ELEC2213: Electrical Machines

Lectures 36 hours
Tutorials 6 hours
Exam 65% (2h)
Coursework CAD 20%
Laboratories 3 Experiments of 5% each (15% total)

Handouts will be made available online each week
Aims and Objectives

Having successfully completed this module, you will be able to:

• Identify different types of electrical machines, compare and contrast their use and operation
• Appreciate the complexity of designing electromechanical devices
• Derive equations describing operations of machines, formulate their equivalent circuits
• Analyse simple problems related to electrical machine operation
• Evaluate the role of CAD in engineering design, identify methods of solving large systems of equations
Learning Outcomes

You should be able to demonstrate knowledge of:

• Theory of electromechanical energy conversion
• The fundamental torque equation, rotating and oscillating fields
• The principles of operation of electrical generators and motors
• Fundamental characteristics of various types of machines
• Construction and design issues associated with electrical machines
• CAD systems for electromagnetics
Skills

• Analyse the performance and explain the characteristics of actual machines (Lab)

• Apply equivalent circuits to performance prediction, interpret results and correlate them with theoretical predictions (Lab)

• Use electromagnetic CAD packages and write a technical report (CW)

• Work in a small team to conduct simple experiments on rotating electrical machines (synchronous and induction machines) and transformers (Lab)

• Undertake virtual prototyping of electromagnetic devices (CW)
Assessment

• 2 hours Exam worth 65% (answer 3 Questions out of 4)

• Coursework 20% - CAD Prototyping of a magnetic plunger
  • Will be made available on 6\textsuperscript{th} of February
  • Deadline 8\textsuperscript{th} of March)

• 3 Laboratories, 5% each (dates TBC by Dr David Oakley):
  • Transformer - 12\textsuperscript{th} to 23\textsuperscript{rd} of February
  • Induction Machine – 5\textsuperscript{th} to 16\textsuperscript{th} of March
  • Synchronous Machine – 16\textsuperscript{th} to 27\textsuperscript{th} of April
Syllabus 1/3

• Introduction, review of magnetic and power circuits
  • 3 phase systems, star and delta connections
  • Active, reactive, apparent, complex power, power diagrams, power factor
  • Phasor diagrams, complex impedance, impedance triangle

• 3 phase transformers
  • Principles of operation, construction, equivalent circuit, open- and short-circuit tests, regulation, three-phase connections, parallel operation, auto-transformer, 3rd harmonic phenomenon, unbalanced loading

• Introduction to rotating machines
  • Underlying concepts, fundamental torque equation, rotating field principle, air-gap mmf and permeance, 3-phase windings, winding factors.

• Induction machines, polyphaser induction motors
  • Squirrel-cage and wound-rotor motors, equivalent circuit (measurement, parameters), machine equations, speed/torque curves, circle diagram, starting performance, speed control, single-phase induction motor
Syllabus 2/3

• Synchronous machines
  • Generated emf, output equation, armature reaction, phasor diagram, synchronous reactance, equivalent circuit, open- and short-circuit characteristics, regulation, load angle, saturation effects, salient-pole machine, synchronising, V curves, power factor correction.

• Numerical solution of large systems of equations
  • Finite element method for virtual prototyping (coursework)
  • Analysis of errors, matrix and vector norms, condition numbers, comparison of methods

• The CAD environment
  • Pre- and post-processing, automatic and adaptive meshing, design environment, optimisation, future trends
Syllabus 3/3

• Direct current machines
  • Construction, basic equations, steady-state characteristics, windings, field form and armature reaction, commutation and use of interpoles, starting and speed control

• Single-phase AC motors
  • Shaded-pole, universal, permanent magnet and reluctance machines and their applications

• Case studies / Examples
  • Wind turbines, electric vehicles, maglev, small appliances
Resources


John Hindmarsh, Electrical Machines and their Applications, Publisher: Butterworth-Heinemann, 1995

