

Electrical Engineering

Electrical Machines

Comprehensive Theory

with Solved Examples and Practice Questions



MADE EASY
Publications



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Electrical Machines

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Contents

Electrical Machines

Chapter 1

Magnetic Circuits 1

1.1 Magnetic Circuits.....	1
1.2 Leakage Flux	5
1.3 Fringing.....	6
1.4. Induced EMF	6
<i>Student Assignments-1</i>	7
<i>Student Assignments-2</i>	8

Chapter 2

Transformer 10

2.1 Operating Principle	10
2.2 Primary and Secondary.....	11
2.3 Linked Electric and Magnetic Circuits in Power Transformers	11
2.4 E.m.f. Equation of Transformer	13
2.5 Ampere-turns Relation.....	14
2.6 Leakage Reactance.....	15
2.7 Ideal Transformer	16
2.8 Exact Equivalent Circuit of a Transformer.....	20
2.9 Complete Phasor Diagram of Step Down Transformer [$N_1 > N_2$]	21
2.10 Equivalent Circuit Referred to Primary Side	22
2.11 Equivalent Circuit Referred to Secondary Side.....	22
2.12 Approximate Equivalent Circuit Referred to Primary...24	
2.13 Approximate Equivalent Circuit Referred to Secondary Side	25
2.14 Final Approximate Equivalent Circuit	25
2.15 Per Unit Value	25
2.16 Testing of Transformers.....	27

2.17 Voltage Regulation	32
2.18 Losses and Efficiency	36
2.19 Transformer Efficiency.....	37
2.20 Losses	37
2.21 Maximum Efficiency.....	38
2.22 η Considerations in Power Transformer & Distribution Transformer	46
2.23 All Day Efficiency	46
2.24 Auto Transformer	48
2.25 Tertiary Winding	53
2.26 3-Phase Transformers	56
2.27 3-Phase Transformer Connections.....	56
2.28 Open Delta or V Connection	62
2.29 3- ϕ to 2- ϕ Conversion (Scott Connection).....	64
2.30 Parallel Operation of Transformer	67
2.31 Load Sharing.....	67
2.32 Magnetizing Current Phenomenon	73
<i>Student Assignments-1</i>	76
<i>Student Assignments-2</i>	80

Chapter 3

Basics of Electromechanical Energy

Conversion 84

3.1 Principle of Energy Conversion.....	84
3.2 Coupling-field Reaction	86
3.3 Energy in Magnetic System.....	87
3.4 Field Energy and Mechanical Force	90
3.5 Multiple-Excited Magnetic Field Systems.....	95
3.6 Energy Conversion in Electric Field.....	100
3.7 Dynamical Eqns. of Electromechanical Systems	102

Chapter 4

Basic Concept of Rotating Electric Machines 108

4.1 Basic Structure of Rotating Electric Machines	108
4.2 Electromotive Force Generated by Rotation of a Coil	109
4.3 Conversion of Alternating emf to Unidirectional Voltage using Commutator Segments	109
4.4 D.C. Machine	110
4.5 Induction Machine	110
4.6 Synchronous Machine	110
4.7 MMF Space Wave of A Concentrated Coil	111
4.8 MMF of Distributed Single-Phase Winding	112
4.9 Mmf of Three-Phase Windings, Rotating Magnetic Field	113
4.10 Generated Voltages in AC Machines	115
4.11 Machine Torques	116
<i>Student Assignments</i>	119

Chapter 5

Direct Current Machine 120

5.1 Basic of Electric Machines	120
5.2 D.C. Machine Construction	120
5.3 Magnetic Circuit of A D.C. Generator	121
5.4 Equivalent Circuit of A D.C. Machine Armature	121
5.5 Types of D.C. Machine	122
5.6 Direct Current Machines Operation	122
5.7 E.M.F. Equation of D.C. Machine	123
5.8 (i) Types of Armature Windings	125
5.8 (ii) Lap and Wave Windings	125
5.9 Methods of Excitation	126
5.10 Electromagnetic Torque Equation	127
5.11 Classification of Direct Current Machines	128
5.12 Power Balance in Direct Current Machine	128
5.13 Separately Excited Machine (VBD Neglected)	129
5.14 Shunt Excited Machine	129
5.15 Long Shunt Generator	130
5.16 Short Shunt Generator	130
5.17 Condition for Maximum Power Transfer	130
5.18 Maximum Efficiency	132
5.19 Armature Reaction	135
5.20 Commutation	136
5.21 Compensating Winding	138

