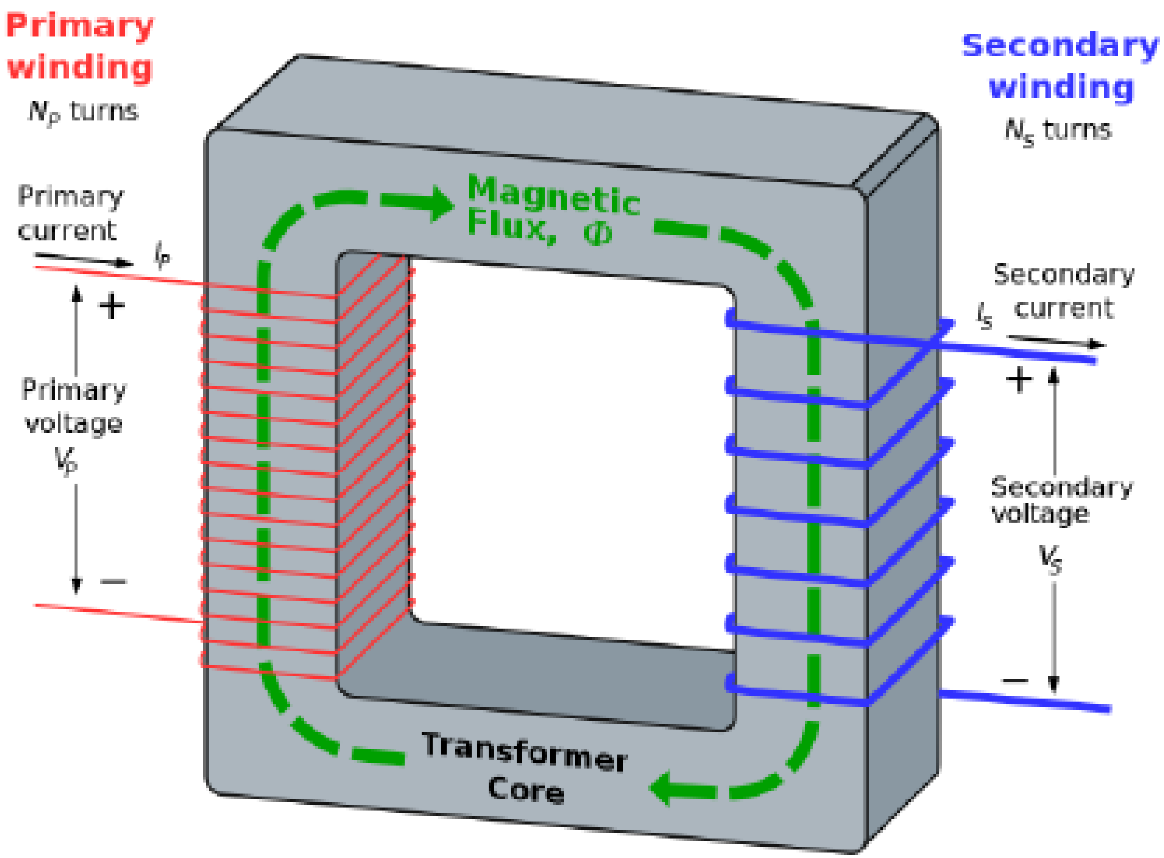
CHAPTER FIVE

A single-phase transformer

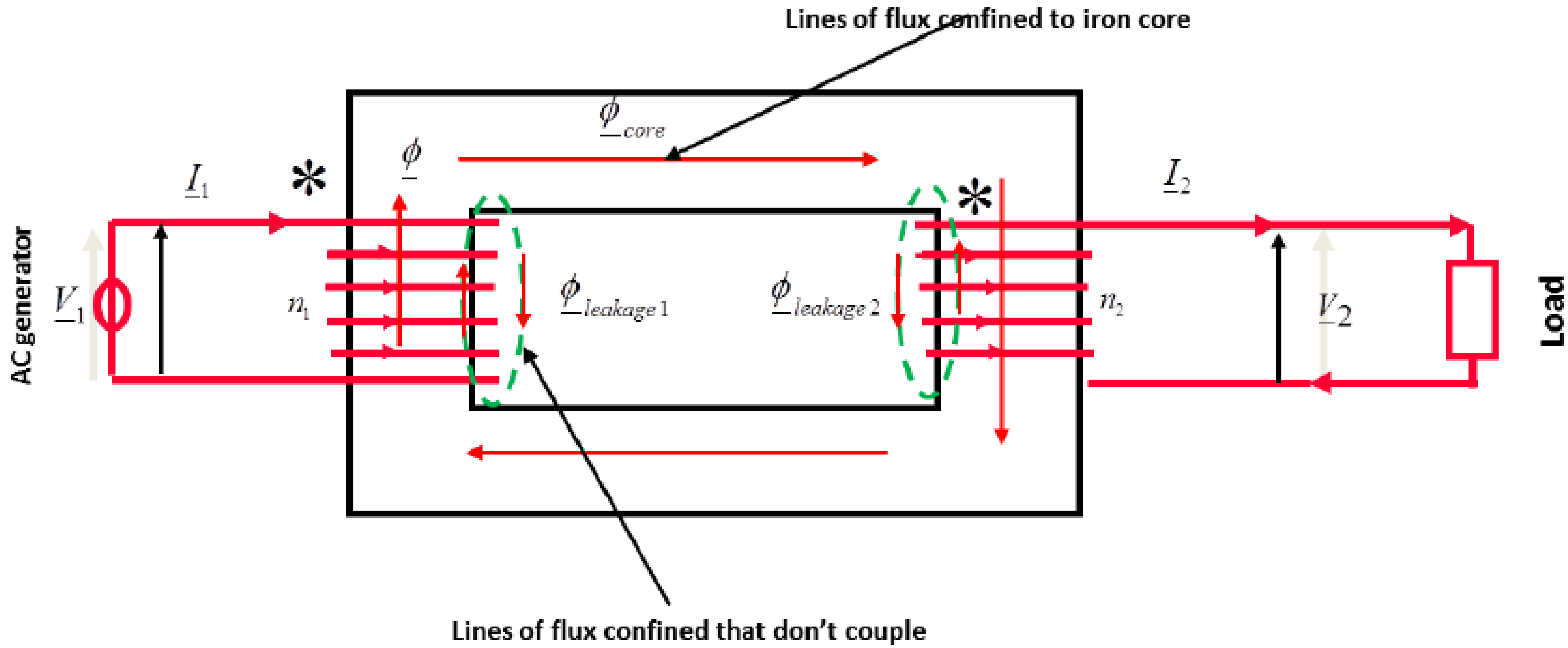
Learning Outcomes:

- Explain the production of eddy current losses within the core, and the constructional features that reduce them
- Calculate applied voltage and induced voltage.
- Draw and label both the full equivalent circuit and the simplified equivalent transformer circuit
- Calculate equivalent resistance and reactance
- Calculate equivalent circuit parameters from open and short circuit test results.
- Calculate transformer efficiency for full load and half load, each with different power factors

A single-phase transformer



A single-phase transformer



Ideal transformer

- The windings of the transformer have no resistance. Thus, there is no copper loss in the winding, and hence no voltage drop.

- Flux is confined within the magnetic core. Therefore, it is the same flux that links the input and output windings.

- Permeability of the core is infinitely high which implies that net mmf (amp-turns) must be zero (otherwise there would be infinite flux) hence $I_1 n_1 - I_2 n_2 = 0$.

- The transformer core does not suffer magnetic hysteresis or eddy currents, which cause inductive loss.

$$\frac{V_2}{V_1} = \frac{n_2}{n_1} = m$$

m : is the winding **turns ratio**, the value of these ratios being respectively higher and lower than unity for step-down and step-up transformers

