

# Block 09/10 — Transformers and Magnetic Coupling

## Student Group

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# Block 09/10 — Transformers and Magnetic Coupling

## Learning objectives

After this 90-minute block, you can

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

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

- explain mutual inductance  $M$  using flux linkage and magnetic reluctance  $R_m$ .
- distinguish **main flux**, **leakage flux**, **copper losses**, and **iron losses** in a real transformer.
- refer secondary-side quantities to the primary side using  $\underline{U}'_2 = n \underline{U}_2$ ,  $\underline{I}'_2 = \frac{1}{n} \underline{I}_2$ ,  $R'_2 = n^2 R_2$ , and  $X'_{2\sigma} = n^2 X_{2\sigma}$ .
- interpret the no-load test and short-circuit test using the reduced equivalent circuit.
- calculate short-circuit voltage  $u_k$ , continuous short-circuit current  $I_{1k}$ , 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  $(R_{\text{m}})$ .
- 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  $(u_{\text{k}})$ .
- 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:

$$\left[ \begin{array}{l} \text{higher voltage} \\ \text{lower current} \end{array} \right] \quad \Longleftrightarrow \quad \left[ \begin{array}{l} \text{lower current} \\ \text{higher voltage} \end{array} \right]$$

- 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.
  - $(R_{\text{Fe}})$ : iron losses in the core.
  - $(L_{\text{H}})$ : main magnetizing inductance needed to create the main flux.
- In engineering, transformer data such as  $(u_{\text{k}})$  are not abstract: they determine voltage drop, fault current, thermal stress, and protection design.

## Core content

### Mutual induction: the key idea before the transformer

## Short Review of the Flux

In EEE1 we considered magnetic flux  $\Phi$ , flux linkage  $\Psi$ , and induction. For one coil with  $N$  turns the flux linkage is

$$\Psi = N\Phi$$

Faraday's law gives

$$u(t) = -\frac{d\Psi}{dt} = -N\frac{d\Phi}{dt}$$

In sinusoidal steady state this becomes the phasor equation

$$\underline{U} = j\omega\underline{\Psi} = j\omega N\underline{\Phi}$$

This is the starting point for the transformer.

Now, we look onto the situation of two coils nearby each other and expand this formula for the induced voltage.

For this, we see:

A changing current in coil (1) creates a changing magnetic flux. If part of this flux passes through coil (2), a voltage is induced in coil (2). This is called **mutual induction**.

Fig. 4: Mutual induction of two coils: only part of the flux created by coil (1) links coil (2).



The flux created by coil  $(1)$  can be split into

$$\Phi_{11} = \Phi_{21} + \Phi_{S1}$$

- $\Phi_{11}$ : total flux created by coil (1).
- $\Phi_{21}$ : part of this flux that also links coil (2).
- $\Phi_{S1}$ : stray or leakage flux that does **not** link coil (2).

The voltage induced in coil (2) is

$$u_{\text{ind},2}(t) = -N_2 \frac{d\Phi_{21}}{dt}.$$

### Analogy: two pendulums connected by a spring

Imagine two pendulums connected by a weak spring.

- If pendulum (1) moves, the spring can make pendulum (2) move as well.
- A strong spring transfers the motion strongly.
- A weak spring transfers the motion only weakly.
- If the spring is missing, pendulum (2) does not react.

For coupled coils:

- the changing motion corresponds to changing current,
- the spring corresponds to the magnetic coupling,
- the motion transferred to the second pendulum corresponds to the induced voltage,
- weak coupling means that only a small part of the magnetic flux links both coils.

### Analogy: a leaky magnetic pipe

The magnetic core can be imagined as a pipe guiding magnetic flux.

- A good iron core is like a wide, low-resistance pipe: most flux reaches the second coil.
- A large air gap is like a narrow, difficult path: less flux reaches the second coil.
- Leakage flux is like flow escaping through side paths: it belongs to the first coil but does not help the second coil.

This image is helpful for transformers, wireless charging coils, and current sensors.

### Engineering examples

- **Transformer:** very strong coupling because the iron core guides most of the flux through both windings.
- **Wireless charger:** weaker coupling because the flux must cross an air gap and the coils may be misaligned.
- **Current transformer:** the measured conductor acts like a one-turn primary winding; the secondary winding detects the changing magnetic field.
- **Relay coil near signal wiring:** unwanted coupling can induce noise voltages in nearby loops.

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## Common pitfalls

- ...

## Exercises

## Worked examples

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## Embedded resources

Explanation (video): ...

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