5.22 Interpoles	140
5.23 Operating Characteristic of D.C. Generators	142
5.24 Operating Characteristics of D.C. Motors	151
5.25 Starting of D.C. Motors	157
5.26 Three-Point D.C. Shunt Motor Starter	157
5.27 Four-Point Starter	158
5.28 D.C. Shunt Motor Starter Design	159
5.29 Speed Control of D.C. Motors	162
5.30 Testing of D.C. Machines	168
5.31 Electric Braking of D.C. Motors	172
5.32 Types of Electric Braking	172
5.33 Present-Day Uses of D.C. Machines	176
<i>Student Assignments-1</i>	176
<i>Student Assignments-2</i>	181

Chapter 6

Synchronous Machine 185

6.1 Advantages of Rotating Field Alternator	186
6.2 Construction of 3-Phase Synchronous Machines	186
6.3 Speed and Frequency	188
6.4 Excitation Systems for Synchronous Machines	190
6.5 Voltage Generation	191
6.6 E.m.f. Equation of Alternator	192
6.7 Armature Windings	193
6.8 Flux and Mmf Phasors in Synchronous Machines	202
6.9 Synchronous Machine Phasor Diagram	206
6.10 Open Circuit Characteristics	208
6.11 Short Circuit Characteristics	209
6.12 Zero Power Factor Characteristics	209
6.13 Methods to Determine Voltage Regulation	211
6.14 Power Angle Equation	215
6.15 (A) Effect of Change in Excitation at Constant (KW) Load	217
6.15 (B) Effect of Change in Load (KW) at Constant Excitation	218
6.16 V-Curve	220
6.17 Compounding Curve	220
6.18 Synchronous Condenser	224
6.19 Transition From Generator to Motor Action	226
6.20 Prime-Mover Characteristics	228
6.21 Parallel Operation of Alternators	229
6.22 Synchronizing Procedure	230

6.23 Synchronizing by A Synchroscope	232
6.24 Operation of Generator	233
6.25 Starting of Synchronous Motors.....	237
6.26 Hunting or Phase Swinging.....	237
6.27 Comparison between 3-Phase Synchronous and Induction Motors	239
6.28 Applications of Synchronous Motors.....	239
6.29 Salient Pole Machines.....	240
<i>Student Assignments-1</i>	247
<i>Student Assignments-2</i>	252

Chapter 7

3- ϕ Induction Machine256

7.1 Stator	256
7.2 Rotor	257
7.3 Induction Motor as a Transformer.....	257
7.4 Difference between IM and Transformer.....	258
7.5 MMF Induced in IM.....	258
7.6 Principle of Operation	260
7.7 Frequency of Induced emf.....	260
7.8 Stator Fed Induction Motor	261
7.9 Rotor Fed Induction Motor.....	264
7.10 Equivalent Circuit of 3- ϕ Induction Motor	264
7.11 Exact Equivalent Circuit Referred to Stator.....	265
7.12 Power Flow in 3- ϕ Induction Motor.....	266
7.13 Power Flow according to Steinmetz Model.....	267
7.14 Computational Convenience in Steinmetz Model.....	267
7.15 Thevenin's Equivalent of 3- ϕ Induction Motor (Steinmetz Model)	268
7.16 For Low Slip Region (Normal Operating Region)	269
7.17 For High Slip Region (Starting Region or Braking Region).....	270
7.18 Maximum Torque or Breakdown Torque or Pull out Torque or Stalling Torque	271
7.19 Slip at Maximum Torque.....	271
7.20 Determination of Equivalent Circuit from No-load & Blocked Rotor Tests.....	275
7.21 Circle Diagram	277
7.22 Construction of Circle Diagram.....	277
7.23 Performance Characteristics (load) of Induction Motor	281
7.24 Starters.....	282