V_1 : designates **input** voltage,

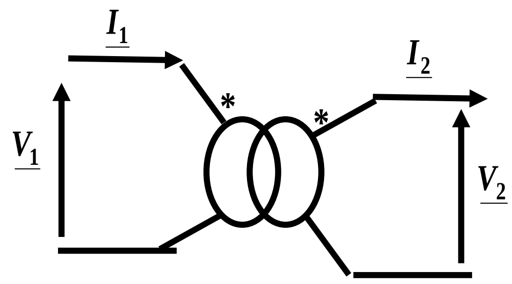
V_2 : designates **output** voltage

Ideal transformer

$$P_1 = P_2$$

$$\underline{V}_1 \underline{I}_1 = \underline{V}_2 \underline{I}_2$$

$$\frac{V_2}{V_1} = \frac{I_1}{I_2}$$

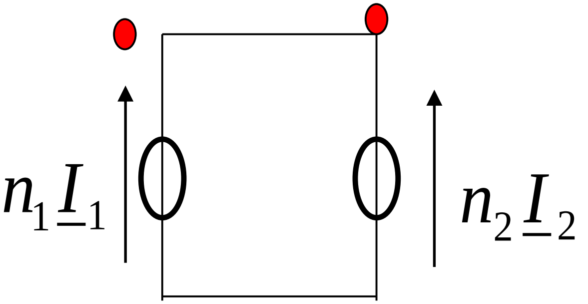


$I_1 = I_2 = 0$;
$r_1 = r_2 = 0$
$\mathcal{R} = 0$;
$R_F=0$

$$\frac{\underline{V}_2}{\underline{V}_1} = \frac{\underline{I}_1}{\underline{I}_2} = \frac{n_2}{n_1}$$

$$n_1 \underline{I}_1 - n_2 \underline{I}_2 = 0$$

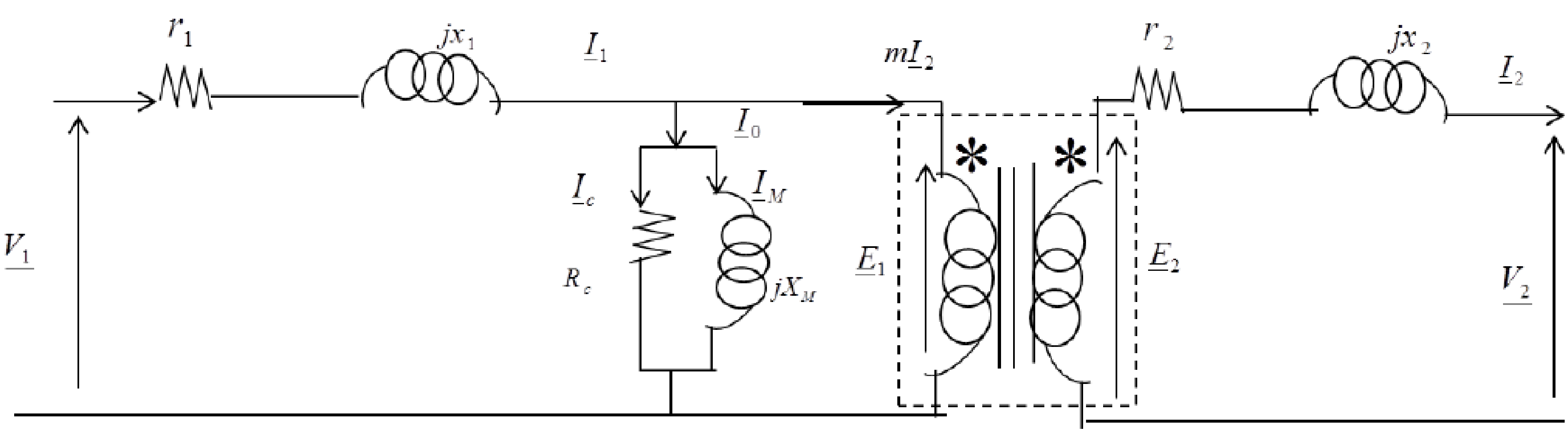
$$\frac{n_2}{n_1} = \frac{I_1}{I_2}$$



Real transformer

- Joule losses due to resistance in the primary and secondary windings
- Hysteresis losses due to nonlinear application of the voltage applied in the transformer core,
- Eddy current losses due to joule heating in the core that are proportional to the square of the transformer's applied voltage.

