EEE363

Electrical Machines

Lecture # 13

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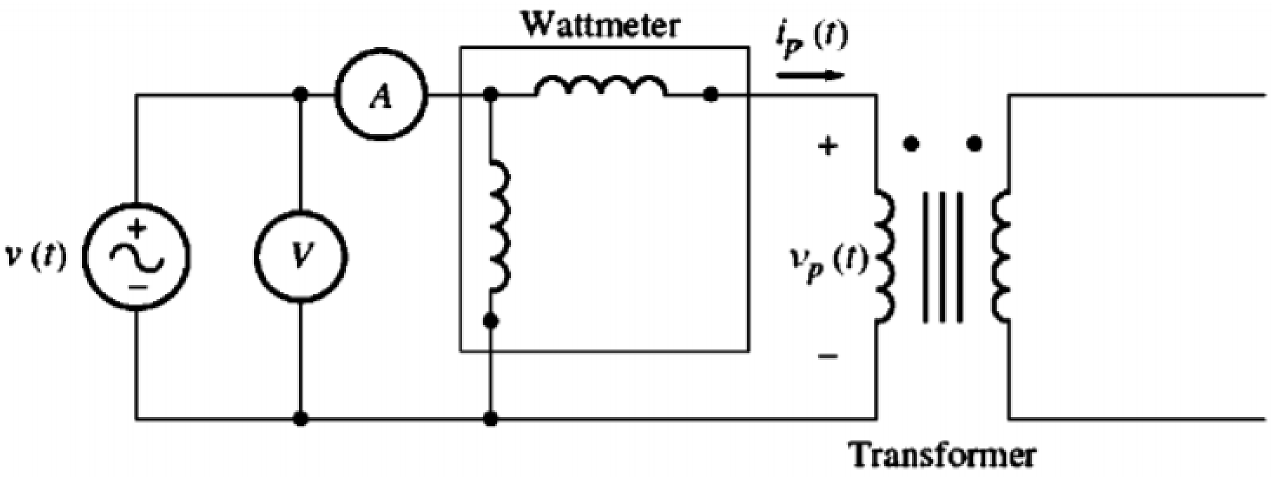
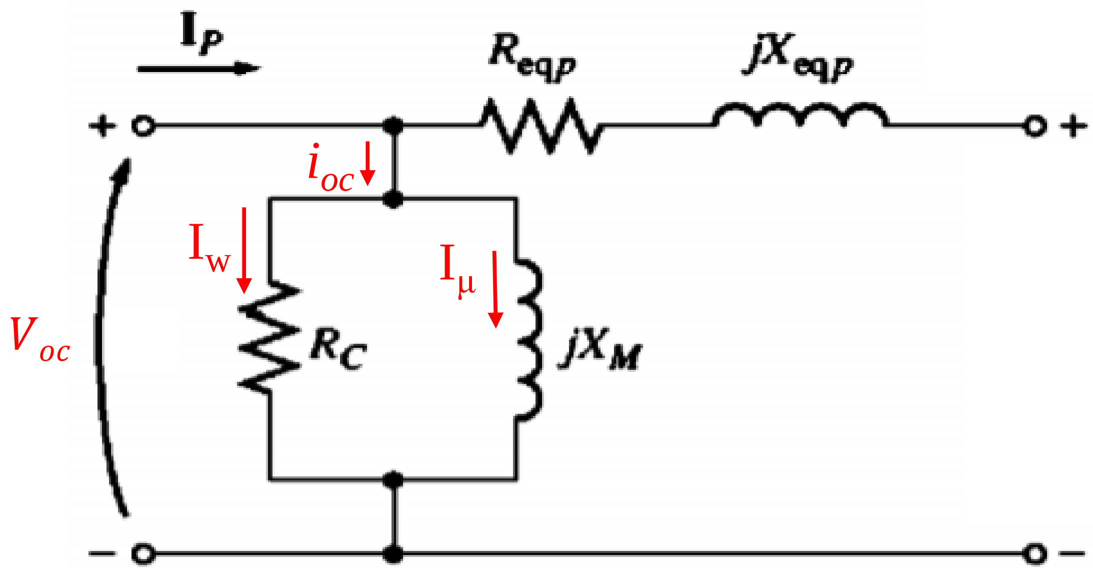
Open circuit test

- Transformer's secondary winding is left open.
- Rated voltage is applied to the primary
- We find R_c and X_m from the measured data. We also get rated Core loss for a transformer from this test.





