_L I_L \cos \phi \\
 I_L &= \frac{18\,000}{\sqrt{3} \times 3350 \times 0,85} \\
 &= 36,5 \text{ A } \checkmark \\
 I_P &= \frac{I_L}{\sqrt{3}} = \frac{36,5}{\sqrt{3}} = 63,2 \text{ A } \checkmark \quad (2)
 \end{aligned}$$

$$\begin{aligned}
 4.1.2 \quad W_1 &= V_L I_L \cos (-30 + \phi) \quad \phi = 31,79 \checkmark \\
 &= 3\,350 \times 36,5 \cos (30 + 31,79) \checkmark \\
 &= 3\,350 \times 36,5 \cos (61,79) \\
 &= 57,8 \text{ kW } \checkmark \\
 W_2 &= V_L I_L \cos (30 - \phi) \\
 &= 3\,350 \times 36,5 \cos (30 - 31,79) \checkmark \\
 &= 122,22 \text{ kW } \checkmark \quad (5)
 \end{aligned}$$

$$\begin{aligned}
 4.1.3 \quad \text{kVA} &= \frac{\sqrt{3} V_L I_L}{1\,000} \\
 &= \frac{\sqrt{3} \times 3350 \times 36,5}{1\,000} \checkmark \\
 &= 211,79 \text{ kW } \checkmark \quad (2)
 \end{aligned}$$

$$4.2 \quad \text{Load } P = 2,45 \text{ MW} = \frac{2,45 \text{ MW}}{3} \text{ per phase}$$

$$\cos \phi = 0,8 \text{ lagging } (\sin \phi = 0,6)$$

$$V_r = \frac{36\,000}{\sqrt{3}} (\cos \phi + j \sin \phi) \checkmark$$

$$= \frac{36\,000}{\sqrt{3}} (0,8 + j0,6)$$

$$= 16\,627,69 + j12\,470,77 \checkmark$$

$$I_p = \frac{2,45 \text{ MW}/3}{36\,000/\sqrt{3}} = 39,29 \text{ A} \checkmark$$

$$\begin{aligned} V_d &= IZ = 39,29 (90 + j160) \\ &= 3536,1 + j6286,4 \checkmark \end{aligned}$$

$$\begin{aligned} V_s &= V_r + V_d \\ &= 16\,627,69 + j12\,470,77 + 3536,1 + j6286,4 \\ &= 20\,163,79 + j18\,757,17 \\ &= 27\,539,24 \angle 42,9^\circ \checkmark \end{aligned}$$

$$V_s \text{ line voltage} = \sqrt{3} \times 27\,539,24 = 47,7 \text{ kV} \checkmark \quad (6)$$

$$\begin{aligned} 4.2.2 \quad \text{Reg} &= \frac{V_s - V_r}{V_r} \\ &= \frac{27\,539,24 - 36\,000/\sqrt{3}}{36\,000/\sqrt{3}} \quad \checkmark \text{ OR } \frac{47\,700 - 36\,000}{36\,000} \\ &= 0,325 \text{ p.u.} \quad \checkmark \qquad \qquad \qquad 0,325 \text{ p.u.} \end{aligned}$$

$$\text{Output} = 2,45 \text{ MW} / 3 \text{ per phase} = 816,67 \text{ kW} \checkmark$$

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

$$= (39,29)^2 \times 90$$

$$= 138,93 \text{ kW} \checkmark$$

$$\text{Input} = \text{output} + \text{losses}$$

$$= 816,67 + 138,93$$

$$= 955,6 \text{ kW} \checkmark \quad (5)$$

$$4.2.3 \quad \text{Efficiency} = \frac{\text{output}}{\text{Input}}$$

$$= \frac{816,67}{955,6} \checkmark$$

$$= 0,85 \quad (85\%) \checkmark$$

(2)
[22]

QUESTION 5

5.1 No ✓ If the rotor were to run at synchronous speed, then there would be no relative speed difference between rotating magnetic field and the rotor ✓, hence no emf will be induced in the rotor ✓ and therefore there will be no rotor current and so no torque. ✓ (4)