7.25 Magnetic Locking (Cogging).....	287
7.26 Crawling.....	288
7.27 Deep Bar Rotor	290
7.28 Starting Technique of Slip-Ring Induction Motor	291
7.29 Speed Control of Induction Motor.....	292
7.30 Double Cage Motor.....	296
7.31 Induction Generator	297
<i>Student Assignments-1</i>	299
<i>Student Assignments-2</i>	303

Chapter 8

Fractional Kilowatt Motors308

8.1 Single-Phase Induction Motors.....	308
8.2 Double Revolving Field Theory.....	309
8.3 Equivalent Circuit.....	311
8.4 Split-Phase Motors.....	315
8.5 Types of Capacitor Split-Phase Motors.....	316
8.6 Shaded-Pole Motor.....	318
8.7 Applications	319
8.8 Single-Phase Synchronous Motors.....	319
8.9 Two-Phase Servomotor.....	321
8.10 Stepper Motors	322
8.11 Types of Stepper Motors.....	323
8.11 A - Torques Vs Pulse Rate	324
8.11 B - Different Types of Torque	324
8.12 Series Motor-Universal Motor.....	325
<i>Student Assignments-1</i>	326
<i>Student Assignments-2</i>	327

Chapter 9

Miscellaneous 329

9.1 Classification of Transformer Protection.....	329
9.2 Buchholz System	330
9.3 Windings and Insulation.....	332
9.4 Instrument Transformer	337
9.5 Current Transformer (CT).....	338
9.6 Voltage Transformer (VT) or Potential Transformer (PT)	339
9.7 Transformer Cooling	339
9.8 Conservator and Breather.....	340
9.9 Rating of the Transformer	340



Magnetic Circuits

Introduction

The electromagnetic system is an essential element of all rotating electric machinery and electromechanical device and static devices like the transformer. Electromechanical energy conversion takes place via the medium of a magnetic field or electrical field, but most practical converters use magnetic field as the coupling medium between electrical and mechanical systems. In transformers, the electrical energy convert from one electrical circuit to another electrical circuit via the medium of a magnetic field as the coupling medium between one electrical circuit to another electrical circuits. This is due to fact that the energy storing capacity of magnetic field is much greater than that of the electric field.

1.1 Magnetic Circuits

- The complete closed path followed by the lines of flux is called a magnetic circuit. In low power electrical machines, magnetic field is produced by permanent magnets. But in high-power electrical machinery and transformers, coupling magnetic field is produced by electric current.

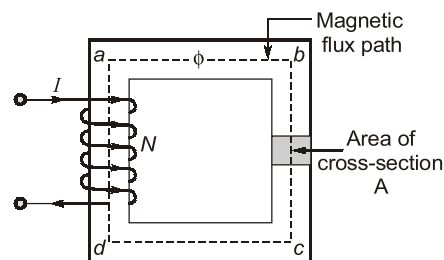


Figure-1.1 : Magnetic circuit

- In a magnetic circuit, the magnetic flux is due to the presence of a magnetomotive force same as in an electric circuit, the current is due to the presence of a electromotive force.
- The mmf is created by a current flowing through one or more turns.

$$MMF = \text{Current} \times \text{Number of turns in the coil}$$

$$f = MMF = NI \text{ (ampere-turns) or (ATs)}$$
- The magnetic flux ϕ may be defined as the magnetomotive force per unit reluctance.

$$\phi = \frac{\text{MMF}}{\text{Reluctance}}$$

where reluctance in magnetic circuit is same as resistance in electric circuit.

- It means the opposition offered by the magnetic flux is called reluctance,

$$Rl = \frac{l}{\mu A} \text{ AT/Wb}$$

where,

l = length of the magnetic path

A = area of cross-section normal to flux path, m^2 .

$\mu = \mu_0 \mu_r$ = permeability of the magnetic material

μ_r = relative permeability of the magnetic material

μ_0 = permeability of free space = $4\pi \times 10^{-7} \text{ H/m}$.

Here the concept of permeability can be understood in easy way with following examples.

Suppose a current I carrying conductor in a free space. (Figure 1.2).

According to the right hand grip rule, around the current carrying conductor a magnetic flux path is generated. Actually right hand grip rule stated that grip the conductor with thumb pointing in the direction of conductor current then four fingers give the direction of magnetic flux created by the current.

