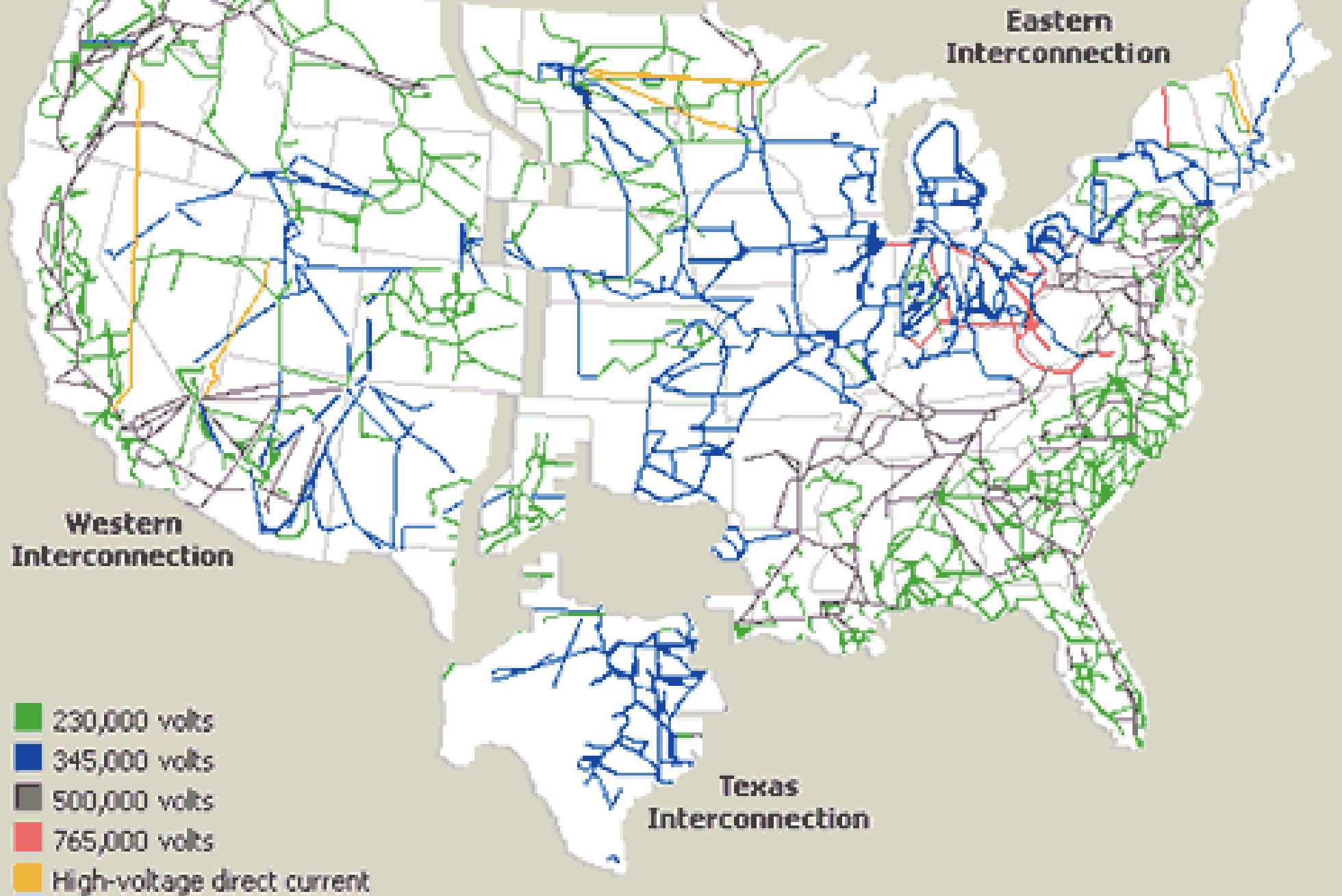
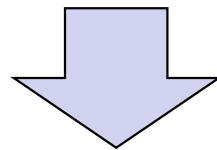
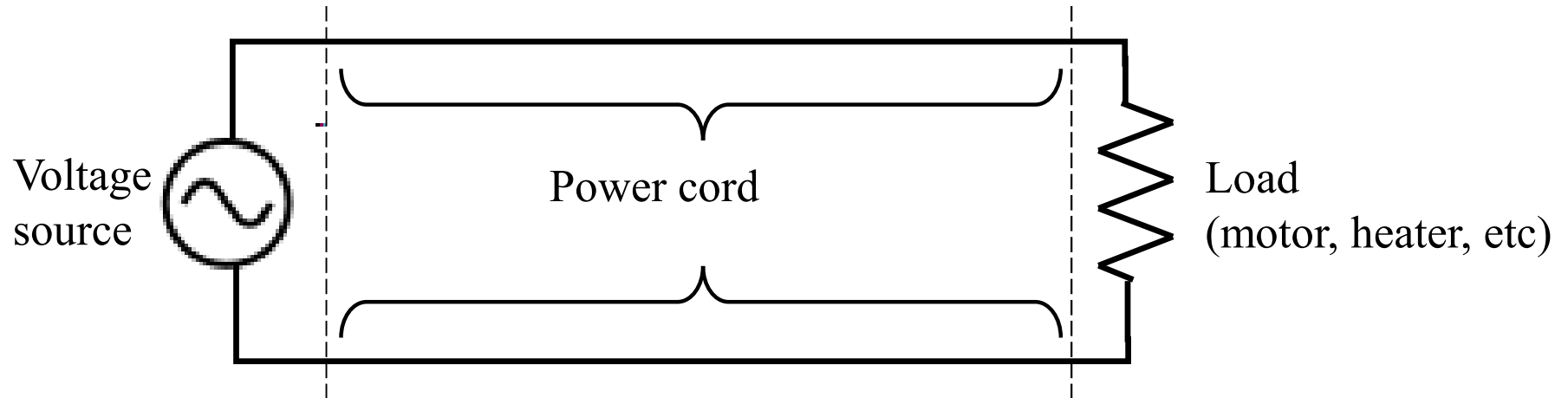