J. Weidauer, R. Messer, Electrical Drives, Publisher: Publicis Publishing, 2014


Hammond P & Sykulski J K, Engineering Electromagnetism - Physical Processes and Computation, Oxford University Press, 1994,

Denis O'Kelly, Performance and Control of Electrical Machines, Publisher: Mc-Graw Hill Book Company, 1991

K Karsai, D Kereny, L Kiss, Studies in Electrical and Electronic Engineering 25, Large Power Transformers, Publisher: Elsevier, 1987


Charles I Hubert, Electric Machines, Theory, Operation, Application, Adjustment and Control, Publisher: Macmillan Publishing Company, 1991

Lectures / Tutorials

• Timetabled 1 hour sessions Tuesdays (16:00-17:00) starting week 20
• Feel free to ask me any questions you might have related to the previous or upcoming session, laboratories, tutorials or coursework during those breaks
• Let me know if I speak too fast, too quiet, too slow, too loud
• There will be regular questions from me during the sessions
• Tutorials will cover the sort of calculations that might come for exams...
Lectures

• Week 1 – Introduction & Transformers
• Week 2 – Transformers & Coursework Introduction
• Week 3 – Rotating Machines: Introduction, Construction
• Week 4 – Asynchronous / Induction Machine
• Week 5 – Synchronous Machines
• Week 6 – DC Machines
• Week 7 & 8 – Special Machines, Examples
• Weeks 10 & 11: Revision
Tutorials

• Problem sheets online (intranet) “ELEC2213 Exercises.pdf”

• 5 sheets, containing problems for:
  • Transformers (sheet 1)
  • Electrical machines windings (sheet 2)
  • Synchronous machines (sheet 3)
  • Induction machines (sheet 4)
  • DC machines (sheet 5)

• Timetabled tutorials will cover these sheets
Coursework

• Coursework document will be published on Tuesday the 6th

• Introduction of the coursework in the lectures that week with Q&A

• Use of MagNet for electromagnetic devices

• 20% of total marks
Introduction to Electrical Machines
Session Aims

• Give historical context to electrical machines
• Review of power circuits: complex power and impedance, power factor, phasor diagrams
• Review three-phase systems, star & delta connections
• Introduce basic concepts of electrical machines and simple magnetic circuits
• Introduce the ideal transformer
• Derive the equivalent circuit of a transformer
What is an Electrical Machine?

- What is an electrical machine?

- Why are electrical machines so common?
A Short History Lesson
1800 Alessandro Volta (Italian) invents battery
1820 Hans Christian Oersted (Danish) first observes magnetic field by deflecting a compass needle, André-Marie Ampere invents Solenoid
1821 Michael Faraday (British) creates experiments for demonstration of electromagnetic rotation
Before 1830 Istvan Jedlik (Hungarian) and Johan Michael Ekling (Austrian) build independently rotary machines (Ekling according to plans by Austrian Andreas von Baumgartner)
1831 Michael Faraday discovers and investigates electromagnetic induction
Real electric machines

- 1834 in May Moritz Hermann Jacobi (Prussian, later Russian) builds first electrical motor with a mechanical power of 15 Watts

- 1835 Francis Watkins (British) realises that motors can also work as generators

- 1837 Thomas Davenport (American) receives first patent on motor

- 1838 Jacobi demonstrates first electrically powered boat (300 W)
• 1842 Robert Davidson (Scottish) constructs first electrical powered locomotive, he makes trial runs with a 5-ton, 4.8 m long locomotive (1 hp / 0.74 kW) on the railway line from Edinburgh to Glasgow, with a **speed of 4 mph**.

• In the following years come a flood of patents regarding electrical machines (over 100 in Britain and US alone)

• 1856 Werner Siemens (German) He is the first one to place a winding into slots. Revolutionary design of electrical machines. All previous designs disappear from the market during the following decades. To date, almost all electric motors are built with windings in slots.
Maxwell summarises all the current knowledge of electromagnetism into 4 fundamental equations, which are still valid today.