Equivalent circuit of real transformer

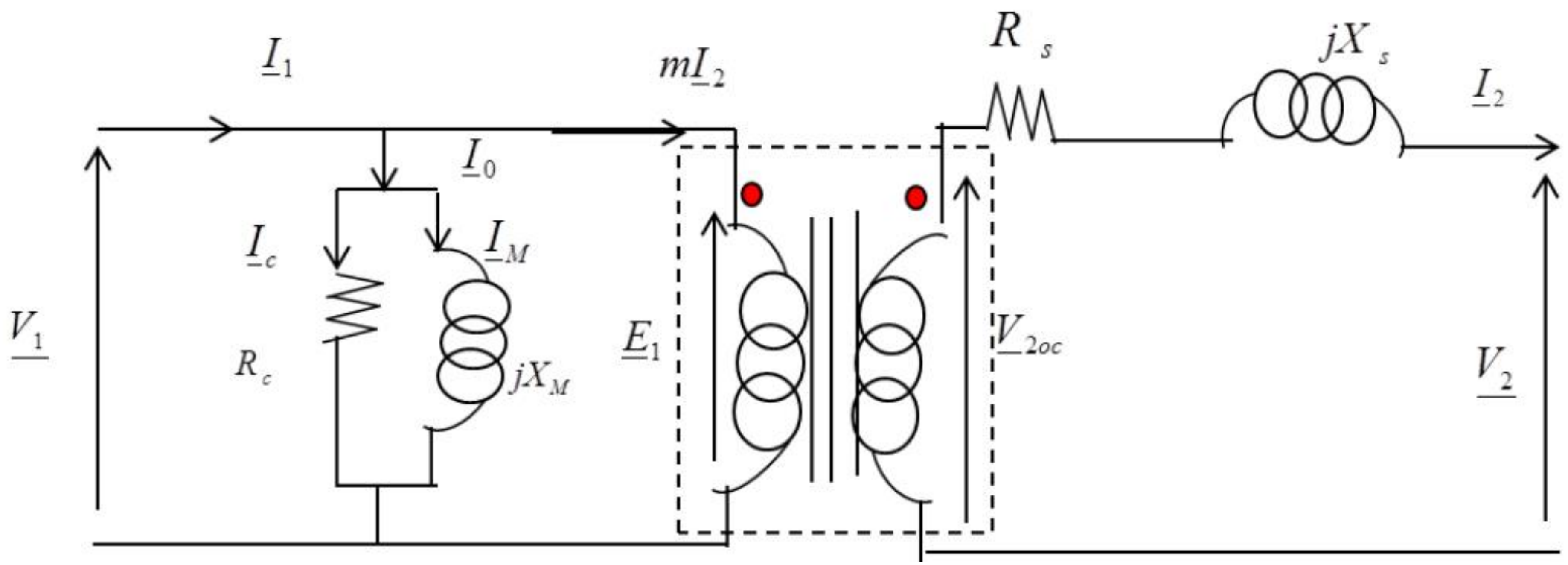


Phenomena not covered in the equivalent circuit

- Saturation
- Inrush current
- Sinusoidal exciting current

- Resistance and reactance of primary winding: r_1, x_1
- Resistance and reactance of secondary winding: r_2, x_2.
- Primary induced voltage: E_1
- Secondary induced voltage: E_2
- Primary terminal voltage: V_1
- Secondary terminal voltage: V_2
- Primary current: I_1
- Secondary current: I_2
- No load primary current: I_0
- Magnetizing current: I_M
- Current accounting for the core losses: I_C
- Core or iron losses: R_C
- Magnetizing reactance: X_M.

Approximate transformer equivalent circuit



R_s : Equivalent resistance transferred to secondary side.

X_s : Equivalent reactance transferred to secondary side.

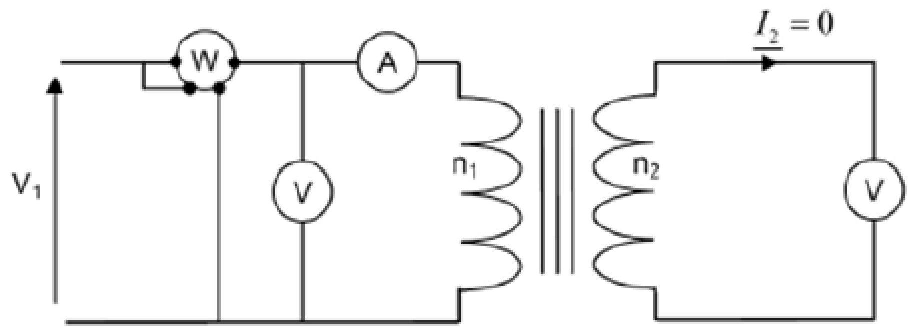
Z_s : Equivalent impedance is transferred to secondary side.

