

ECE 215/S – Principles of Electronic Cyber Warfare

Block 1: Resistive Circuits and Power Distribution

Lesson 9: Transformers and Power Transmission

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Objective 1.6

I can use a transformer's turns ratio, input voltages and currents, and output voltages and currents to calculate the efficiency, source voltage, and current of a power transmission system with one or more transformers.

- Everything from Lessons 6–8 comes together here for the first time
- Assessed on **Quiz 3** along with Objective 1.7

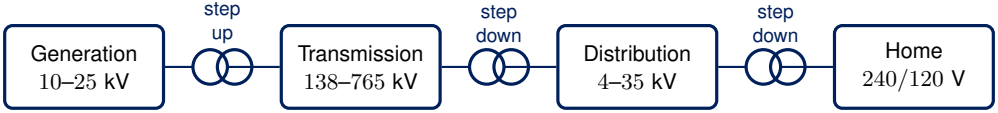
Where We Are Going

By the end of this lesson, you will be able to:

- Explain why long-distance transmission must run at **high voltage**
- Relate primary and secondary voltage, current, and turns through the **turns ratio** a
- Identify a transformer as **step-up** or **step-down** from a alone
- Compute **line losses** and the **overall efficiency** of a transmission system
- Work back from the load to the **source voltage and current**

The Power Grid

Power is generated in one place and consumed somewhere else — often hundreds of miles away. It changes voltage several times on the way:



Every one of those steps is a transformer. The question is why bother.

Why Not Just Send It at Low Voltage?

The wire has resistance, so it burns power on the way:

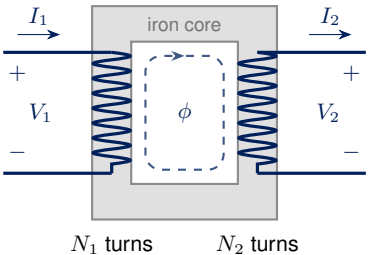
$$P_{\text{line}} = I^2 R_{\text{line}}$$

- Delivering a fixed load power $P = VI$, you may choose *either* high V and low I, *or* low V and high I
- Line loss scales with I^2 — so **halving the current cuts the loss by a factor of four**
- Raise the transmission voltage by $10\times$ and the current drops $10\times$; the loss drops $100\times$

Transmit at high voltage and low current. That is the entire argument.

AC is what transformers work on — HVDC uses converter stations instead, Lesson 10 territory.

The Physics: Faraday's Law



- A **changing** magnetic flux through a coil induces a voltage across that coil
- Two coils sharing an iron core see the *same* flux ϕ
- Each coil's voltage is proportional to its own turn count:

$$V_1 = N_1 \frac{\partial \phi}{\partial t}, \qquad V_2 = N_2 \frac{\partial \phi}{\partial t}$$

Note the word "changing." With DC the flux is constant, nothing is induced, and a transformer does nothing at all.

Turns Ratio

Take the ratio of the two coil voltages and the flux cancels:

$$a = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

An **ideal** transformer conserves power:

$$P_1 = P_2 \implies V_1 I_1 = V_2 I_2$$

That is why current inverts when voltage scales.

- $a < 1$ — **step up** ($V_2 > V_1$)
- $a > 1$ — **step down** ($V_2 < V_1$)

Watch the current term. $a = I_2/I_1$, not I_1/I_2. Voltage and current move in opposite directions.

Transmission Line Losses

Line resistance is quoted **per unit length** — call it r, in Ω/km — so over a distance d:

$$R_{\text{line}} = r\,d$$

A typical overhead conductor runs $r = 250\,\text{m}\Omega/\text{km}$.

- The **loss** is $P_{\text{line}} = I^2 R_{\text{line}}$
- The **drop** is $V_{\text{line}} = I\,R_{\text{line}}$
- The source must supply load *plus* loss

System efficiency

$$\eta = \frac{P_{\text{useful}}}{P_{\text{total}}} = \frac{P_{\text{load}}}{P_{\text{load}} + P_{\text{line}}}$$

Same η definition as Lesson 8 — the "lost" stage here is the wire itself.

Notation. V_{line} always means the **drop across the wire**, never the voltage at a transformer terminal. It is what KVL needs to get you back to the source.