Gauss’ law for electricity: \[ \oint E \cdot d\vec{A} = \frac{q}{\varepsilon_0} \] \[ \nabla \cdot E = \frac{\rho}{\varepsilon_0} \] Electric field leaving a volume is prop. to the charge inside

Gauss’ law for magnetism: \[ \oint B \cdot d\vec{A} = 0 \] \[ \nabla \cdot B = 0 \] No magnetic monopoles

Faraday’s law of induction: \[ \oint E \cdot d\vec{s} = -\frac{d\Phi_B}{dt} \] \[ \nabla \times E = -\frac{\partial B}{\partial t} \] Voltage accumulated around a closed circuit is prop. to time rate of changing magnetic field

Ampere’s law: \[ \oint B \cdot d\vec{s} = \mu_0 \frac{1}{c^2} \frac{\partial}{\partial t} \int E \cdot d\vec{A} \] \[ \nabla \times B = \mu_0 \left( J + \varepsilon_0 \frac{\partial E}{\partial t} \right) \] Change in electric current is prop. to the magnetic field circulating about the area
The Three Phase System

• 1882 Nikola Tesla (Croatian, later US-American) first formulates ideas about multi-phase systems while studying in Graz, Austria
• 1885 Galileo Ferraris (Italian) builds first 2-phase induction motor
• 1887 Friedrich August Haselwander (German) builds first 3-phase synchronous generator with salient poles (however, the German postal authority prohibits its use)
• 1889 Michael Dolivo-Dobrovolsky builds first 3-phase cage induction motor.
• 1893 the first 13 km long AC power transmission system is installed in Sweden, following work by Jonas Wenström (Swedish)
Reduction in Motor Mass
(N. Glew, IEE Colloquium 99/178, 1999)

W/kg

[Graph showing the trend of reduction in motor mass from 1900 to 2000 with W/kg on the y-axis and years on the x-axis.]
Modern Power Systems
And the electrical machines that sustain them.
Introduction

Much of our current High Voltage infrastructure comes from a time...
The Old Ways

Power Flow
Intelligent Grids

No unidirectional power flow.

Result of...
- Government deregulation
- Social and economic changes
Extra high voltage transmission network

High voltage transmission network

Medium voltage distribution network

Low voltage distribution network

Large scale

Medium size

Small scale
By 2020:
• Every member state should have 10% interconnection capacity

By 2030:
• Interconnection target raised to 15%

Status 2014:

above 10%:
AT - 29%
BE - 17%
BG - 11%
CZ - 17%
DE - 10%
DK - 44%
FI - 30%
FR - 10%
GR - 11%
HR - 69%
HU - 29%
LU - 245%
NL - 17%
SI - 65%
SE - 26%
SK - 61%

below 10%:
IE - 9%
IT - 7%
RO - 7%
PT - 7%
EE[4] - 4%
LT4 - 4%
LV4 - 4%
UK - 6%
ES - 3%
PL - 2%
CY - 0%
MT - 0%

Market Liberalisation

Before 1996
• Power Generation, Transmission and Distribution Networks usually combined and nationalised
• No choice for consumer or business where they receive their energy from
• Often fixed plans with no flexibility

Now:
• Separate companies are involved in Power Generation, Transmission and Distribution of Power.
• Consumer and businesses have free choice of electricity suppliers and switching is easy.
UK:

**Generation**
- Aquamarine Power
- BES Utilities
- Centrica
- Drax Group
- E.ON UK
- Ecotricity
- EDF Energy
- Flow Energy
- Green Energy UK
- Northern Electric
- REG
- RWE UK
- Southern Electric
- The Co-Operative
- Vattenfall UK