5.2 5.2.1 $X_s = 6,5 \Omega$ per phase $\theta = 30$
 $V_P = 2675 \text{ V}$

$$\begin{aligned} E_Z &= jEA - (EB \sin \theta + jEB \cos \theta) \quad \checkmark \\ &= j2675 - (2675 \sin 30 + j2675 \cos 30) \\ &= j2675 - 1337,5 - j2316,62 \quad \checkmark \\ &= -1337,5 + j358,38 \\ &= 184,68 \quad \checkmark \end{aligned}$$

$$\begin{aligned} \text{Circulating } I &= \frac{E_Z}{2X_s} = \frac{1384,68}{2 \times 6,5} \quad \checkmark \\ &= 106,5 \text{ A} \quad \checkmark \end{aligned} \quad (5)$$

$$\begin{aligned} 5.2.2 \quad \text{Terminal } V/P &= E_a \cos \frac{\theta}{2} \quad \checkmark \\ &= 2675 \cos 15 \\ &= 2583,85 \text{ V} \quad \checkmark \end{aligned} \quad (2)$$

$$\begin{aligned} 5.2.3 \quad P &= \sqrt{3} I_L V_L \\ V_L &= \sqrt{3} V_p = \sqrt{3} \times 2583,85 = 4475,36 \text{ V} \quad \checkmark \\ &= \sqrt{3} \times 106,5 \times 4475,36 \text{ W} \quad \checkmark \\ &= 825,540 \text{ kW} \quad \checkmark \end{aligned} \quad (3)$$

5.3 5.3.1 $V_L = 800 \text{ N} = 1500 \text{ r/min}$ $f = 50$

$$\begin{aligned} f &= Np/60 \\ 50 &= \frac{1500 \times p}{60} \quad \checkmark \\ p &= 2 \end{aligned}$$

$$\text{No of poles} = 2 \times 2 = 4 \quad \checkmark \quad (2)$$

Past Examination Papers



**higher education
& training**

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

APRIL 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080085)

**31 March 2014 (Y-Paper)
13:00 – 16:00**

Calculators may be used.

This question paper consists of 5 pages and 1 formula sheet of 2 pages.

**DEPARTMENT OF HIGHER EDUCATION AND TRAINING
REPUBLIC OF SOUTH AFRICA
NATIONAL CERTIFICATE
ELECTROTECHNICS N5
TIME: 3 HOURS
MARKS: 100**

INSTRUCTIONS AND INFORMATION

1. Answer ALL the questions.
 2. Read ALL the questions carefully
 3. Number the answers according to the numbering system used in this question paper.
 4. Keep subsections of questions together.
 5. Write neatly and legibly.
-

QUESTION 1:

1.1 Name and explain THREE methods to improve commutation. (6)

1.2 An eight-pole, 1 600 kW, 520 V, DC generator has a wave connected winding with 240 armature conductors. (5)

Calculate the number of turns per pole required for the commutating poles. Assume the com pole ampere-turns per pole to be about 1,6 times the armature ampere turns per pole and the brushes to be in geometric neutral axis.

1.3 An eight-pole, lap-wound, 350 V, shunt-excited DC machine draws an armature current of 7,5 A on no-load at 1 200 rpm. When loaded, it draws an armature current of 80 A from the supply and runs at the same speed. The resistance of the armature circuit is $0,6 \Omega$ and there are 900 armature conductors.

Calculate the following:

1.3.1 the generated EMF (2)

1.3.2 the useful flux per pole (4)

1.3.3 the useful torque developed by the machine in Nm (3)

[20]

QUESTION 2:

2.1 An impedance of $9 + j 11 \Omega$ is connected in series with two impedances in parallel, one of $11 + j 15 \Omega$ and the other of $15 - j 8 \Omega$. This combination is then connected across a 150 V alternating current supply.

Calculate the following:

2.1.1 The total impedance (5)

2.1.2 The total current (3)

2.1.3 The power factor (2)

2.2 A coil with a resistance of 30Ω and an inductance of 0,06 H, is connected in parallel with a circuit consisting of a $190 \mu f$ capacitor in series with a 28Ω resistor. The supply is 280 V, 50 Hz.