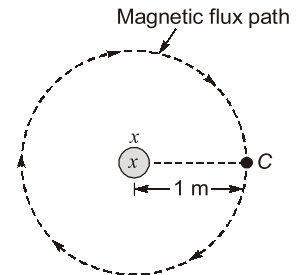
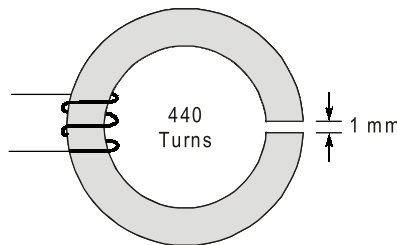


Figure-1.2

Example 1.1

An iron ring with a mean length of magnetic path of 20 cm and of small cross-section has an air gap of 1 mm. It is wound uniformly with a coil of 440 turns. A current of 1 A in the coil produces a flux density of $16\pi \times 10^{-3} \text{ Wb/m}^2$. Neglecting leakage and fringing, calculate the relative permeability of iron.



Solution:

The above figure shows an iron ring of mean length = 20 cm = ℓ_1

Length of air gap = 1 mm = $1 \times 10^{-3} \text{ m} = \ell_2$

Number of turns would = 440 turns = N

Current in the coil = 1 A = I

Flux density = $16\pi \times 10^{-3} \text{ Wb/m}^2 = B$

The electrical equivalent is as shown given figure,

Here,

R_1 = Reluctance of iron.

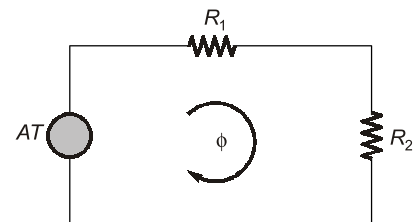
R_2 = Reluctance of air gap.

\therefore

$$AT = \phi(R_1 + R_2)$$

$$\phi = BA \text{ (A = Area)}$$

$$AT = BA \left(\frac{\ell_1}{\mu_0 \mu_1 A} + \frac{\ell_2}{\mu_0 A} \right) = \frac{B}{\mu_0} \left[\frac{\ell_1}{\mu_1} + \ell_2 \right]$$



$$\therefore \frac{\ell_1}{\mu_1} + \ell_2 = \frac{\mu_0 AT}{B} = \frac{4\pi \times 10^{-7} \times 440 \times 1}{16\pi \times 10^{-3}}$$

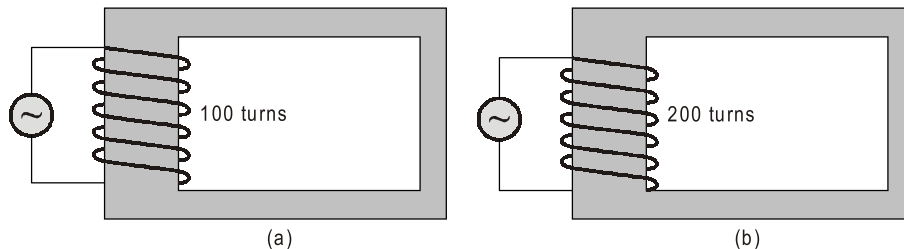
$$\frac{20 \times 10^{-2}}{\mu_r} + 1 \times 10^{-3} = 110 \times 10^{-4}$$

$$\therefore \frac{20 \times 10^{-2}}{\mu_r} = 11 \times 10^{-3} - 1 \times 10^{-3} = 10 \times 10^{-3}$$

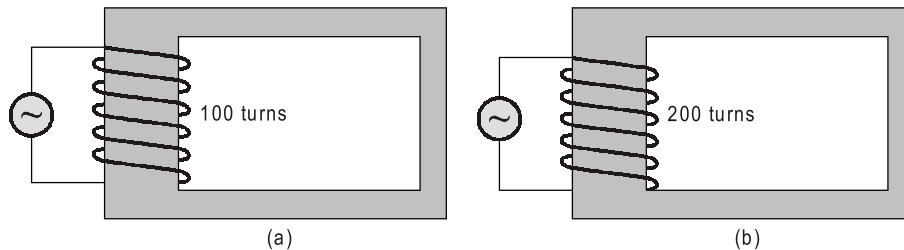
$$\therefore \mu_r = \frac{20 \times 10^{-2}}{10 \times 10^{-3}} = 20$$

Example 1.2

A magnetic core is excited with two different arrangements of exciting coils as shown in figure. The resistance of the exciting coils is negligible. The same sinusoidal voltage at a specified frequency is applied to the exciting coil in each case. If the flux density and the exciting current in case (a) are $B = 0.1$ tesla and $I = 8$ A, calculate the values of these quantities in case (b).