**Transmission**

**Examples:**
- Aquamarine Power
- BES Utilities
- Centrica
- Drax Group
- E.ON UK
- Ecotricity
- EDF Energy
- Flow Energy
- Green Energy UK
- Northern Electric
- REG
- RWE UK
- Southern Electric
- The Co-Operative
- Vattenfall UK

Turbo Generator
mechanical force from steam or gas turbine
Turbo Generator
stator and rotor
Hydro Generators
mechanical force from falling water
Hydro Generator
stator and rotor
Wind Turbines

• Very large turbines as direct-drive turbines (no gearbox).
• 8 MW direct drive turbines operational (synchronous generator),
• Asynchronous generators are now mostly used as doubly-fed generator in medium to large turbines.
Large Electric Motor
Squirrel Cage Induction Motor stator and rotor winding
Stator Winding Construction
magnetic steel, copper conductors and electrical insulation

Cross-section of a three turn stator coil

Multi-turn coil being inserted in a laminated steel stator core
MULTITURN STATOR COIL SLOT CROSS-SECTION
Transportation & Daily Life
8,000 kW to 16,000 kW traction power
15 kV 16 2/3 Hz AC
3 kV DC 25 kV 50 Hz AC

568 kW
3 phase induction

MagLev: 25 kV AC
603 km/h / 375 mph

DC & Inverter

AC 3 phase or DC with inverter
few 100 W to few kW
Phasors and Complex Numbers
Euler’s Identity:

\[ e^{j\omega t} = \cos(\omega t) + j \sin(\omega t) \]

For sinusoidally varying quantities:

\[ V(t) = V_m \cos(\omega t) \]

Can be written as:

\[ V(t) = \Re\{V_m e^{j\omega t}\} \]

Alternatively:

\[ V(t) = V_m \sin(\omega t) \]

And:

\[ V(t) = \Im\{V_m e^{j\omega t}\} \]
Instead of the magnitude $V_m$, we usually use RMS values, simply $V$.

For sinusoidally varying quantities:

$$V(t) = V_m \cos(\omega t)$$

Can be written as:

$$V(t) = Re\{V_m e^{j\omega t}\}$$

More generally:

$$V(t) = Re\{V_m e^{j(\omega t \pm \phi)}\}$$
Notation

\[ c = a + jb \]

or:

\[ c = r \angle \theta \]

where:

\[ r = |c| = \sqrt{a^2 + b^2} \]

\[ \theta = \text{arg}(c) = \arctan \frac{b}{a} = \tan^{-1} \left( \frac{b}{a} \right) \quad \text{if } a > 0 \]

Complex conjugate:

\[ \bar{c} = a - jb \]

Useful formulae:

\[ a = \text{Re}(c) = \frac{1}{2} \left( c + \bar{c} \right) \]

\[ b = \text{Im}(c) = \frac{1}{2} \left( c - \bar{c} \right) \]

\[ cc^* = a^2 + b^2 \]

\[ \frac{1}{c} = \frac{c^*}{cc^*} = \frac{c^*}{a^2 + b^2} \]
More useful formulae

\[ j^0 = 1 \]
\[ j^1 = j \]
\[ j^2 = -1 \]
\[ j^3 = -j \]
\[ j^4 = 1 \]

**Complex addition:**
\[ (a_1 + jb_1) + (a_2 + jb_2) = (a_1 + a_2) + j(b_1 + b_2) \]

**Complex subtraction:**
\[ (a_1 + jb_1) - (a_2 + jb_2) = (a_1 - a_2) + j(b_1 - b_2) \]

**Complex multiplication:**
\[ (a_1 + jb_1)(a_2 + jb_2) = (a_1a_2 - b_1b_2) + j(a_1b_2 + a_2b_1) \]

**Complex division:**
\[ \frac{a_1 + jb_1}{a_2 + jb_2} = \frac{(a_1a_2 + b_1b_2)}{a_2^2 + b_2^2} + j\left(\frac{a_1b_2 - a_2b_1}{a_2^2 + b_2^2}\right) \]