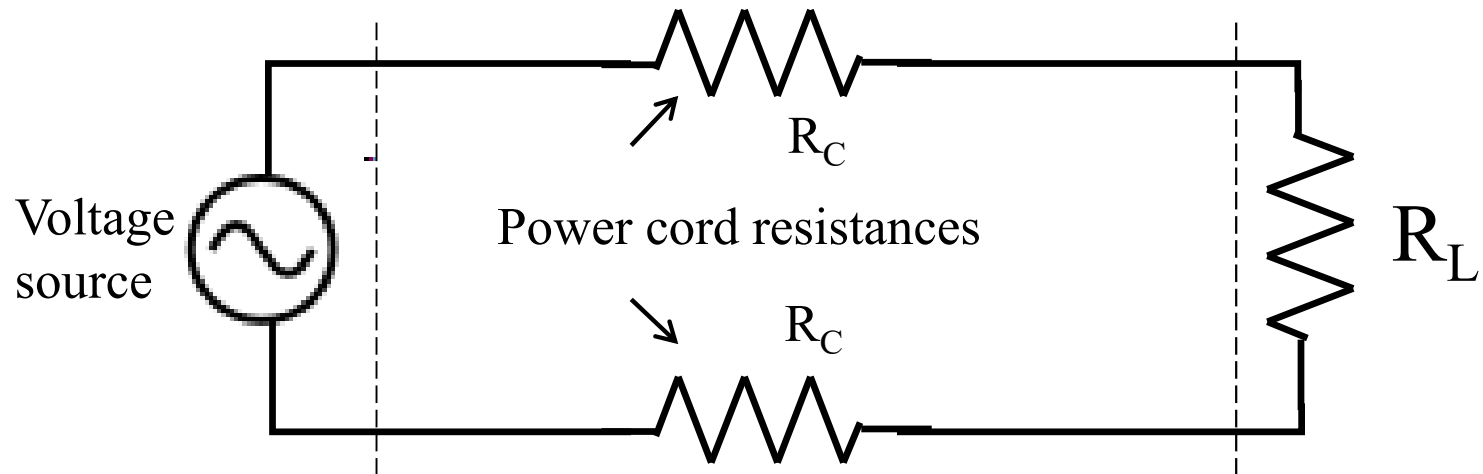
Power grid map



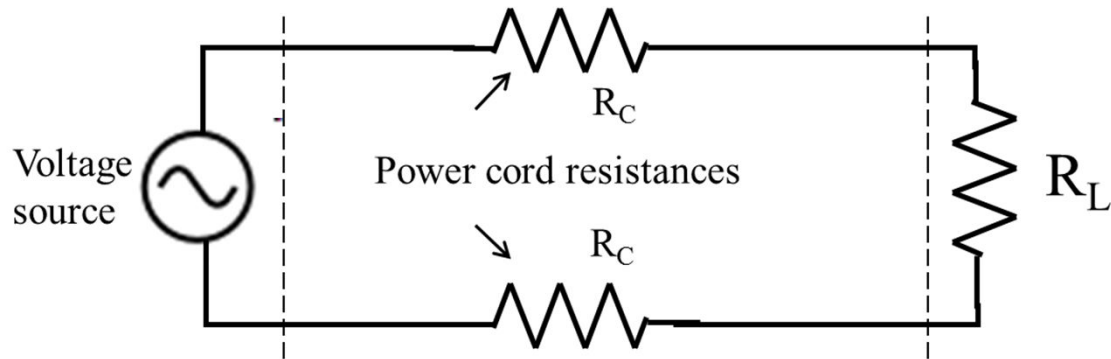
Power loss in power cords



Equivalent circuit

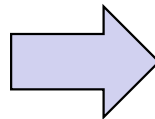


Power loss estimate



As a simple example, consider a 1 m long cord made of 1 mm diameter copper wire

Material	Resistivity ρ (ohm m)
Copper	1.68×10^{-8}
Aluminum	2.65×10^{-8}



$$\begin{aligned}
 D &= 1 \text{e-}3 \text{m;} \\
 A &= \pi * D^2 / 4 = 7.85 \text{e-}7 \text{m} \\
 L &= 1 \text{ m} \\
 \rho &= 1.68 \text{e-}8 \\
 R_C &= \rho L / A = 0.021 \text{ Ohm}
 \end{aligned}$$

L, m	R_C , Ohm
1	0.02
10	0.2
100	2

Voltage drop along the cord, which is **voltage loss**, $V_C = I * R_C$

To keep V_C low, the current must be as low as possible.

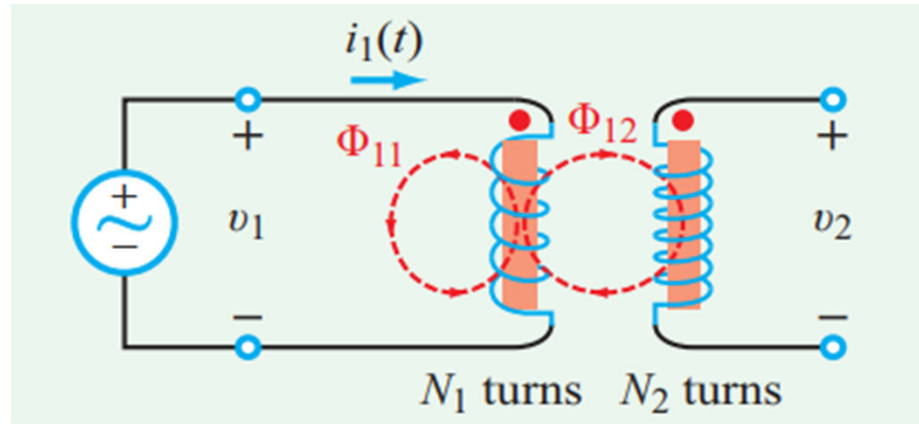
However, the power delivered to the load must be high enough.

$$P = V * I$$

Solution: increase the voltage in transmission lines.

This is the main reason why power grids use very high voltage levels.

Magnetic circuits: mutual inductance



Current i_1 induces magnetic fluxes Φ_{11} and Φ_{12} . \Rightarrow In turn, Φ_{12} induces voltage v_2

Total flux through coil 1: $\Phi_1 = \Phi_{11} + \Phi_{12}$.

Voltage induced in coil 1: $v_1 = N_1 \frac{d\Phi_1}{dt}$

Voltage induced in coil 2: $v_2 = N_2 \frac{d\Phi_{12}}{dt}$

Note that Φ_{12} comes from coil 1.