Calculate the following:

2.2.1 The total line current and the current in each branch (8)

- 2.2.2 Power and power factor (2)
[20]

QUESTION 3:

- 3.1 Name TWO methods that are used to cool transformers. (2)
- 3.2 A single phase transformer with a supply voltage of 310 V has an equivalent resistance of $0,4 \Omega$ and an equivalent leakage reactance of $0,95 \Omega$, referred to the primary. (11)

The secondary is connected to a coil with a resistance of 50Ω and a reactance of 180Ω . The secondary winding has 5 times as many turns as the primary.

Calculate the secondary terminal voltage.

- 3.3 Three similar inductors, each of resistance 29Ω and inductance $0,028 \text{ H}$, are delta-connected to a three-phase, 400 V , 50 Hz sinusoidal supply.

Calculate the following:

- 3.3.1 Line current (5)
- 3.3.2 Power factor (2)
[20]

QUESTION 4:

- 4.1 Draw a neat labelled sketch showing how the two-wattmeter method can be used to measure power in a three-phase network. (6)
- 4.2 Two wattmeters are connected to measure the input to a balanced three phase circuit. The readings are $3\ 300 \text{ W}$ and 720 W respectively.

Find the power factor of the circuit when:

- 4.2.1 both the readings are positive. (4)
- 4.2.2 the latter reading is obtained after reversing the connections to the current coil of one instrument. (4)
- 4.3 Calculate the total resistance, inductance and capacitance of a single-phase, 36 km , overhead line with solid conductors of $1,8 \text{ cm}$ diameter spaced $0,8 \text{ m}$ between centres. Take resistivity of conductor material as $1,7 \mu\Omega \text{ cm}$. (8)

[22]

QUESTION 5:

- 5.1 Calculate the efficiency and the output power of a three-phase 450 V (10) induction motor, running on load with a fractional slip of 0,05 and drawing a current of 80 A at a power factor of 0,8. When running light at 450 V, the motor has an input current of 30 A and the power taken is 3 000 W. The resistance per phase of the stator winding is 0,8 Ω , delta-connected
- 5.2 A three-phase, six-pole star-connected alternator delivers 375 V between lines on open circuit, running at a speed of 1 450 r/min. There are two conductors per slot and three slots per pole, per phase.

Assume the winding has a pitch factor of 0,8 and a distribution factor of 0,96 - and assuming a sine wave form.

Calculate the following:

- 5.2.1 The frequency (2)
- 5.2.2 Turns per phase (3)
- 5.2.3 Useful flux per pole (3)

[18]

