

Instrumentation Engineering

Electrical Machines

Comprehensive Theory

with Solved Examples and Objective Practice Set



MADE EASY
Publications



MADE EASY Publications Pvt. Ltd.

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016

E-mail: infomep@madeeasy.in

Contact: 011-45124660, 8860378007

Visit us at: www.madeeasypublications.org

Electrical Machines

© Copyright by MADE EASY Publications Pvt. Ltd.

All rights are reserved. No part of this publication may be reproduced, stored in or introduced into a retrieval system, or transmitted in any form or by any means (electronic, mechanical, photo-copying, recording or otherwise), without the prior written permission of the above mentioned publisher of this book.

First Edition : 2020

Second Edition : 2021

Third Edition : 2022

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</i>	7

Chapter 2

Transformer	10
2.1 Operating Principle	10
2.2 Primary and Secondary.....	11
2.3 Linked Electric & Magnetic Circuits in Power Trans	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 ...	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 Equi. 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 Efficiency Considerations in Power Transformer and Distribution Transformer	46
2.23 All Day Efficiency	46
<i>Student Assignments</i>	49

Chapter 3

Basics of Electromechanical Energy Conversion	55
3.1 Principle of Energy Conversion.....	55
3.2 Coupling-field Reaction	57
3.3 Energy in Magnetic System.....	58
3.4 Field Energy and Mechanical Force	61
3.5 Multiple-Excited Magnetic Field Systems.....	66
3.6 Energy Conversion in Electric Field	71
3.7 Dynamical Equations of Electromechanical Systems.....	73

Chapter 4

Basic Concept of Rotating Electric Machines	79
4.1 Basic Structure of Rotating Electric Machines	79
4.2 Electromotive Force Generated by Rotation of a Coil..	80
4.3 Conversion of Alternating emf to Unidirectional Voltage using Commutator Segments	80
4.4 D.C. Machine	81
4.5 Induction Machine	81
4.6 Synchronous Machine.....	81
4.7 MMF Space Wave of A Concentrated Coil	82
4.8 MMF of Distributed Single-Phase Winding.....	83
4.9 Mmf of Three-Phase Windings, Rotating Magnetic Field ..	84
4.10 Generated Voltages in AC Machines	86
4.11 Machine Torques	87
<i>Student Assignments</i>	90

Chapter 5

Three Phase Induction Machine91

5.1 Stator	91
5.2 Rotor	92
5.3 Induction Motor as a Transformer.....	92
5.4 Difference between IM and Transformer.....	93
5.5 MMF Induced in IM.....	93
5.6 Principle of Operation	95
5.7 Frequency of Induced emf.....	95
5.8 Stator Fed Induction Motor.....	96
5.9 Rotor Fed Induction Motor	99
5.10 Equivalent Circuit of 3-f Induction Motor.....	99
5.11 Exact Equivalent Circuit Referred to Stator.....	100
5.12 Power Flow in 3-f Induction Motor	101
5.13 Power Flow according to Steinmetz Model.....	102
5.14 Computational Convenience in Steinmetz Model.....	102
5.15 Thevenin's Equivalent of 3-f Induction Motor	103

5.16 For Low Slip Region (Normal Operating Region)	104
5.17 For High Slip Region.....	105
5.18 Maximum Torque or Breakdown Torque	106
5.19 Slip at Maximum Torque.....	106
5.20 Determination of Equivalent Circuit from No-load and Blocked Rotor Tests.....	110
5.21 Circle Diagram.....	112
5.22 Construction of Circle Diagram.....	112
5.23 Performance Characteristics (load) of Induction Motor...	116
5.24 Starters.....	117
5.25 Magnetic Locking (Cogging).....	122
5.26 Crawling.....	123
5.27 Deep Bar Rotor	125
5.28 Starting Technique of Slip-Ring Induction Motor	126
5.29 Speed Control of Induction Motor.....	127
5.30 Double Cage Motor	131
Student Assignments	132



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.

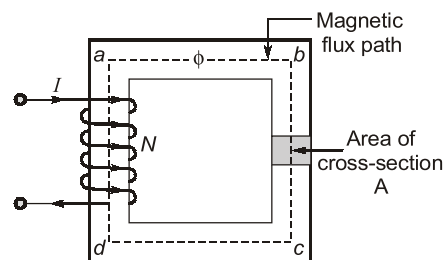


Figure-1.1 : Magnetic circuit

- 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 .

$\mu = \mu_0 \cdot \mu_r$ = 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.

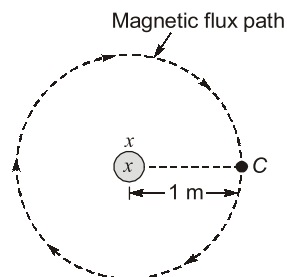
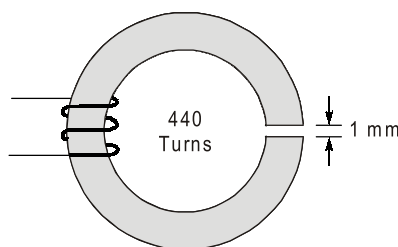


Figure-1.2

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.

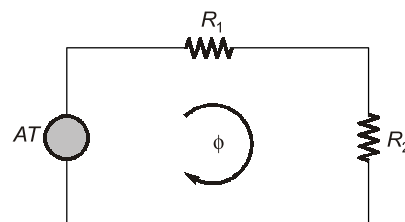
R_2 = Reluctance of air gap.