Let us link v_2 to i_1

$$v_2 = N_2 \frac{d\Phi_{12}}{dt} = N_2 \frac{d\Phi_{12}}{di_1} \frac{di_1}{dt}$$

Mutual inductance: $M_{21} = N_2 \frac{d\Phi_{12}}{di_1}$

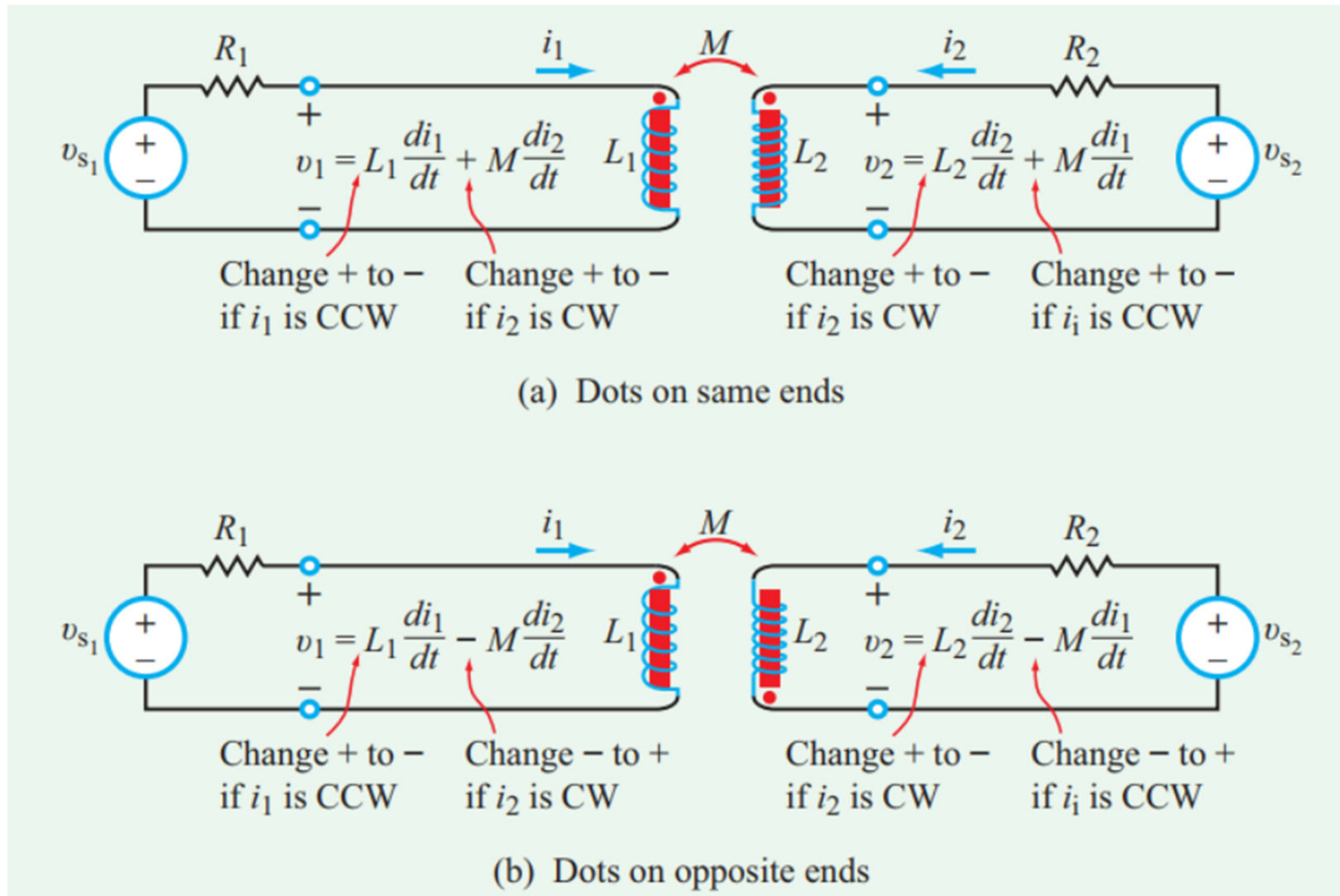
$$v_2 = \pm M_{21} \frac{di_1}{dt}$$

Voltage v_2 is induced by current i_1

The " \pm " sign is here because the sign of v_2 depends on the direction of winding in coil 2

With current flowing only through L1: $v_2 = \pm M_{21} \frac{di_1}{dt}$

In general, when currents flow through both L1 and L2, mutual inductance induces voltages in both coils:

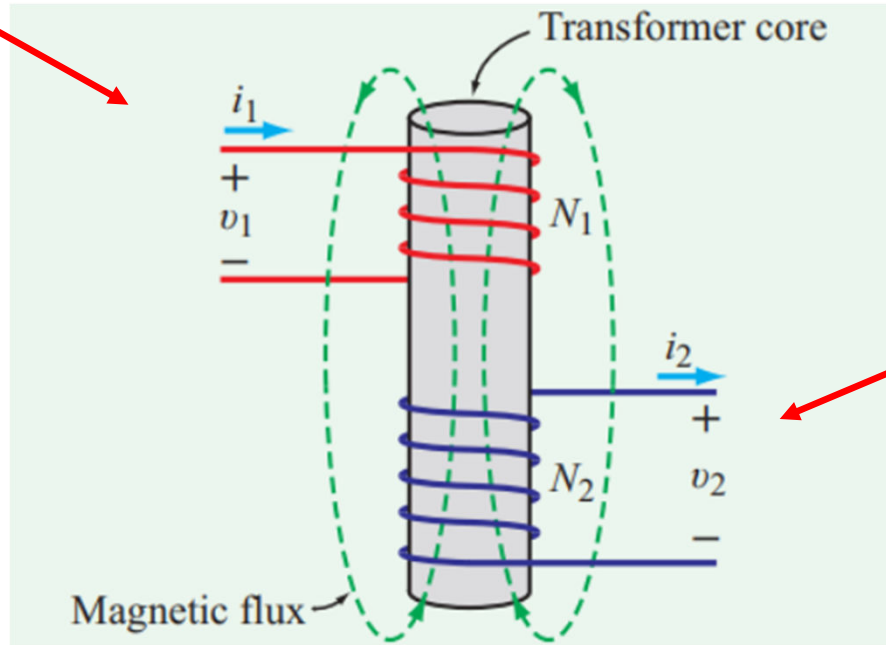


Circuits containing mutual inductance are called magnetically-coupled circuits

Voltage transformers

"p" refers to primary coil

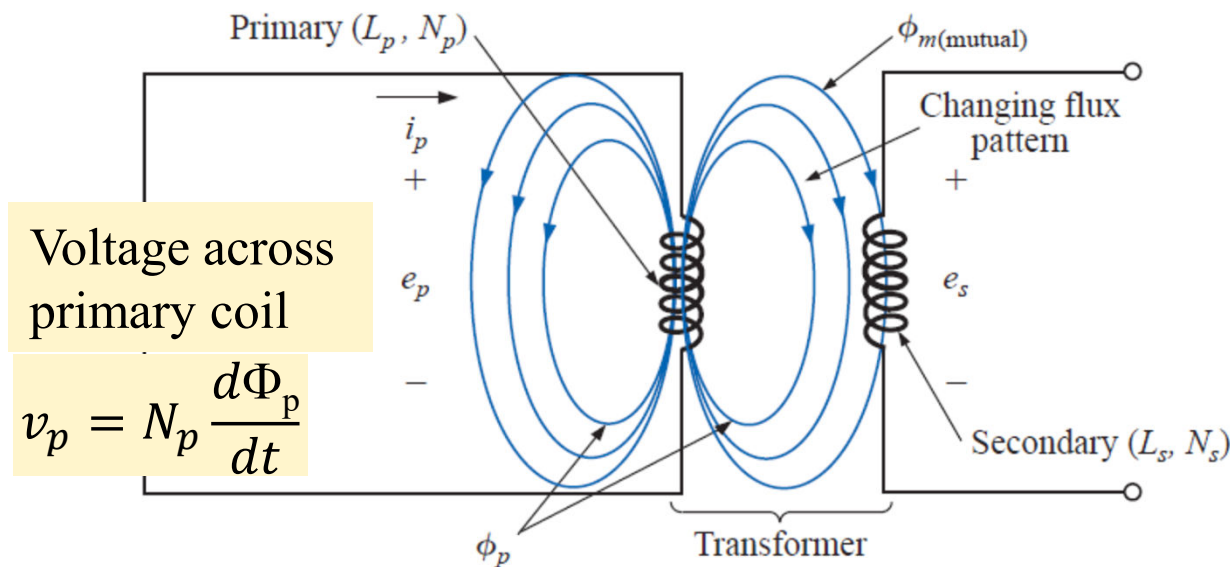
$$v_p = N_p \frac{d\Phi_p}{dt}$$



"s" refers to secondary coil

$$v_s = N_s \frac{d\Phi_s}{dt}$$

Transformer: a device to change the voltage level



Voltage across primary coil

$$v_p = N_p \frac{d\Phi_p}{dt}$$

Voltage across secondary coil

$$v_s = N_s \frac{d\Phi_s}{dt} = N_s \frac{d\Phi_m}{dt}$$

(secondary flux comes from mutual inductance)

Φ_p and Φ_m are the primary and the mutual magnetic fluxes; the coupling coeff.: $k = \Phi_m / \Phi_p$

If $\Phi_p = \Phi_m$ (no loss in the transformer's core), then

$$v_s = N_s \frac{d\Phi_m}{dt} = N_s \frac{d\Phi_p}{dt} = \frac{N_s}{N_p} \times N_p \frac{d\Phi_p}{dt} = \frac{N_s}{N_p} v_p$$

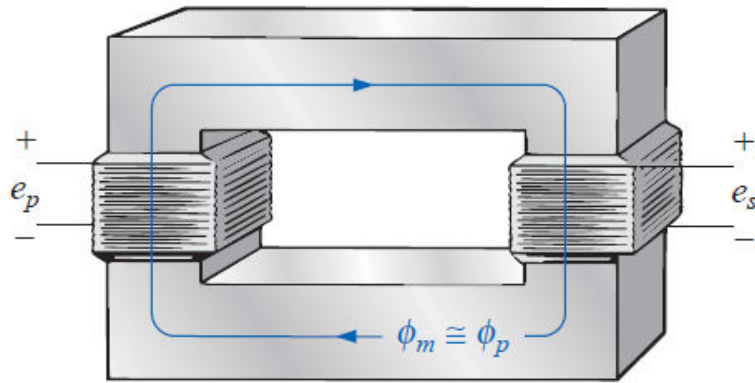
In ideal transformer, $v_s = \frac{N_s}{N_p} v_p$ Power transfer in ideal transformer: $P_s = P_p$; therefore, the secondary current

$$I_s = \frac{N_p}{N_s} I_p$$

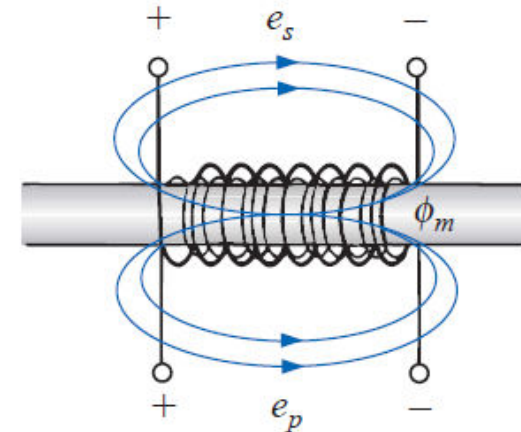
Step-up: $N_p = 10$; $N_s = 1000$; Output voltage, $e_s = 100 \cdot e_p = 100 \times$ input voltage

Step-down: $N_p = 1000$; $N_s = 10$; Output voltage, $e_s = 0.01 \cdot e_p = 0.01 \times$ input voltage