TOTAL: 100

ELECTROTECHNICS N5

FORMULA SHEET

Armature ampere-turns/pole

$$= \frac{1}{2} \cdot \frac{I_a}{C} \cdot \frac{Z}{2P}$$

$$E = V \pm I_a R_a$$

$$E = \frac{2pNZ\Phi}{60c}$$

$$T = 0,318 \frac{I_a}{c} ZP\Phi$$

$$k = n \sqrt{\frac{R_1}{r_m}}$$

$$r_1 = R_1 \left[\frac{k-1}{k} \right]$$

$$r_1 = R_s \frac{1-y}{1-y^m}$$

$$R_1 = bR_1 (k-1) \times \frac{1-b^n}{1-b} + r_m$$

$$y = \frac{I_2}{I_1}$$

$$r_1 = bR_1 (k-1)$$

$$\frac{E_1}{E_2} = \frac{K\Phi_1 N_1}{K\Phi_2 N_2}$$

$$\frac{T_1}{T_2} = \frac{K\Phi_1 I_{a1}}{K\Phi_2 I_{a2}}$$

$$I_{ave} = \frac{i_1 + i_2 + i_3 + \dots + i_n}{n}$$

$$I_{rms} = \sqrt{\frac{i_1^2 + i_2^2 + i_3^2 + \dots + i_n^2}{n}}$$

$$f = \frac{1}{2\pi\sqrt{LC}}$$

$$f = \frac{1}{2\pi L} \sqrt{\frac{L}{C} - R^2}$$

$$P = \sqrt{3} I_L V_L \cos \phi$$

$$P_1 = V_L I_L \cos (30 - \phi)$$

$$P_2 = V_L I_L \cos (30 + \phi)$$

$$\tan \phi = \frac{\sqrt{3} (P_2 - P_1)}{(P_2 + P_1)}$$

% Voltage regulation

$$= I_1 \frac{(R_e \cos \phi \pm X_e \sin \phi)}{v_1} \times \frac{100}{1}$$

$$Z_e = \sqrt{R_e^2 + X_e^2}$$

$$\% Z_e = \frac{I Z_e}{V} \times \frac{100}{1}$$

$$S_1 = S \frac{Z_2}{Z_1 + Z_2}$$

$$E = 2,222 k_d k_p Z \Phi f$$

$$I_r = \frac{E_r}{Z_r}$$

$$E_o = V_p \frac{Z_r}{Z_s}$$

$$\cos \phi_r = \frac{R}{Z_r}$$

$$s = \frac{2\pi T (n_s - n_r)}{2\pi T n_s}$$

$$L = 0,05 + 0,2 \text{ Lin } \frac{d}{r}$$

$$C = \frac{1}{36 \text{ Lin } \frac{d-r}{r}}$$

$$C = \frac{1}{18 \text{ Lin } \frac{de}{r}}$$

% Regulation

$$= \frac{V_s - V_R}{V_R} \times \frac{100}{1}$$

Marking Guidelines



higher education
& training

Department:
Higher Education and Training
REPUBLIC OF SOUTH AFRICA

APRIL 2014

NATIONAL CERTIFICATE

ELECTROTECHNICS N5

(8080074)

31 March 2014 (Y-Paper)
13:00 – 16:00

QUESTION 1

1.1 Shifting of brushes. ✓

Moving brushes forward in a generator and backwards in a motor.

Increasing the brush contact resistance. ✓

If carbon brushes are used instead of copper brushes, the resistance is much higher, therefore the current is much lower and the arc much smaller. ✓

Using commutating poles (interpoles). ✓

The interpole induces an EMF in the short-circuit coil, which lies directly under the interpole. ✓

The EMF in the interpole reduces the reactive voltage in the short-circuit coil, resulting in smooth commutation. ✓

(6)

$$\begin{aligned}
 1.2 \quad P &= 1\,600\,000\text{W}, V = 520, \text{pole} = 8, P = 4, Z = 240, C = 2 \text{ WAVE,} \\
 I_a &= P/V \\
 &= 1\,600\,000 / 520 \\
 &= 3\,076,92 \text{ A} \checkmark
 \end{aligned}$$

$$\begin{aligned}
 \text{Armature At/p} &= I_a Z / 4 p c \\
 &= \frac{3\,076,92 \times 240}{4 \times 4 \times 2} \checkmark \\
 &= 23\,076,9 \checkmark
 \end{aligned}$$

$$\begin{aligned}
 \text{Compole At/p} &= 1,6 \times 23\,076,9 \\
 &= 36\,923,04 \checkmark \\
 t/p &= \frac{\text{compole At/p}}{I_a} \\
 &= 36\,923,04 / 3\,076,92 \\
 &= 12 \text{ turns / pole} \checkmark
 \end{aligned}$$

(5)

$$\begin{aligned}
 1.3 \quad 1.3.1 \quad p &= 4 \quad (8 \text{ pole}) \\
 c &= 2p = 8 \\
 V &= 350 \quad N = 1\,200 \text{ r/min} \quad Z = 900 \\
 E &= V - I_a R_a \\
 &= 350 - (80 \times 0,6) \checkmark \\
 &= 302 \text{ V} \checkmark
 \end{aligned}$$

$$\begin{aligned}
 1.3.2 \quad E &= \frac{2 \Phi Z p N}{60 c} \\
 302 &= \frac{2 \times \Phi \times 900 \times 4 \times 1200}{60 \times 8} \checkmark \\
 \Phi &= \frac{302 \times 60 \times 8}{2 \times 900 \times 4 \times 1200} \checkmark \\
 &= \frac{1\,449\,60}{8\,640\,000} \checkmark \\
 &= 0,01678 \text{ Wb.} \checkmark
 \end{aligned}$$