In polar form:
\[ \frac{c_1}{c_2} = \frac{r_1}{r_2} \angle (\theta_1 - \theta_2) \]
\[ \frac{c_1 c_2}{r_1} = r_1 r_2 \angle (\theta_1 + \theta_2) \]

which is clearly simpler than using the \( a + j b \) notation.

\[ (a_1 + jb_1)(a_2 + jb_2) = (a_1a_2 - b_1b_2) + j(a_1b_2 + a_2b_1) \]

\[ \frac{a_1 + jb_1}{a_2 + jb_2} = \frac{(a_1a_2 + b_1b_2)}{a_2^2 + b_2^2} + j\left(\frac{a_1b_2 - a_2b_1}{a_2^2 + b_2^2}\right) \]
Using Phasors

\[ V(t) = Re\{V_m e^{j(\omega t \pm \phi)}\} = V_m \cos(\omega t \pm \phi) \]

At a given frequency \( f \) (\( \omega = 2\pi f \)) we require two quantities:

- Magnitude \( V_m \) respectively RMS value \( V \)
- Phase angle \( \phi \)

This can be expressed as \( V \)

and similarly for current \( I \)

and impedance \( Z = R + jX \)
Power in Single-phase Circuits
Real power, reactive power, apparent power

- **Real power (power, active power):**
  \[ P = V \cdot I \cdot \cos(\varphi) \text{ in W (Watts)} \]
  \( \varphi \) = phase angle between voltage and current

- **Reactive power (imaginary power)**
  \[ Q = V \cdot I \cdot \sin(\varphi) \text{ in VAr (Volt-Ampere reactive)} \]

- **Apparent power**
  \[ S = V \cdot I \text{ in VA (Volt-Ampere)} \]
Complex power, power factor

- Complex power can be summarized by use of the power triangle:

Power factor:

\[
\cos(\varphi) = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}}
\]

\[
\varphi = \arctan \frac{Q}{P} = \tan^{-1} \frac{Q}{P}
\]

\[
P = V \cdot I \cdot \cos(\varphi)
\]

\[
S = V \cdot I
\]

\[
Q = V \cdot I \cdot \sin(\varphi)
\]
• The sign of reactive power

We adopt the sign convention as recommended by the International Electrotechnical Commission (IEC)

• Q (+) at the load
  when the power factor is lagging
  ▪ The reactive power absorbed by an inductive load has a positive sign
  ▪ A capacitor supplies reactive power, whereas an inductor consumes reactive power
Complex Power (cont.)

• Complex power $S$ is the product of the voltage and the conjugate of the current

$$S = V \cdot I^*$$

Consider the case when $I$ lags $V$, referring to the phasor diagram:

$$S = Ve^{j\varphi_1} \times e^{-j\varphi_2} = Vle^{j\varphi} = VI\cos\varphi + jVI\sin\varphi = P+jQ$$

The magnitude of the complex power $S$ is called the apparent power

$$S = Se^{j\varphi} = S\angle \varphi = S\cos\varphi + jS\sin\varphi = P + jQ$$

To obtain the proper sign for the reactive power it is necessary to calculate $VI^*$, not $V^*I$
Complex Impedance
Complex Impedance

\[ Z = R + jX \]

\[ Z = |Z| = \sqrt{ZZ^*} = \sqrt{R^2 + X^2} \]

\[ R = Z \cos \theta \]
\[ X = Z \sin \theta \]

Inductive reactance:
\[ X_L = \omega L \]

where \( \omega = 2\pi f \)

Capacitive reactance:
\[ X_C = \frac{1}{\omega C} \]

Total reactance:
\[ X = X_L - X_C \]

Impedance triangle

Series connections:
\[ Z_{total} = \sum_{i=1}^{n} Z_i \]

Parallel connections:
\[ \frac{1}{Z_{total}} = \sum_{i=1}^{m} \frac{1}{Z_i} \]
Three-phase Circuits
Why a 3-Phase System?