$$R_s = r_2 + m^2 r_1$$
$$X_s = x_2 + m^2 x_1$$
$$Z_s = R_s + jX_s$$

Determining transformer parameters

1. Open circuit test

- Performed at **rated voltage**
- Determines **shunt components**



$$m = \frac{n_2}{n_2} = \frac{V_{2oc}}{V_1}$$

$$R_C = \frac{V_1^2}{P_{oc}}$$

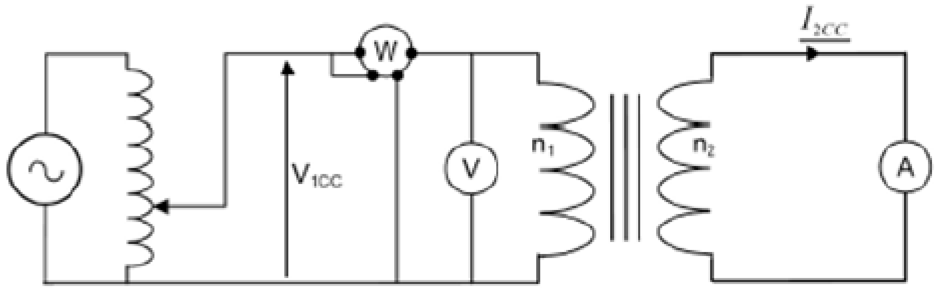
$$X_M = \frac{V_1^2}{Q_M}$$

$$Q_M = \sqrt{S_{1oc}^2 - P_{OC}^2}$$

$$S_{1oc} = V_1 I_{0c}$$

2. Short circuit test

- Performed at **rated current**
- Determines **series components**



$$Z_s = \frac{V_{2sc}}{I_{2sc}}$$

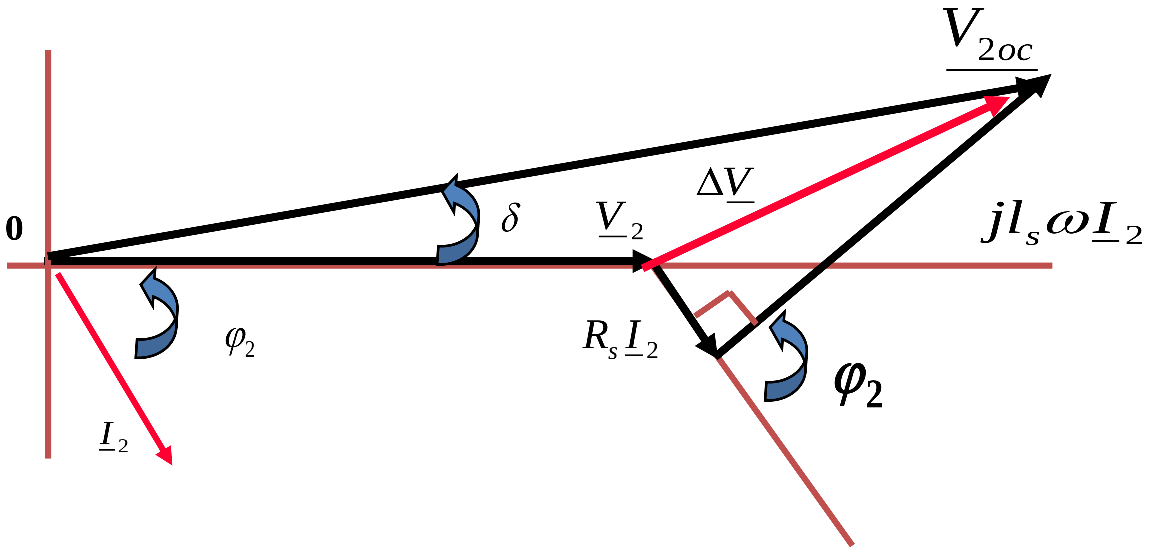
$$R_s = \frac{P_{sc}}{I_{2sc}^2}$$

$$X_s = \frac{Q_{sc}}{I_{2sc}^2} = \sqrt{Z_s^2 - R_s^2}$$

$$Q_{sc} = \sqrt{S_{1sc}^2 - P_{sc}^2}$$

$$S_{1sc} = V_{1sc} I_{1sc}$$

Voltage Drop Calculations



$$\Delta V = R_s I_2 \cos\varphi_2 + X_s I_2 \sin\varphi_2$$

Transformer Formulas

$$V_{2oc} = \frac{I_1}{I_2} \times V_1$$

$$m = \frac{n_2}{n_1} = \frac{V_{2oc}}{V_1} = \frac{I_1}{I_2}$$

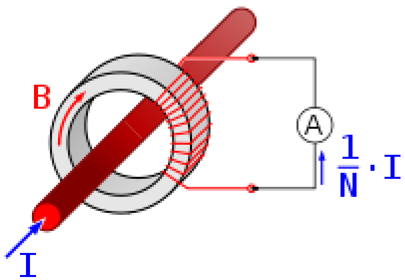
$$S_r = V_{1r} \times I_{1r} = V_{2oc} \times I_{2r}$$