(2)

$$\begin{aligned}
 1.3.3 \quad \text{Output} &= \frac{2 \pi NT}{60} \\
 E_{\text{la}} &= \frac{2 \pi NT}{60} \\
 302 \times 80 &= \frac{2 \pi 1200 T}{60} \quad \checkmark \quad (4)
 \end{aligned}$$

$$24\,160 \times 60 = 2 \pi \times 1200 T$$

$$T = \frac{1449600}{7539,8} \quad \checkmark$$

$$= 192,26 \text{ Nm.} \quad \checkmark$$

ALTERNATE SOLUTION

$$\begin{aligned}
 T &= 0,318 \text{ Ia/c ZP}\Phi \\
 &= 0,318 \times 80/8 \times 900 \times 4 \times 0,01678 \\
 &= 192,1 \text{ Nm} \quad (3) \\
 & \quad \quad \quad [20]
 \end{aligned}$$

QUESTION 2

$$2.1.1 \quad Z_3 = 9 + j11 = 14,21 \angle 50,7$$

$$Z_2 = 15 - j8 = 17 \angle -28,07$$

$$Z_1 = 11 + j15 = 18,6 \angle 53,75$$

$$\begin{aligned}
 Z_P &= \frac{Z_1 \times Z_2}{Z_1 + Z_2} \\
 &= \frac{18,6 \angle 53,75 \times 17 \angle -28,07}{11 + j15 + 15 - j8} \quad \checkmark
 \end{aligned}$$

$$= \frac{316,2 \angle 25,68}{26 + j7}$$

$$= \frac{316,2 \angle 25,68}{26,93 \angle 15,07} \quad \checkmark$$

$$= 11,74 \angle 10,61$$

$$= 11,54 + j2,16 \quad \checkmark$$

$$\begin{aligned}
 Z_T &= Z_3 + Z_P \\
 &= 9 + j11 + 11,54 + j2,16 \quad \checkmark \\
 &= 20,54 + j13,16 \\
 &= 24,39 \angle 32,65 \quad \checkmark \quad (5)
 \end{aligned}$$

QUESTION 3

3.1 Oil cooling ✓ (1)

Air cooling ✓ (1)

$$3.2 \quad \tan \phi_2 = X/R = 180/350 = 0,514$$

$$\phi_2 = 27,2 \quad \checkmark$$

$$\begin{aligned} R_t &= R_e + R_L (N_1/N_2)^2 \\ &= 0,4 + 350(1/5)^2 \\ &= 14,4 \, \Omega \quad \checkmark \end{aligned}$$

$$\begin{aligned} X_t &= X_e + X_L (N_1/N_2)^2 = 0,95 + 180(1/5)^2 \\ &= 8,15 \, \Omega \quad \checkmark \end{aligned}$$

$$\begin{aligned} Z_t &= \sqrt{(R_t)^2 + (X_t)^2} \\ &= \sqrt{(14,4)^2 + (8,15)^2} \\ &= 16,55 \, \Omega \quad \checkmark \end{aligned}$$

$$\begin{aligned} \text{or} \quad &= R_t + j X_L \\ &= 14,4 + j 8,15 \\ &= 16,55 \angle 29,5 \end{aligned}$$

$$I_1 = V_1 / Z_t = 310 / 16,55 = 18,73 \, \text{A} \quad \checkmark$$

$$\begin{aligned} V/\text{reg} &= I_1 (R_e \cos \phi + X_e \sin \phi) \\ &= \frac{18,73 (0,4 \cos 27,2 + 0,95 \sin 27,2)}{310} \quad \checkmark \\ &= 0,0477 (4,8 \%) \quad \checkmark \end{aligned}$$

$$V_{2(\text{NO LOAD})} = V_1 \times N_2/N_1 = 310 \times 5/1 = 1550 \, \text{V} \quad \checkmark$$

$$\begin{aligned} \text{Difference} &= V_{2(\text{NO LOAD})} \times \text{reg} \\ &= 1550 \times 0,048 \\ &= 74,4 \, \text{V} \quad \checkmark \end{aligned}$$

$$\begin{aligned} V(\text{terminal}) &= 1550 - 74,4 \quad (\cos \phi \text{ lagging}) \quad \checkmark \\ &= 1475,6 \, \text{V} \quad \checkmark \end{aligned}$$