- ?
\[
V = V_{\text{line}} = \sqrt{3}V_{\text{phase}}
\]

\[
(V_{\text{line}} = V_{\text{line-to-line}})
\]

\[
I = I_{\text{line}} = I_{\text{phase}}
\]

\[
V = V_{\text{line}} = V_{\text{phase}}
\]

\[
I = I_{\text{line}} = \sqrt{3}I_{\text{phase}}
\]
Star-Delta Transformation
Star-Delta Transformation

Consider resistance between $N_1$ and $N_2$:

$$R_Y(N_1, N_2) = R_1 + R_2$$

$$R_\Delta(N_1, N_2) = R_c \|(R_a + R_b) = \frac{R_c (R_a + R_b)}{R_a + R_b + R_c}$$

It must be the same, hence:

$$\frac{R_c (R_a + R_b)}{R_a + R_b + R_c} = R_1 + R_2$$

Similarly, between $N_2$ and $N_3$ as well as between $N_1$ and $N_3$

$$\frac{R_a (R_b + R_c)}{R_a + R_b + R_c} = R_2 + R_3$$

$$\frac{R_b (R_a + R_c)}{R_a + R_b + R_c} = R_1 + R_3$$
Star-Delta transformation

**D → Y**

\[
R_1 = \frac{R_b R_c}{R_a + R_b + R_c}
\]

\[
R_2 = \frac{R_a R_c}{R_a + R_b + R_c}
\]

\[
R_3 = \frac{R_a R_b}{R_a + R_b + R_c}
\]

**Y → D**

\[
R_a = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_1}
\]

\[
R_b = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_2}
\]

\[
R_c = \frac{R_1 R_2 + R_2 R_3 + R_3 R_1}{R_3}
\]
Power in Three-phase Circuits
• Real Power $P$ is a scalar quantity and so the three-phase power is simply the addition of the powers in the three phases:

$$P = P_A + P_B + P_C$$

• in the balanced system:

$$P = 3P_{ph} = 3V_{ph}I_{ph}\cos\phi$$

• For a delta:

$$V = V_{ph} \quad I = \sqrt{3}I_{ph}$$

• For a star:

$$I = I_{ph} \quad V = \sqrt{3}V_{ph}$$

• For both star and delta:

$$P = \sqrt{3}VI \cos \phi$$

$V$ : line to line voltage

$I$ : line current

$\phi$ : angle between load phase current and load phase voltage

$V_{ph}$ : phase voltage

$I_{ph}$ : phase current
• Note that the power factor of a balanced three-phase system, \(\cos(\varphi)\) is the power factor of one phase

• The term power factor has no meaning for an unbalanced system

• In an unbalanced system, each phase will have its own power factor

• When solving balanced three-phase systems, we can work with a single-phase equivalent of the three-phase system

• When the three-phase network contains delta-connected elements, they have to be converted to their equivalent star connections first
Electrical Machine Fundamentals
The Magnetic Field

Four basic principles describe how magnetic fields are used in devices:

• A current-carrying wire produces a magnetic field in the area around it

• A time-changing magnetic field induces a voltage in a coil of wire, if it passes through that coil (This is the basis of the transformer)

• A current-carrying wire in the presence of a magnetic field has a force induced on it (This is the basis of the motor)

• A moving wire in the presence of a magnetic field has a voltage induced in it (This is the basis of the generator)
Ampere’s Law

- One of Maxwell’s equations, the basic law governing the production of a magnetic field by a current:

\[ \int H \cdot dl = I_{\text{net}} \]

\[ H_l c = N i \quad \Rightarrow \quad H = \frac{N i}{l_c} \quad B = \mu H = \frac{\mu N i}{l_c} \]

\[ \phi = \int_A B \cdot dA \approx BA = \frac{\mu N i A}{l_c} \]