Solution:



Method-1:

The resistance of exciting coil is negligible,

$$B_1 = 0.1 \text{ tesla, } I_1 = 8 \text{ A}$$

We know,

$$AT = \text{flux} \times \text{reluctance}$$

$$\therefore AT = \phi \times \frac{\ell}{\mu_0 \mu_r A} = B \times \frac{\ell}{\mu_0 \mu_r}$$

Since,

$$B = \frac{\phi}{A}$$

$$AT = \text{Ampere-turns} = I \times T$$

I = Number of turns.

$$\therefore I_1 T_1 = B_1 \times \frac{\ell}{\mu_0 \mu_r}$$

$$\text{Similarly, } I_2 T_2 = B_2 \times \frac{\ell}{\mu_0 \mu_r}$$

$$\therefore \frac{I_1 T_1}{I_2 T_2} = \frac{B_1}{B_2}$$

$$\therefore \frac{8 \times 100}{I_2 \times 200} = \frac{0.1}{B_2}$$

$$\therefore I_2 = 40 B_2$$

$$\text{Induced emf} = -N \frac{d\phi}{dt}$$

$$\therefore \frac{E_1}{E_2} = \frac{-N_1 \frac{d\phi_1}{dt}}{-N_2 \frac{d\phi_2}{dt}} = \frac{N_1}{N_2} \times \frac{\phi_1}{\phi_2} = \frac{N_1 B_1}{N_2 B_2}$$

$$\text{Since, } E_1 = E_2 \text{ (same)}$$

$$N_1 B_1 = N_2 B_2$$

$$\therefore 100 \times 0.1 = 200 \times B_2$$

$$\therefore B_2 = \frac{100 \times 0.1}{200} = 0.05 \text{ tesla}$$

Method-2:

$$L \propto N^2$$

$$L_2 = 4 L_1$$

$$\Rightarrow X_2 = 4 L_1$$

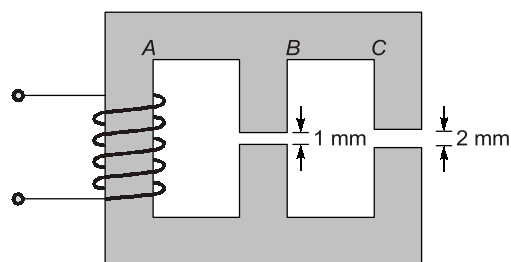
$$\Rightarrow I_2 = \frac{1}{4} I_1$$

$$MMF_2 = \frac{1}{2} MMF_1$$

$$\text{For same magnetic circuit, } B_2 = \frac{1}{2} B_1 = \frac{0.1}{2} = 0.05 \text{ tesla}$$

Example 1.3

In the magnetic circuit shown in figure, the areas of cross-section of limbs *B* and *C* are respectively 0.01 m^2 and 0.02 m^2 . Air gaps of lengths 1.0 mm and 2.0 mm respectively are cut in the limbs *B* and *C*. If the magnetic medium can be assumed to have infinite permeability and the flux in limb *B* is 1.0 Wb , the flux in limb *A* is



- (a) 3 Wb
(c) 2 Wb

- (b) 1.5 Wb
(d) 4 Wb

Solution :