Method: Analyzing a Transmission System

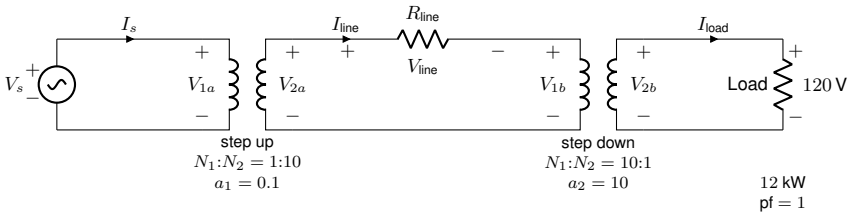
Work **backward from the load**, exactly as in Lesson 8:

1. Start at the load. On an AC segment $I = P/(V \cdot \text{pf})$; for a **unity-pf** load that reduces to $I_{\text{load}} = P_{\text{load}}/V_{\text{load}}$. State which one you are using
2. Step through each transformer with $a = V_1/V_2 = I_2/I_1$
3. On the transmission line, compute $P_{\text{line}} = I^2 R_{\text{line}}$ using the **line** current
4. Add the line loss to get the power the source must supply
5. **Work back to the source voltage:** KVL along the line adds the drop $V_{\text{line}} = I R_{\text{line}}$, then step through any remaining transformer for V_s and I_s
6. Compute $\eta = P_{\text{load}}/P_{\text{source}}$

Use the current that actually flows in the segment you are analyzing.

Worked Example

A house draws 12 kW at 120 V RMS at **unity power factor**. It sits 20 km down a line of $r = 0.25\,\Omega/\mathrm{km}$, with a **step-up** transformer at the generator and a **step-down** transformer at the house.



Find **(1)** the current in each segment, **(2)** the line loss, **(3)** the source voltage V_s and current I_s, **(4)** the efficiency η. *Work it before the next slide.*

Worked Example — Solution

1. Start at the load. Unity pf, so $I = P/V$:

$$I_{\text{load}} = \frac{12{,}000}{120} = 100\,\text{A}$$

2. Through the step-down ($a_2 = 10$):

$$V_{1b} = a_2 V_{2b} = 10(120) = 1200\,\text{V}$$

$$I_{1b} = \frac{I_{2b}}{a_2} = \frac{100}{10} = 10\,\text{A}$$

3. On the line ($R_{\text{line}} = (0.25)(20) = 5\,\Omega$, carrying $10\,\text{A}$):

$$P_{\text{line}} = (10)^2(5) = 500\,\text{W}$$

4. Source power = load + loss:

$$P_s = 12{,}000 + 500 = 12{,}500\,\text{W}$$

5. Work back to the source. KVL along the line, $V_{\text{line}} = (10)(5) = 50\,\text{V}$:

$$V_{2a} = V_{1b} + V_{\text{line}} = 1200 + 50 = 1250\,\text{V}$$

$$V_s = a_1 V_{2a} = 0.1(1250) = 125\,\text{V}$$

$$I_s = I_{2a}/a_1 = 10/0.1 = 100\,\text{A}$$

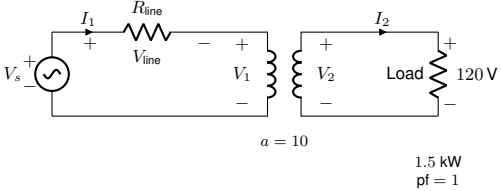
6. Efficiency. Check: $V_s I_s = 12{,}500\,\text{W}$ ✓

$$\eta = \frac{12{,}000}{12{,}500} = 96.00\%$$

Same load, same wire, no transformers: $100\,\text{A}$ the whole way, so $P_{\text{line}} = (100)^2(5) = 50{,}000\,\text{W}$ and $\eta = 12/62 = 19.35\%$.

Your Turn

A generator feeds a 1.5 kW house load at 120 V RMS, **unity power factor**, through a line with $R_{\text{line}} = 4\,\Omega$. A transformer with $a = 10$ sits at the house end.



1. What current I_2 flows on the *house* side of the transformer?
2. What are the transformer's *line-side* voltage V_1 and current I_1?
3. What is the power lost in the line, and the *drop* V_{line} across R_{line}?
4. Work back to the source: find V_s and I_s
5. What is the overall efficiency of the system?

Wrap-Up

Key ideas:

- Line loss is $I^2 R_{\text{line}}$, so transmission runs at **high voltage and low current**
- Transformers work on **changing** flux — which is why the grid is AC
- $a = N_1/N_2 = V_1/V_2 = I_2/I_1$; $a < 1$ steps up, $a > 1$ steps down
- Work backward from the load, using the current that actually flows in each segment
- V_{line} is the **drop** IR_{line} — add it with KVL to get back to V_s

Next lesson:

- **Lesson 10 — Objective 1.7: Power Converters.** Getting between AC and DC
- **Quiz 2** (Objectives 1.3–1.5) is due at Lesson 10