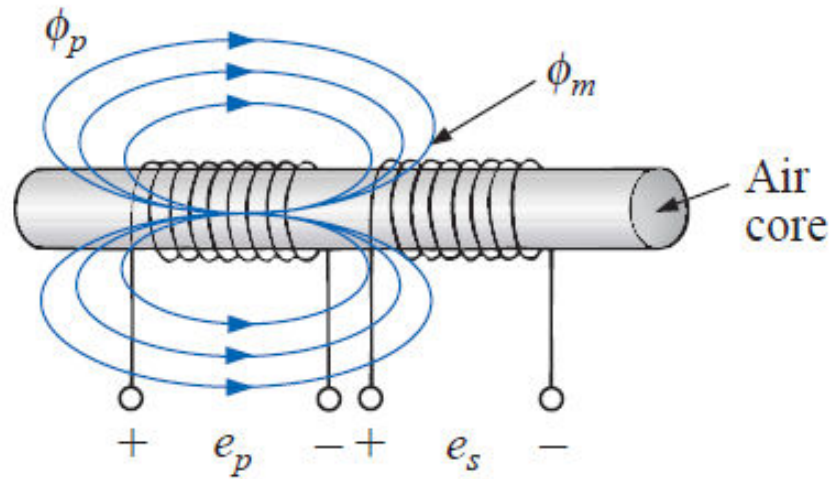
Transformer types



Steel core
 $k \cong 1$

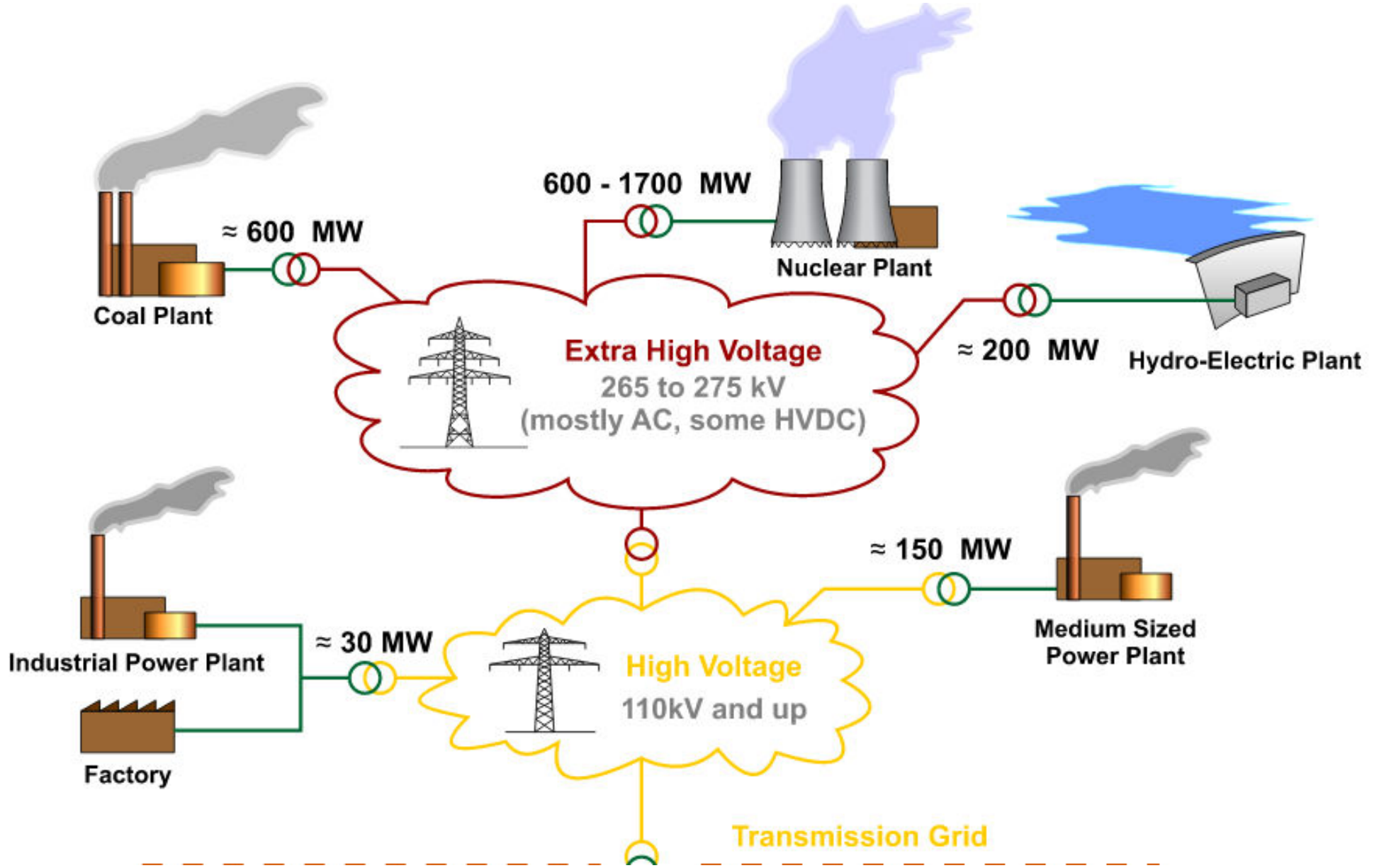


Any core
 $k \cong 1$

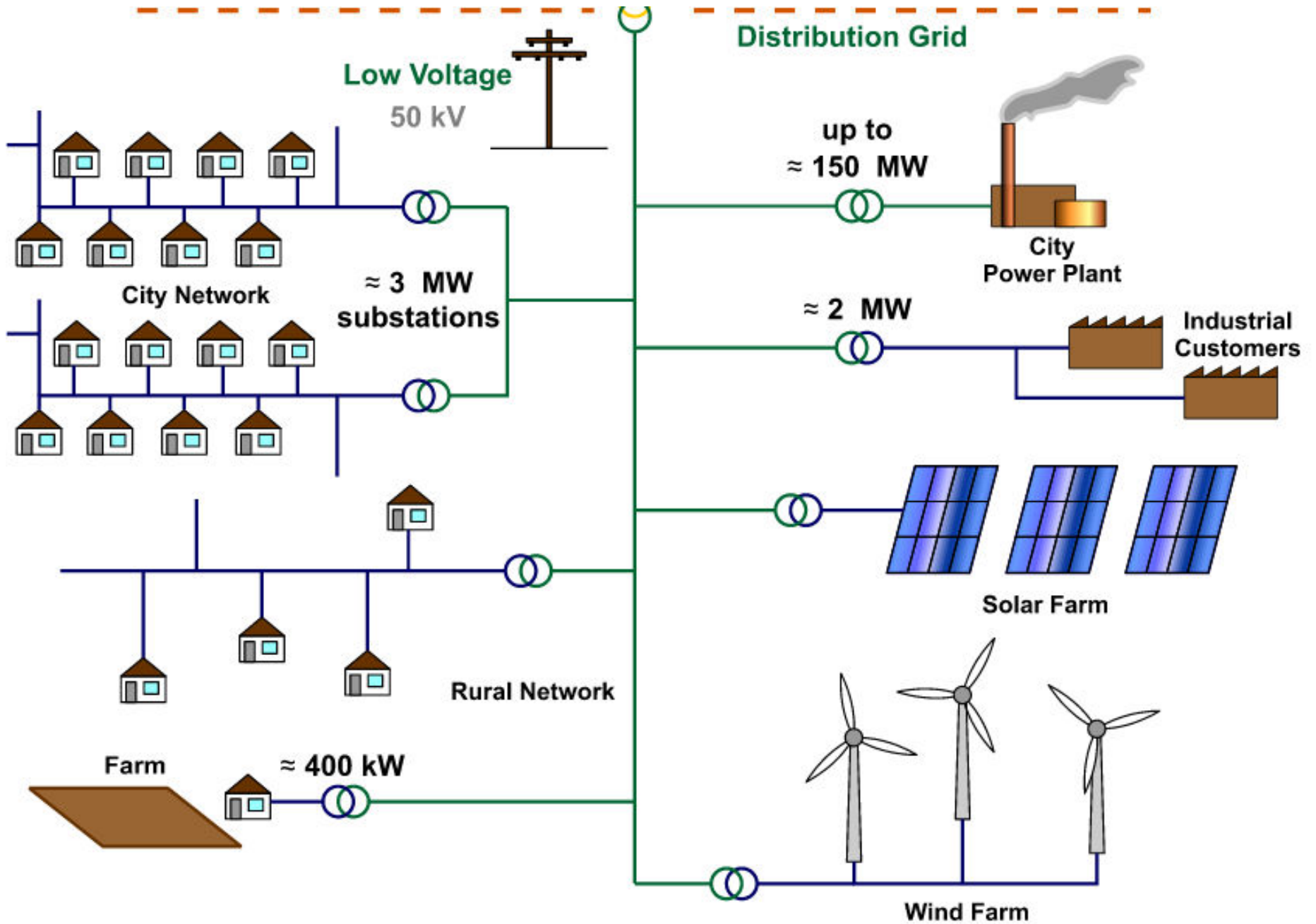


$$k = \frac{\phi_m}{\phi_1} \ll 1 \text{ (0.01} \rightarrow \text{0.3)}$$

Power distribution lines



Power distribution lines (cont.)



Other applications of transformers