Area of cross-section of limb $B = 0.01 \text{ m}^2$

Area of cross-section of limb $C = 0.02 \text{ mm}^2$

Air gap length = 1.0 mm for limb B

Air gap length = 2.0 mm for limb C

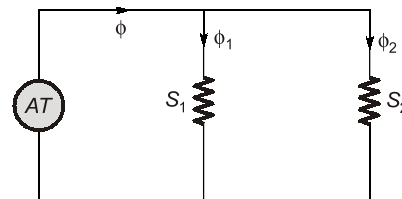
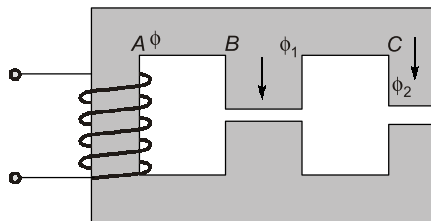
Magnetic medium is assumed as infinite permeability

\therefore Reluctance of iron path is zero since

$$R = \frac{1}{\mu}$$

Flux in limb,

$$B = 1.0 \text{ Wb}$$



where,

R_1 – reluctance of air gap of limb B

R_2 – reluctance of air gap of limb C

ϕ_1 – flux across air gap of limb B

ϕ_2 – flux across air gap of limb C

$$\therefore R_1 \times \phi_1 = R_2 \times \phi_2$$

$$\therefore \frac{\ell_1}{\mu_0 \times A_1} \times \phi_1 = \frac{\ell_2}{\mu_0 \times A_1} \times \phi_2$$

$$\therefore \phi_2 = \frac{A_2}{A_1} \times \frac{\ell_1}{\ell_2} \times \phi_1 = \frac{0.02}{0.01} \times \frac{1}{2} \times 1 = 1 \text{ Wb}$$

$$\therefore \text{Flux in limb A} = \phi_1 + \phi_2 = 1 \text{ Wb} + 1 \text{ Wb} = 2 \text{ Wb}$$

1.2 Leakage Flux

In Ideal magnetic circuits, all the flux produced by an exciting coil is confined to the desired magnetic path of negligible reluctance. But in practical magnetic circuits, a small amount of flux does follow a path through the surrounding air. Therefore, leakage flux may be defined as that flux which does not follow the intended path in a magnetic circuit. Leakage flux does exist in all practical ferromagnetic device. Its effect on the analysis of electrical machinery is carried out by replacing it by an equivalent leakage reactance.

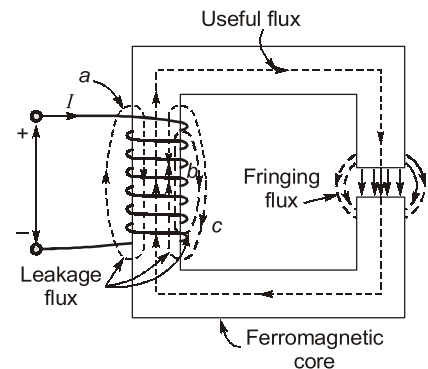


Figure-1.3 : Leakage flux

1.3 Fringing

At an air-gap in a magnetic core, the flux fringes out into neighboring air path as shown in the given Figure-1.3. Longer the air gap, more is the flux fringing. The effect of fringing flux is to increase the effective cross-sectional area of the air gap. As a result, flux density in the air gap is not uniform and average flux density gets reduced,

$$\therefore B = \frac{\phi}{A}$$

If area of air gap increases, then total area of core with consideration of air gap increases. Then average flux density gets reduced.

1.4. Induced EMF

Faraday's law of electromagnetic induction states that an e.m.f. is induced in a coil when the magnetic flux linking this coil change with time.

$$e \propto \frac{d\Psi}{dt} \propto \frac{d(\phi N)}{dt}$$

$$e = - \frac{Nd\phi}{dt}$$

where,

e = e.m.f. induced in volts

N = Number of turns in the coil

$\Psi = N\phi$ = Flux linkages with the coil, wb-turns

t = time, seconds.

Here minus (–) sign shows that induced current opposes very cause of its production. This theory is called Lenz's law. According to this law; the induced current develops a flux which always opposes the change responsible for inducing this current.