Condition for Maximum Efficiency

Iron Loss = Copper Loss

$$p_{core} = p_{cu} = R_s I_2^2$$

$$I_2 = \sqrt{\frac{p_{core} = p_{cu}}{R_s}}$$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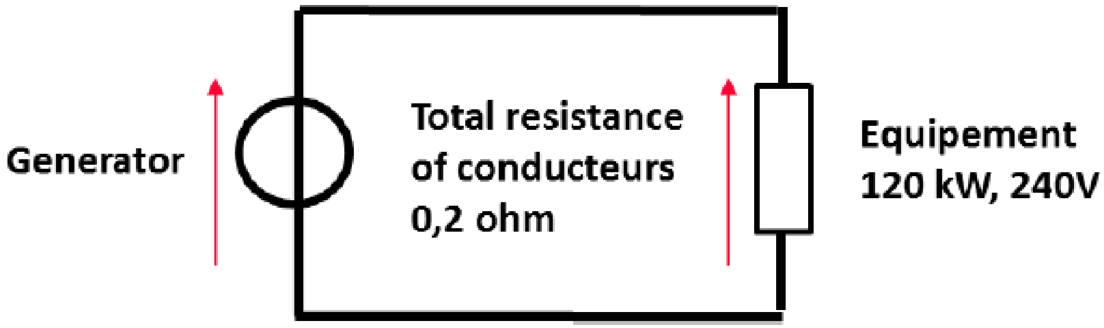
Exercise 1. A farmer installs a private hydroelectric generator to provide power for equipment rated a 120 kW 240 V AC. The generator is connected to the equipment by two conductors which have a tota resistance of $0{,}2\Omega$ -. The system is shown schematically in the figure below.



a) The equipment is operating at its rate power. Calculate:

(1) The power loss in the cables;

(2) The voltage which must be developed by the generator;

(3) The efficiency of the transmission system.

Solution

(1) The power loss in the cables;

$$P_s = VI\cos\varphi = 240 \times I \times 1 = 120000W$$

$$I = \frac{120000}{240} = 500A$$

$$P_{cable} = RI^2 = 0{,}2 \times 500^2 = 50kW$$

(2) The voltage which must be developed by the generator;

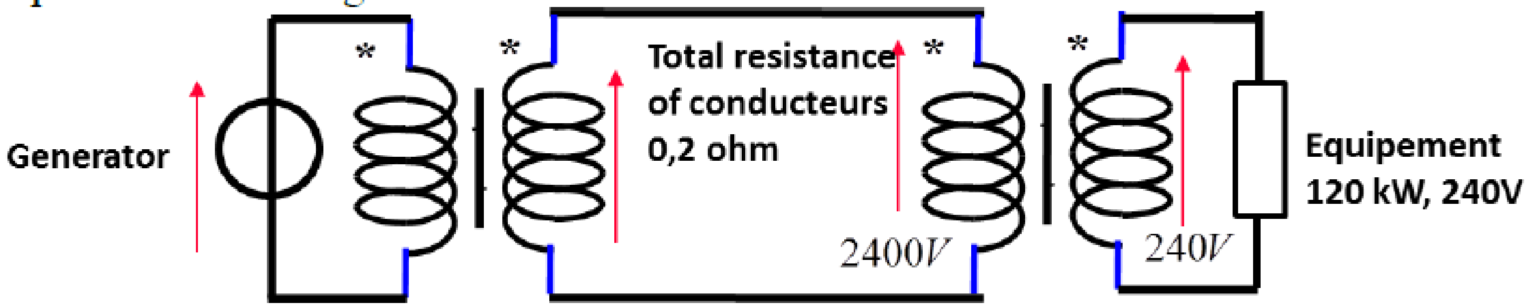
$$V_{in} = RI + 240 = 0{,}2 \times 500 = 240 = 340V$$