(11)

3.3 3.3.1
$$I_P = \frac{V_P}{Z_1} = \frac{400}{30,31} < 0 \checkmark$$

$$= 13,12 < -16,88 \checkmark$$

$$I_L = \sqrt{3} I_P$$

$$= \sqrt{3} \times 13,12 \checkmark$$

$$= 22,72 \text{ A} \checkmark$$

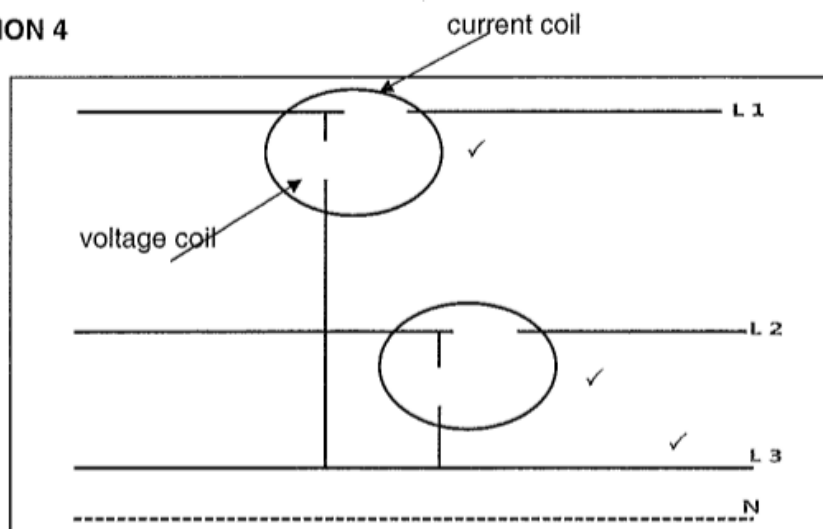
(5)

3.3.2
$$P_f = \cos \phi = \cos -16,88 \checkmark = 0,96 \text{ lagging} \checkmark$$

(2)
[20]

QUESTION 4

4.1



TWO WATTMETERS IN A THREE-PHASE CIRCUIT

Sketch = 3 marks; labelling = 3marks (6)

4.2 4.2.1
$$P_1 = 720 \text{ W} \quad P_2 = 3300 \text{ W}$$

$$\tan \phi = \frac{\sqrt{3}(P_2 - P_1)}{P_2 + P_1}$$

$$= \frac{\sqrt{3}(3300 - 720)}{3300 + 720} \checkmark$$

$$\begin{aligned} \tan \phi &= 1,11 \checkmark \\ \phi &= 47,98 \checkmark \\ \cos \phi &= 0,67 \checkmark \end{aligned}$$

(4)

$$\begin{aligned}
 4.2.2 \quad P1 &= -720 \text{ W} \\
 \text{Tan } \phi &= \frac{\sqrt{3} (P2 - P1)}{P2 + P1} \\
 &= \frac{\sqrt{3} [3300 - (-720)]}{3300 + (-720)} \checkmark \\
 &= 2,7 \checkmark \\
 \phi &= 69,68 \text{ (} \phi > 60^\circ \text{ lagging) } \checkmark \\
 \text{Cos } \phi &= 0,347 \checkmark \tag{4}
 \end{aligned}$$

$$\begin{aligned}
 4.3 \quad \text{Loop resistance} &= \frac{\rho l}{a} \\
 &= \frac{1,7 \times 72 \times 10^5}{10^6 \times \pi \times 0,9^2} \checkmark \\
 &= 4,81 \text{ } \Omega \checkmark \\
 \text{Loop inductance} &= 72 [0,05 + 0,2 \log_e d/r] \text{ mH } \checkmark \\
 &= 72 [0,05 + 0,2 \log_e (80/0,9)] \text{ mH } \checkmark \\
 &= 68,22 \text{ mH } \checkmark \\
 \text{Total capacitance} &= \frac{36}{36 \log_e \left(\frac{d-r}{r} \right)} \checkmark \\
 &= \frac{36}{36 \log_e \left(\frac{80 - 0,9}{0,9} \right)} \checkmark \\
 &= 0,23 \text{ } \mu\text{F} \checkmark \tag{8}
 \end{aligned}$$