Example 1.4

The laws of electromagnetic induction (Faraday's and Lenz's laws) are summarized in the following equation:

(a) $e = iR$

(b) $e = \frac{Ldi}{dt}$

(c) $e = - \frac{d\Psi}{dt}$

(d) None of these

Solution: (c)

Example 1.5

“In all cases of electromagnetic induction, an induced voltage will cause a current to flow in a closed circuit in such a direction that the magnetic field which is caused by the current will oppose the change that produces the current” is the original statements of

(a) Lenz's law

(b) Faraday's law of magnetic induction

(c) Fleming's law

(d) Ampere's law

Solution: (a)



**Student's
Assignments****1**

Q.1 A cast steel electromagnet has an airgap of length 2 mm and an iron path of length 30 cm. Find the number of ampere turns necessary to produce a flux density of 0.8 Wb/m² in the gap. Neglect leakage and fringing. (For 0.8 Wb/m² cast steel requires 750 AT/m).

Q.2 A cast steel ring has a circular cross-section 3 cm in diameter and a mean circumference of 80 cm. The ring is uniformly wound with 600 turns.

- Estimate the current required to produce a flux of 0.5 m Wb in the ring.
- If a saw cut 2 mm wide is made in the ring, find approximately the flux produced by the current found in (a),
- Find the current value which will give the same flux as in (a).

Assume the gap density to be the same as in the iron and neglect fringing.

(For 0.705 Wb/m² cast steel requires 670 AT/m and 365 AT/m will produce a flux density of 0.15 Wb/m²)

Q.3 An iron ring of mean length 50 cm has an air gap of 1 mm and a winding of 200 turns. If the permeability of the iron is 300 when a current of 1 A flows through the coil, find the flux density.

**Student's
Assignments****1****Explanations****1. Solution:**

The required for air gap

$$\begin{aligned} AT &= \frac{B}{\mu_0} l = \frac{0.8}{4\pi \times 10^{-7}} \times 2 \times 10^{-3} \\ &= 1273 \end{aligned}$$

For 0.8 Wb/m² cast steel requires 750 AT/m

∴ AT required for iron path

$$= 750 l = 750 \times 0.3 = 225 \text{ AT}$$

∴ The total AT required

$$= 1273 + 225 \approx 1498$$

2. Solution:

(a) The cross-sectional area

$$\begin{aligned} &= \frac{\pi d^2}{4} \times 10^{-4} = \frac{\pi \times 9}{4} \times 10^{-4} \\ &= 7.068 \approx 7.1 \times 10^{-4} \text{ m}^2 \end{aligned}$$

The flux density,

$$\begin{aligned} B &= \frac{\phi}{A} = \frac{0.5 \times 10^{-3}}{7.1 \times 10^{-5}} = \frac{5}{7.1} \\ &= 0.705 \text{ Wb/m}^2 \end{aligned}$$

$$\therefore \text{AT required} = 670 \times 0.8 = 536$$

∴ The current required

$$= \frac{AT}{N} = \frac{536}{600} = 0.89 \text{ A}$$

(b) If all the available 536 AT is used by the air gap

$$H = \frac{536}{2 \times 10^{-3}} = 268 \times 10^3$$

$$\begin{aligned} B &= \mu_0 H = 4\pi \times 10^{-7} \times 268 \times 10^3 \\ &= 0.33 \text{ Wb/m}^2 \end{aligned}$$

Since same AT are required by the iron path as well the actual flux density produced will be lower than this assume a flux density of 0.15 Wb/m².

The AT required for air gap

$$= 536 \times \frac{0.15}{0.33} = 244$$

The AT available for iron

$$= 536 - 244 = 292$$

$$\text{or, } \frac{292}{0.8} = 365 \text{ AT/m}$$

$$\begin{aligned} \therefore \text{The approximate flux density} \\ &= 0.15 \text{ Wb/m}^2 \end{aligned}$$

(c) For 0.705 Wb/m² AT required by the 2 mm air gap

$$\begin{aligned} &= \frac{B}{\mu_0} l = \frac{0.705}{4\pi \times 10^{-7}} \times 2 \times 10^{-3} \\ &= 1122 \end{aligned}$$