H = magnetic field intensity
\( \mu \) = permeability of the material
B = resulting magnetic flux density produced
\( \phi \) = common magnetic flux
\( l_c \) = mean path length
\( \mu_0 = 4\pi \cdot 10^{-7} \) H/m
The Magnetic Circuit

\[ V = I \cdot R \]

\[ \mathcal{I} = \phi R \]

\[ \mathcal{I} = Ni \]

\[ \phi = \text{flux of circuit} \]

\[ \Phi = \text{reluctance of circuit} \]

\[ \mathcal{I} = \text{magnetomotive force of circuit} \]

\[ R = \frac{I_c}{\mu A} \]
Conventional Current vs. Electron Flow

• Many (physics) textbooks show the force acting on a wire as result of conventional current, that is: the current as if positive charge carriers would cause current flow.

• In reality, current is mostly transmitted via negative electrons, the electron current flow is in the opposite direction of the conventional current.

\[
\begin{align*}
F &= (q\vec{v} \times \vec{B})nA_l \\
I &= nqvA \\
\rho &= \frac{\delta}{\delta} \\
F &= I\vec{l} \times \vec{B} \\
\end{align*}
\]

\( n = \text{amount of charge carriers} \)
Transformers
Role of the Transformer

• Main role of the transformer is to convert one voltage level into another voltage level and facilitate interconnections between different parts of the power system

• Why do we have different voltage levels?
Types of Transformers

There are a large number of different types of transformers, those integrated in the power system can be broadly classified as:

• Generation transformers
• Transmission transformers
• Distribution transformers
Power Transformers

Step-up transformers ranging from 100 to 1200+ MVA and up to 800 kV for transmission

Laminated metal core

Coils insulated by paper and immersed in oil
Transformer Monitoring

A fault in a power transformer has enormous implications on the stability of the power grid, hence utilities invest heavily in monitoring of these precious devices.

Much research by transformer manufacturers is done on predicting faults and improving monitoring techniques.

Transformer failure: https://youtu.be/ZCzdPFJ4tog
Distribution Transformers

- Various shapes and sizes
- Transforming voltage down to level consumers can use
- Often Oil-Paper type
Cast Resin Transformers

Less affected by
• Harmonic distortions
• Switching surges and lightning overvoltages
• Extreme environmental conditions (desert, tropics, arctic, high altitude)
• Low fire hazard

X Thermal issues (low thermal conduction)
X Failures prove terminal
Cast Resin Transformer Applications

• Naval applications
• Railway
• Oil platforms
• Shopping centres
• Data centres (financial institutes)
• Offshore wind turbines
The Ideal Transformer

\[
\frac{N_1}{N_2} = \frac{E_1}{E_2} = \frac{I_2}{I_1} = k \text{ (turns ratio)}
\]

\[
E_1 I_1 = E_2 I_2
\]
Magnetic Core of a Transformer

Core type transformers

(a) With a core of stacked laminated sheets
(b) With a wound core

Shell type transformers

(a) With a wound core
(b) With a wound core
Equivalent Circuit
\[ V_1 \] - primary terminal voltage
\[ V_2 \] - secondary terminal voltage
\[ E_1 \] - primary induced emf
\[ E_2 \] - secondary induced emf
\[ I_0 \] - primary no-load current
\[ I_m \] - primary magnetising current
\[ I_p \] - primary core loss current
\[ I_2' \] - load component of total primary current
\[ I_1 \] - total primary current (including \( I_0 \) and \( I_2' \))
\[ R_1 \] - primary resistance
\[ R_2 \] - secondary resistance
\[ X_1 \] - primary leakage reactance
\[ X_2 \] - secondary leakage reactance
\[ R_m \] - resistance representing core losses
\[ X_m \] - magnetising reactance
Simplified Equivalent Circuit
Next Session

- Transformer windings
- Transformer testing
- Voltage regulation
- Parallel operation
- Auto-transformer
- Harmonics
- Unbalanced loading
- Even more pictures of transformers