Impedance matching

$$e_s = \frac{N_s}{N_p} e_p$$

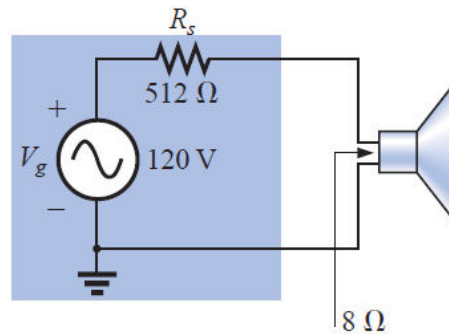
$$I_s = \frac{N_p}{N_s} I_p$$

Input impedance $Z_{IN} = e_s/I_s$

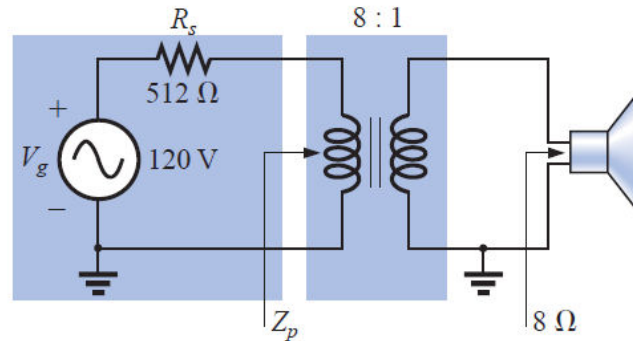
Output impedance $Z_{OUT} = e_p/I_p$

$$Z_{OUT} = a^2 Z_{IN}$$

a is the turn ratio: $a = N_s/N_p$

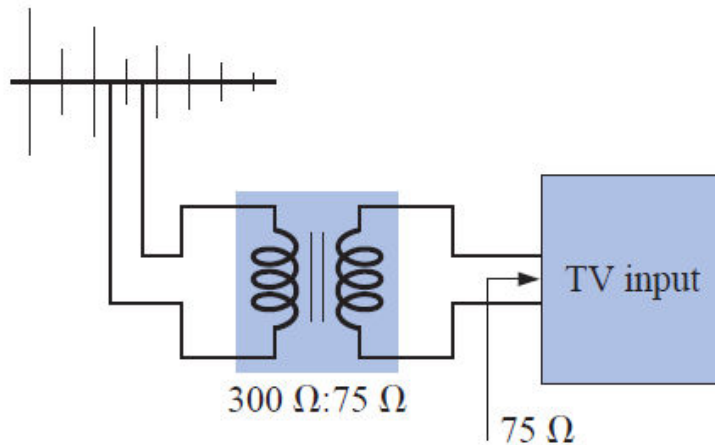


Poor matching (a)