∴ The total AT required

$$= 1122 + 536 = 1658$$

$$\therefore \text{The current} = \frac{1658}{600} \approx 2.763 \text{ A}$$

3. Solution:

The reluctance,

$$R = \frac{l}{A\mu}$$

∴ The total reluctance

$$\begin{aligned} &= R_1 + R_2 \\ &= \frac{1 \times 10^{-3}}{A\mu_0} + \frac{0.5}{300A\mu_0} \\ &= \frac{8 \times 10^{-3}}{3A\mu_0} \text{ AT/Wb} \end{aligned}$$

$$\therefore \text{The total flux} = \frac{\text{Total AT}}{\text{Reluctance}} = \frac{200 \times 1 \times 3A\mu_0}{8 \times 10^{-3}}$$

$$\begin{aligned} \therefore \text{The flux density} &= \frac{600 \times \mu_0}{8 \times 10^{-3}} \text{ Wb/m}^2 \\ &= \frac{600 \times 4\pi \times 10^{-7} \times 10^3}{8 \times 10^{-3}} \\ &= 94.2 \text{ mWb/m}^2 \end{aligned}$$

Student's
Assignments

2

Q.1 Why the transformer stampings are varnished before being used to build the core?

- To increase air-gap between stampings
- To reduce hysteresis loss
- To reduce eddy current loss
- To provide strength to the core

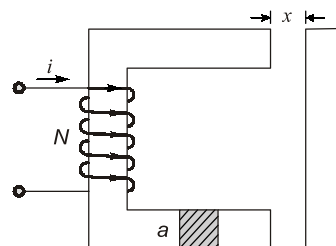
Q.2 Maximum flux established in an AC excited iron core is determined by

- impressed frequency only
- impressed voltage only
- both impressed voltage and frequency
- reluctance of the core

Q.3 A circular iron core has an air-gap cut in it and is excited by passing direct current through a coil wound on it. The magnetic energy stored in the air-gap and the iron core is

- in inverse ratio of their reluctance
- in direct ratio of their reluctances
- equally divided among them
- energy resides wholly in the iron core

Q.4 In the electromagnetic relay of given figure below the reluctance of the iron path is negligible. The coil self-inductance is given by the expression



- $\mu_0 N^2 a/x$
- $\mu_0 N/2 ax$
- $\mu_0 N^2 a/2x$
- $\mu_0 N^2/2 ax$

Q.5 An iron-cored choke with 1 mm air-gap length, draws 1 A when fed from a constant voltage AC source of 220 V. If the length of air-gap is increased to 2 mm, the current drawn by the choke would

- become nearly one half
- remain nearly the same
- become nearly double
- become nearly zero

Q.6 Match List-I (Electric and Magnetic Quantities) with List-II (SI Units) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Flux	1. AT/Wb
B. Magnetomotive force	2. Wb
C. Reluctance	3. Wb/AT
D. Permeance	4. AT

Codes:

	A	B	C	D
(a)	1	3	4	2
(b)	3	1	4	2
(c)	4	3	2	1
(d)	2	4	1	3

Q.7 Match List-I (Electric and Magnetic Quantities) with List-II (SI Units) and select the correct answer using the codes given below the lists:

List-I	List-II
A. Flux linkage	1. AT/m
B. Flux density	2. Wb T or V.s
C. Magnetic field strength	3. H/m
D. Permeability	4. Wb/m ² or Tesla

Codes:

	A	B	C	D
(a)	4	3	2	1
(b)	4	2	1	3
(c)	1	3	4	2
(d)	2	4	1	3

Q.8 The unit of inductance is

- (a) Wb T/A
- (b) V s/A
- (c) H-turns²
- (d) All three are equivalent

Q.9 Building steel core out of stampings reduces eddy current loss because,

- (a) it increases core resistivity.
- (b) it increases the effective length of eddy current paths thereby increasing effective resistance to the flow of eddy currents.

- (c) it increases core permeability.
- (d) it reduces the effective length of eddy current path, thereby reducing effective resistance to the flow of eddy currents.

Q.10 Magnetostriction noise in ferromagnetic materials is caused by

- (a) hysteresis loss
- (b) eddy current loss
- (c) changes in linear dimensions of crystals under DC excitation
- (d) changes in linear dimension of crystals under AC excitation

Answer Key :

- | | | | | |
|---------------|---------------|---------------|---------------|----------------|
| 1. (c) | 2. (c) | 3. (b) | 4. (c) | 5. (c) |
| 6. (d) | 7. (d) | 8. (d) | 9. (b) | 10. (d) |

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