(8)
[22]

QUESTION 5

$$\begin{aligned}
 5.1 \quad V &= 450 \text{ V} & s &= 0,05 & I &= 80 \text{ A [stator is } \Delta \text{ } I_p = 80/\sqrt{3}] \\
 & & \text{Pf} &= 0,8 & & \\
 I \text{ no load} & & &= 30 \text{ A [stator is } \Delta \text{ } I_p = 30/\sqrt{3}] & P \text{ no load} &= 3\,000 \text{ W} \\
 & & R &= 0,8 \, \Omega & &
 \end{aligned}$$

$$\begin{aligned}
 \text{Stator input} &= \sqrt{3} I_L V_L \cos \phi \\
 &= \sqrt{3} \times 80 \times 450 \times 0,8 \quad \checkmark \\
 &= 49\,883,06 \text{ W} \quad \checkmark
 \end{aligned}$$

losses

$$\begin{aligned}
 \text{Stator cu losses} &= 3 I^2 R = 3 (80 / \sqrt{3})^2 \times 0,8 \\
 &= 5\,120 \text{ W} \quad \checkmark
 \end{aligned}$$

$$\begin{aligned}
 \text{Rotor cu loss} &= s (\text{rotor input}) \\
 &= 0,05 (49\,883 - 5\,120) \\
 &= 2\,238,15 \text{ W} \quad \checkmark
 \end{aligned}$$

$$\begin{aligned}
 \text{Constant losses} &= P \text{ no load} - \text{Cu losses (no load)} \\
 &= 3\,000 - [3 \times (30 / \sqrt{3})^2 \times 0,8] \quad \checkmark \\
 &= 3\,000 - 720 \\
 &= 2\,280 \text{ W} \quad \checkmark
 \end{aligned}$$

$$\begin{aligned}
 \text{Total losses} &= \text{Stator cu losses} + \text{Rotor cu loss} + \text{Constant losses} \quad \checkmark \\
 &= 5\,120 + 2\,238 + 2\,280 \\
 &= 9\,638 \text{ W} \quad \checkmark
 \end{aligned}$$

$$\begin{aligned}
 \text{Output} &= \text{Input} - \text{losses} \\
 &= 49\,883 - 9\,638 \\
 &= 40\,245 \text{ W} \quad (40,25 \text{ kW}) \quad \checkmark
 \end{aligned}$$

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

$$= \frac{40\,245}{49\,883}$$

$$= 0,81 \text{ per unit.} \quad 81 \% \quad \checkmark$$

(10)

$$5.2 \quad 5.2.1 \quad f = n \times p = \frac{1\,450}{60} \times 3 \quad \checkmark$$

$$= 72,5 \text{ Hz} \quad \checkmark$$

(2)

5.2.2 No of slots = 3 slots x no of poles = 3 x 6 = 18 (per phase)

$$z/\text{ph} = 2\text{cond} \times 18 = 36$$

or

$$Z = 2 \times 9 \times 6 = 108 \quad \text{or} \quad Z = 36 \times 3 \text{ (PH)} = 108 \checkmark$$

$$Z/\text{ph} = 108 / 3 = 36 \checkmark \quad (3)$$

$$\text{Turns/ ph} = 36/2 = 18 \checkmark$$

5.2.3 $E / \text{ph} = 375 / \sqrt{3} = 216,51 \text{ V} \checkmark$

$$E / \text{ph} = 4 \times \phi \times f \times T_p \times K_f \times K_p \times K_d$$

$$216,51 = 4 \times \phi \times 72,5 \times 18 \times 1,11 \times 0,8 \times 0,96 \checkmark$$

$$\begin{aligned} 216,51 &= 4 \ 450 \ \phi \\ \phi &= 0,0487 \text{ Wb} \\ &= 48,7 \text{ mWb} \checkmark \end{aligned}$$

(3)
[18]

TOTAL: 100

N5 Electrotechnics is one of many publications introducing the gateways to Engineering Studies. This course is designed to develop the skills for learners that are studying toward an artisanship in the mechanical, engineering and related technology fields and to assist them to achieve their full potential in an engineering career.

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