(b) Perfect matching

$$Z_{LEQ} = 8 \text{ Ohm} * 8^2 = 512 \text{ Ohm}$$



TV antenna – TV input matching

Other applications of transformers

Isolation

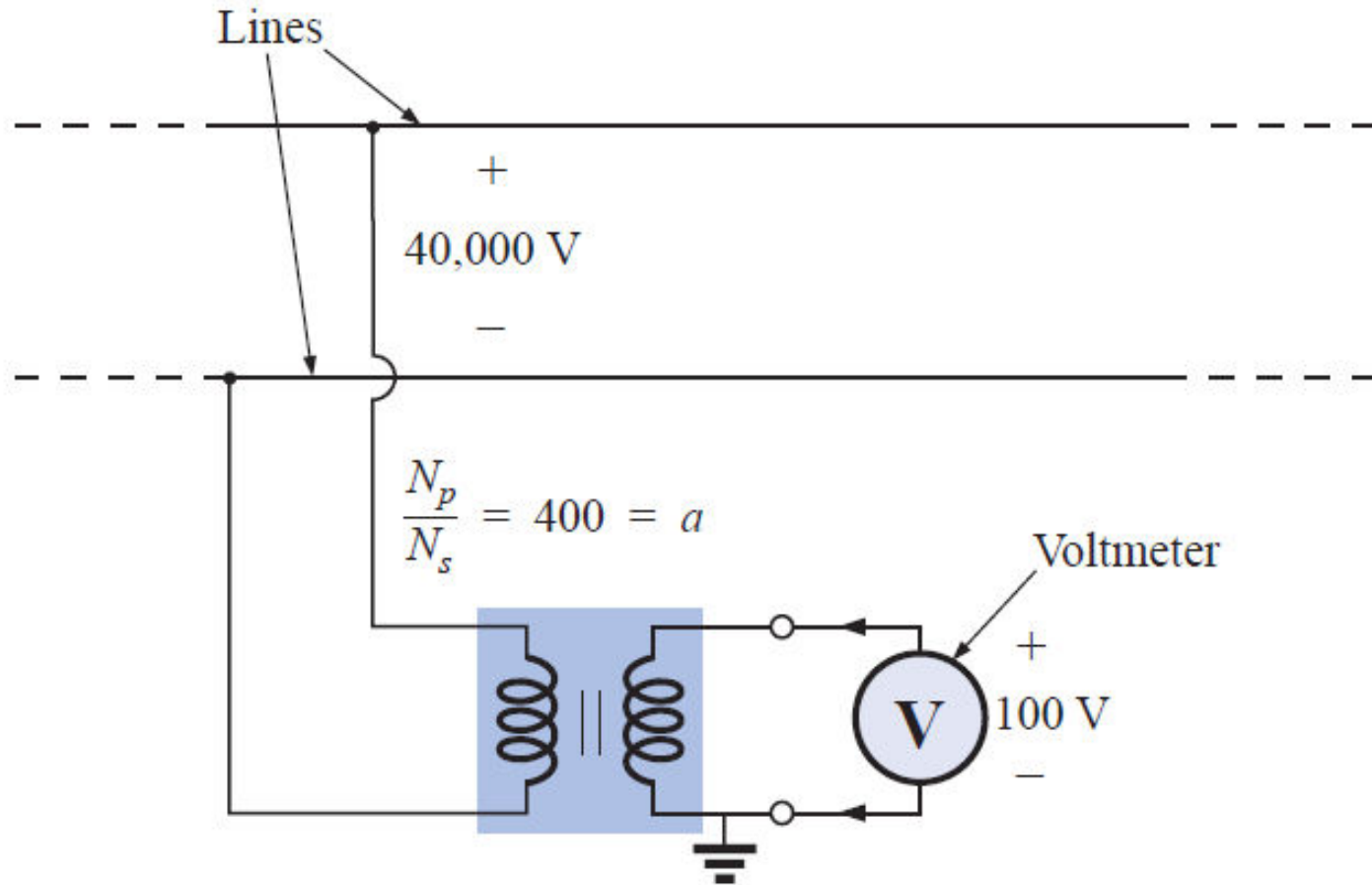
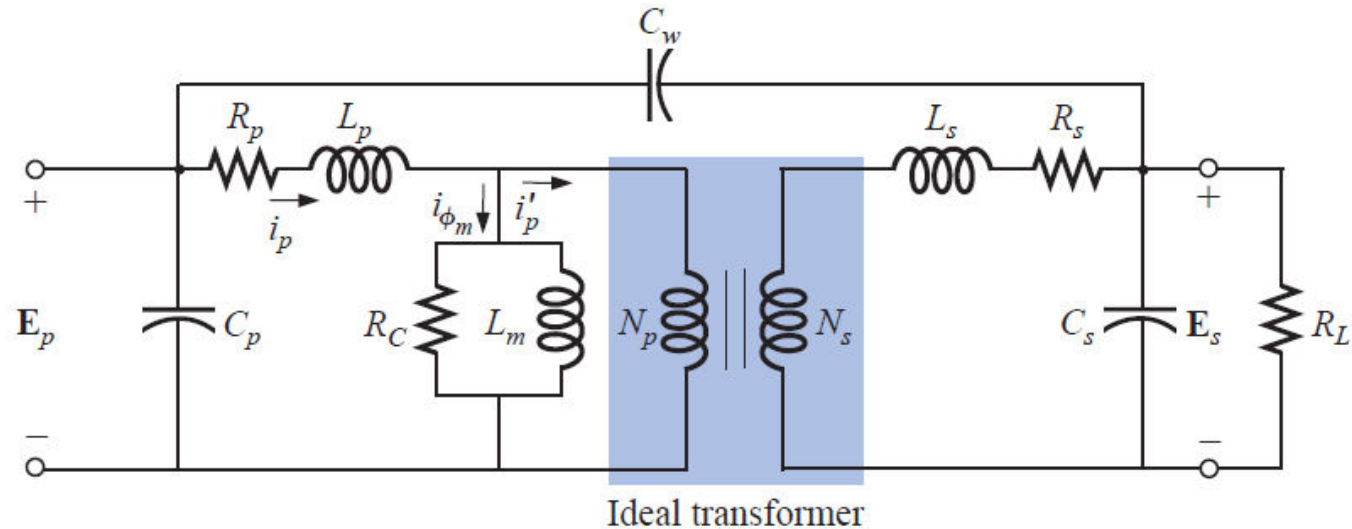


FIG. 21.11

Isolating a high-voltage line from the point of measurement.

Non-ideal transformer equivalent circuit



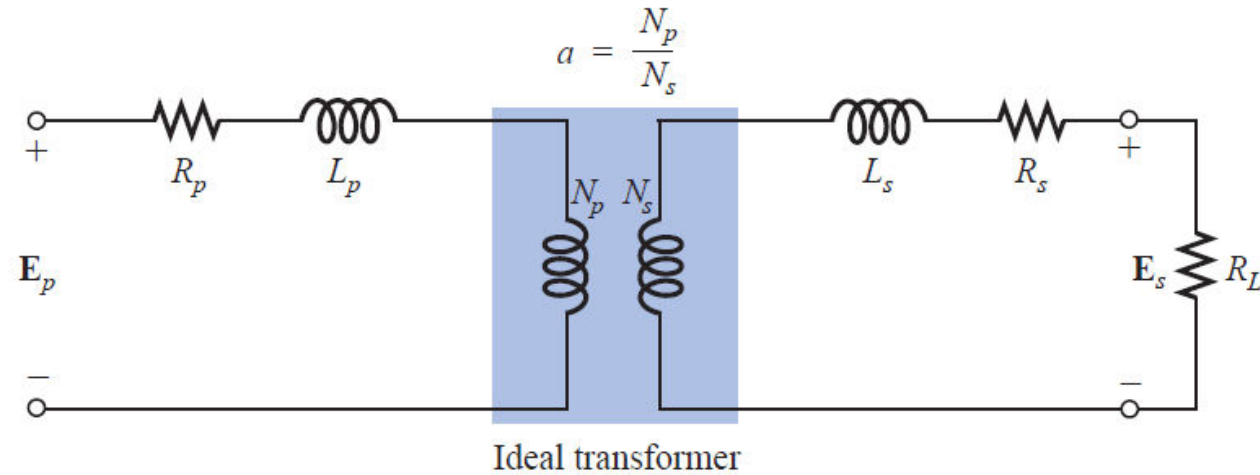
The resistances R_p and R_s are simply the dc resistance of the primary and secondary windings, respectively.

The leakage flux, which does not pass through the 2nd coil, i.e. the loss in the system, is represented by an inductance L_p in the primary circuit and an inductance L_s in the secondary circuit.

The resistance R_c and inductance L_m represent the loss due to hysteresis in the steel core.

The capacitances C_p and C_s are the lumped capacitances of the primary and secondary circuits, respectively, and C_w represents the equivalent lumped capacitances between the windings of the transformer.