\therefore

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

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

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



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

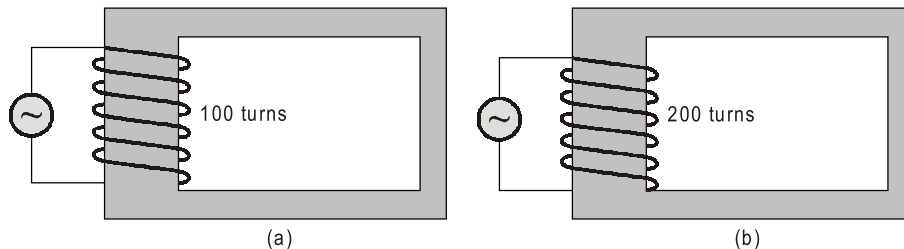
$$\frac{20 \times 10^{-2}}{\mu_r} + 1 \times 10^{-3} = 110 \times 10^{-4}$$

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

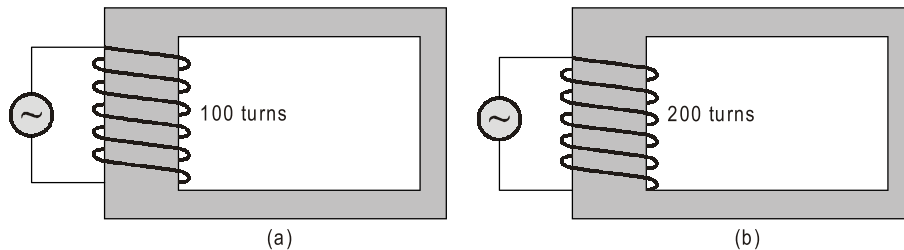
$$\therefore \mu_r = \frac{20 \times 10^{-2}}{10 \times 10^{-3}} = 20$$

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.

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

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

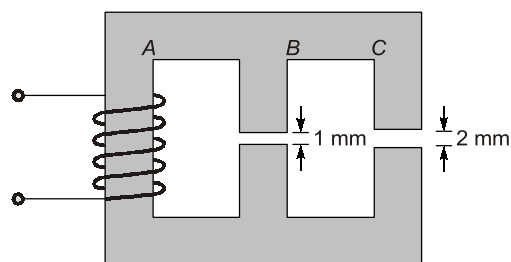
$$\begin{aligned} \therefore \frac{I_1 T_1}{I_2 T_2} &= \frac{B_1}{B_2} \\ \therefore \frac{8 \times 100}{I_2 \times 200} &= \frac{0.1}{B_2} \\ \therefore I_2 &= 40 B_2 \\ \text{Induced emf} &= -N \frac{d\phi}{dt} \\ \therefore \frac{E_1}{E_2} &= \frac{-N_1 \frac{d\phi_1}{dt}}{-N_2 \frac{d\phi_2}{dt}} = \frac{N_1}{N_2} \times \frac{\phi_1}{\phi_2} = \frac{N_1 B_1}{N_2 B_2} \\ \text{Since, } E_1 &= E_2 \text{ (same)} \\ N_1 B_1 &= N_2 B_2 \\ \therefore 100 \times 0.1 &= 200 \times B_2 \\ \therefore B_2 &= \frac{100 \times 0.1}{200} = 0.05 \text{ tesla} \end{aligned}$$

Method-2:

$$\begin{aligned} L &\propto N^2 \\ L_2 &= 4 L_1 \\ \Rightarrow X_2 &= 4 L_1 \\ \Rightarrow I_2 &= \frac{1}{4} I_1 \\ MMF_2 &= \frac{1}{2} MMF_1 \\ \text{For same magnetic circuit, } B_2 &= \frac{1}{2} B_1 = \frac{0.1}{2} = 0.05 \text{ tesla} \end{aligned}$$

Example 1.3

In the magnetic circuit shown in figure, the areas of cross-section of limbs *B* and *C* are respectively 0.01 m² and 0.02 m². 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

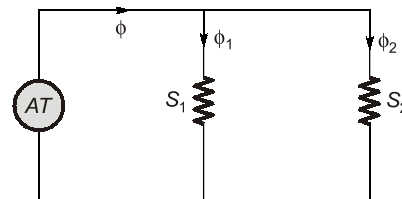
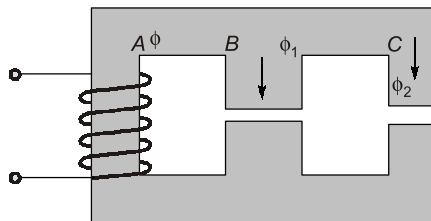
Magnetic medium is assumed as infinite permeability

\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.

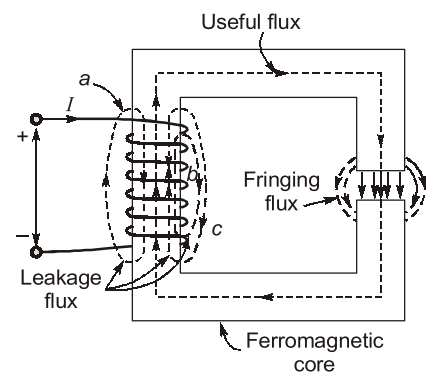


Figure-1.3 : Leakage flux

**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.

(a) Estimate the current required to produce a flux of 0.5 m Wb in the ring.

(b) If a saw cut 2 mm wide is made in the ring, find approximately the flux produced by the current found in (a),

(c) 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

$$= 536 - 244 = 292$$

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

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

(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

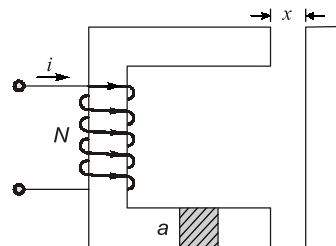
Q.2 Maximum flux established in an AC excited iron core is determined by

- 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