Block 09/10 — Transformers and Magnetic Coupling

Student Group

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Table of Contents

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Learning objectives

After this 90-minute block, you can

- explain how two coils can exchange energy by a common magnetic flux Φ.
- use the ideal transformer equations

$$\begin{aligned} \frac{\underline{U}_1}{\underline{U}_2}=\frac{N_1}{N_2}=n, \qquad \frac{\underline{I}_1}{\underline{I}_2}=-\frac{1}{n} \end{aligned}$$ with a clear sign convention.

- explain mutual inductance M using flux linkage and magnetic reluctance $R_{\rm m}$.
- distinguish **main flux**, **leakage flux**, **copper losses**, and **iron losses** in a real transformer.
- refer secondary-side quantities to the primary side using $\underline{U}'_2=n\underline{U}_2$, $\underline{I}'_2=\frac{1}{n}\underline{I}_2$, $R'_2=n^2R_2$, and $X'_{2\sigma}=n^2X_{2\sigma}$.
- interpret the no-load test and short-circuit test using the reduced equivalent circuit.
- calculate short-circuit voltage $u_{\rm k}$, continuous short-circuit current $I_{\rm 1k}$, and an estimated initial peak short-circuit current.
- connect transformer parameters to engineering applications in mechatronics and robotics, such as isolated power supplies, motor current measurement, welding transformers, and safety transformers.

Preparation at Home

Well, again

- read through the present chapter and write down anything you did not understand.
- Repeat the EEE1 ideas of magnetic flux and induction, magnetic circuits, and inductance and magnetic energy.
- Repeat from EEE2 the use of sinusoidal quantities, complex calculation, and complex power.

For checking your understanding please do the quick checks in the exercise section.

90-minute plan

- **Warm-up (10 min):**
  - Where do transformers occur in robots and automation systems?
  - Recall: Faraday induction from EEE1 — a changing magnetic flux induces a voltage.
  - Recall: in AC analysis we use RMS phasors $\underline{U}$, $\underline{I}$, and impedances $j\omega L$.

- **Core concepts and derivations (55 min):**
  - Ideal transformer: common flux, voltage ratio, current ratio, power balance.
  - Mutual inductance: how flux from one coil links another coil.
  - Magnetic coupling with reluctance $R_{\rm m}$.
  - Real transformer: winding resistances, leakage inductances, iron-loss resistance.
  - Reduced equivalent circuit: refer secondary quantities to the primary side.
  - No-load and short-circuit operation: what can be measured, what can be neglected.
- **Practice (20 min):**
  - Quick ratio calculations for step-up and step-down transformers.
  - Unit checks for $j\omega L$, $j\omega N\Phi$, and $u_{\rm k}$.
  - Short-circuit current calculation for a transformer used in an actuator supply.
- **Wrap-up (5 min):**
  - Summary box: ideal transformer, mutual inductance, real transformer, reduced circuit, short-circuit parameters.
  - Common pitfalls checklist.

Conceptual overview

- A transformer is **not** a DC component. It needs a changing magnetic flux. In normal operation this is usually a sinusoidal flux created by AC voltage.
- The transformer does not “create power”. Ideally, it trades voltage for current:

$$\begin{align*} \text{higher voltage} \quad \Longleftrightarrow \quad \text{lower current} \end{align*}$$

- The link between the two windings is the magnetic field in the iron core. This continues directly from EEE1:
  - induction explains why a changing flux induces voltage.
  - magnetic circuits explains why the iron core guides the flux.
  - inductance explains how flux linkage and current are connected.
- Mutual inductance M measures how strongly one coil “notices” the changing current in another coil.
- A real transformer is almost ideal, but not quite:
  - R_1, R_2: copper losses in the windings.
  - $L_{1\sigma}, L_{2\sigma}$: leakage flux that does not couple both windings.
  - $R_{\rm Fe}$: iron losses in the core.
  - $L_{\rm H}$: main magnetizing inductance needed to create the main flux.
- In engineering, transformer data such as $u_{\rm k}$ are not abstract: they determine voltage drop, fault current, thermal stress, and protection design.

Core content

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Common pitfalls

- …

Exercises

Worked examples

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Embedded resources

Explanation (video): …