(3) The efficiency of the transmission system.

$$P_e = P_{cable} + P_L = 50 \times 10^3 + 120 \times 10^3 = 170kW$$

$$\eta = \frac{P_s}{P_e} = \frac{120 \times 10^3}{170 \times 10^3} = 0{,}705$$

b) An engineer suggest that the farmer uses a transformer to convert the generator output to give a 2400 V at the end of the transmission line, as shown in the next figure. A second transformer is to be used to step down this voltage to 240 V.



(4) Explain briefly how a transformer makes use of electromagnetic induction to produce an output voltage several times bigger than the input voltage.

(5) The transformer is 100 % efficient. Calculate the power loss in the new transmission system.

Solution

(4) Explain briefly how a transformer makes use of electromagnetic induction to produce an output voltage several times bigger than the input voltage.
There is a direct relationship between voltage, impedance, current, and the number of primary and secondary coil turns in a transformer

$$m = \frac{n_2}{n_1} = \frac{V_{2oc}}{V_1} = \frac{I_1}{I_2}$$

(5) The transformer is 100 % efficient. Calculate the power loss in the new transmission system.

$$\frac{V_{20C}}{V_1} = \frac{I_1}{I_2} \rightarrow I_1 = \frac{V_{20C}}{V_1} \times I_2 = \frac{240}{2400} \times 500 = 50A$$

$$P_{cable} = RI^2 = 0{,}2 \times 50^2 = 500W$$

Transformateur monophasé 600 kV

Reminders

- A transformer is a device which transfers electrical energy (power) from one voltage level to another voltage level.
- Unlike in rotating machines, there is no energy conversion.
- A transformer is a static device and all currents and voltages are AC.
- The transfer of energy takes place through the magnetic field.

Transformer Construction

Iron Core

- The iron core is made of thin laminated silicon steel (2-3 % silicon)

- Pre-cut insulated sheets are cut or pressed in form and placed on the top of each other .

- The sheets are overlap each others to avoid (reduce) air gaps.

Transformer Construction

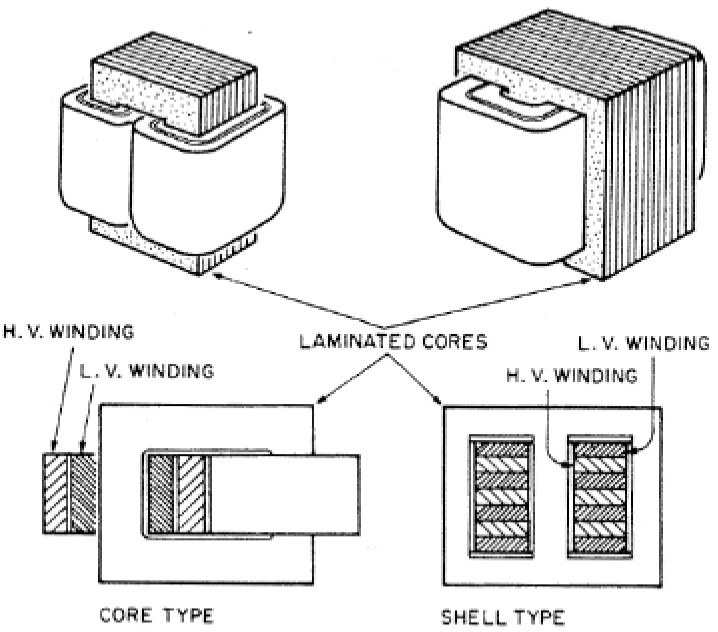
Iron Core

Small transformer winding

- The windings are manufactured in several layers, and insulation is placed between windings.

- The primary and secondary windings are placed on top of each others but insulated by several layers of insulating sheets.

- The windings are dried in vacuum and impregnated to eliminate moisture.

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