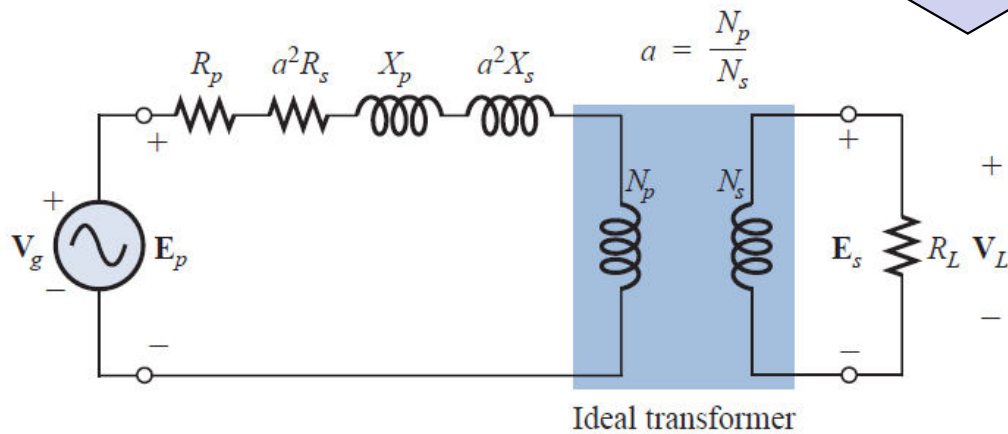
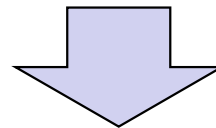
Non-ideal transformer simplified equivalent circuit



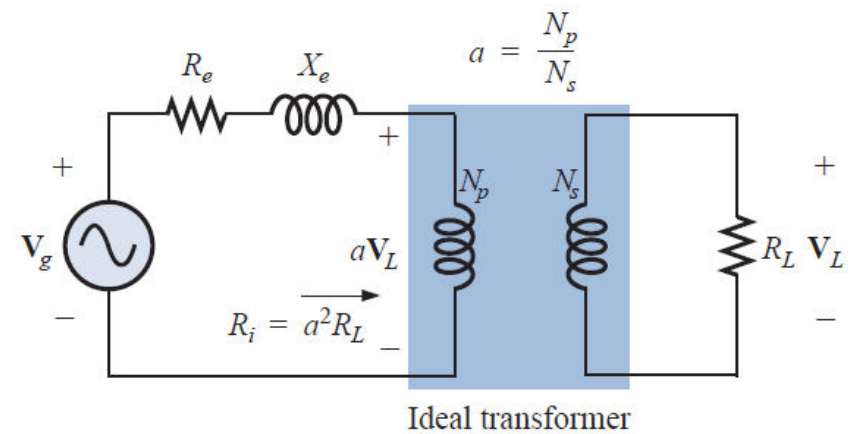
The total resistance and inductive reactance of the primary circuit

$$R_{\text{equivalent}} = R_e = R_p + a^2 R_s$$

$$X_{\text{equivalent}} = X_e = X_p + a^2 X_s$$

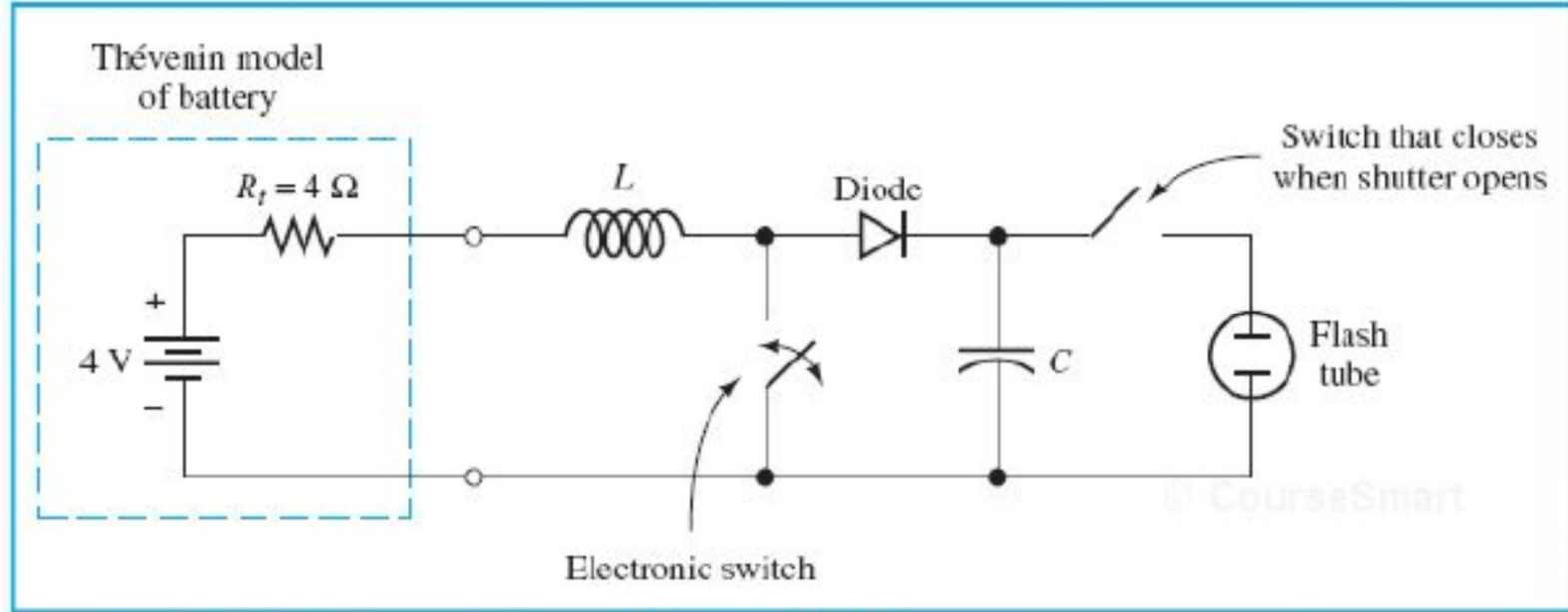


(a)



(b)

Electronic "transformer": boost converter



The electronic switch alternates between open and closed approximately 10,000 times per second. (In some units, you can hear a high-pitched whistle resulting from incidental conversion of some of the energy to acoustic form.) While the electronic switch is closed, the battery causes the current in the inductor to build up. Then when the switch opens, the inductor forces current to flow through the diode, charging the capacitor. (Recall that the current in an inductor cannot change instantaneously.) Current

can flow through the diode only in the direction of the arrow. Thus, the diode allows charge to flow into the capacitor when the electronic switch is open and prevents charge from flowing off the capacitor when the electronic switch is closed. Thus, the charge stored on the capacitor increases each time the electronic switch opens. Eventually, the voltage on the capacitor reaches several hundred volts. When the camera shutter is opened, another switch is closed, allowing the capacitor to discharge through the flash tube.