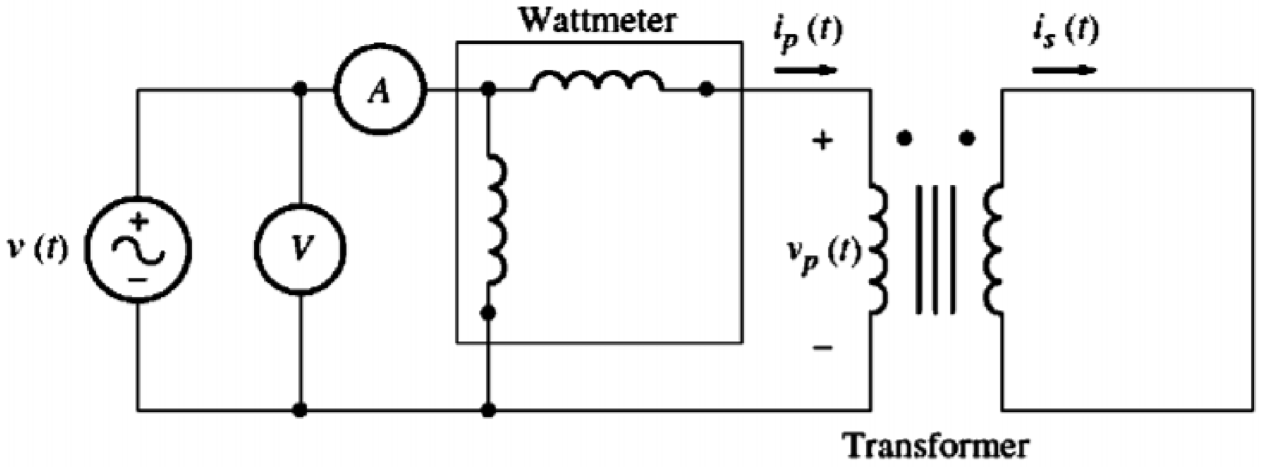
$$P_{oc} = V_{oc} I_{oc} cos\theta$$

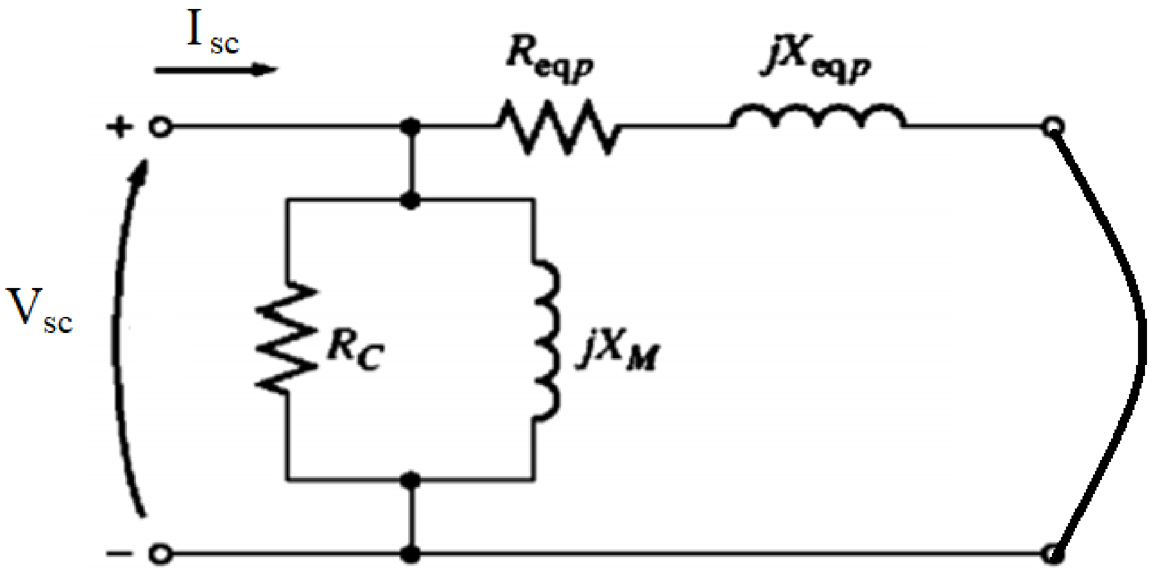
$$I_w = i_{oc} cos\theta \qquad I_\mu = i_{oc} sin\theta$$

$$R_c = \frac{V_{oc}}{I_w} \qquad X_m = \frac{V_{oc}}{I_\mu}$$

Short circuit test

- ✓ Secondary terminal is shorted
- ✓ A small voltage (5% – 10% of the rated voltage) is applied to the primary so that rated current flows.
- ✓ We find R_{eq} and X_{eq} from the measured data. We also get FL Cu loss for a transformer from this test.





$$|Z_{SE}| = \frac{V_{SC}}{I_{SC}} \qquad \cos\theta = \frac{P_{SC}}{V_{SC} I_{SC}}$$

$$Z_{SE} = R_{eq} + jX_{eq}$$

$$P_{sc} = I_{sc}^2 \,.\, R_{eq} \qquad X_{eq} = \sqrt{(Z_{SE}^2 - R_{eq}^2)}$$

Problem # 1

Example 2–2. The equivalent circuit impedances of a 20-kVA, 8000/240-V, 60-Hz transformer are to be determined. The open-circuit test and the short-circuit test were performed on the transformer, and the following data were taken:

Open-circuit test	Short-circuit test
$V_{OC} = 8000$ V	$V_{SC} = 489$ V
$I_{OC} = 0.214$ A	$I_{SC} = 2.5$ A
$V_{OC} = 400$ W	$P_{SC} = 240$ W

*Find the impedances of the approximate **equivalent circuit** referred to the primary side, and sketch that circuit.*

$$\text{PF} = \cos\theta = \frac{P_{OC}}{V_{OC} I_{OC}} = \frac{400 \text{ W}}{(8000 \text{ V})(0.214 \text{ A})} = 0.234$$

$$sin\theta = \sqrt{1 - (cos\theta)^2} = 0.9452$$

$$I_w = i_{oc}cos\theta = 0.214 \times 0.234 = 0.05007 \text{ A}$$

$$I_\mu = i_{oc}sin\theta = 0.214 \times 0.9452 = 0.20227 \text{ A}$$

$$R_c = \frac{V_{oc}}{I_w} = \frac{8000}{0.05007} = 159.8\ k\Omega$$

$$X_m = \frac{V_{oc}}{I_\mu} = \frac{8000}{0.20227} = 39.5\ k\Omega$$

PF for short ckt test

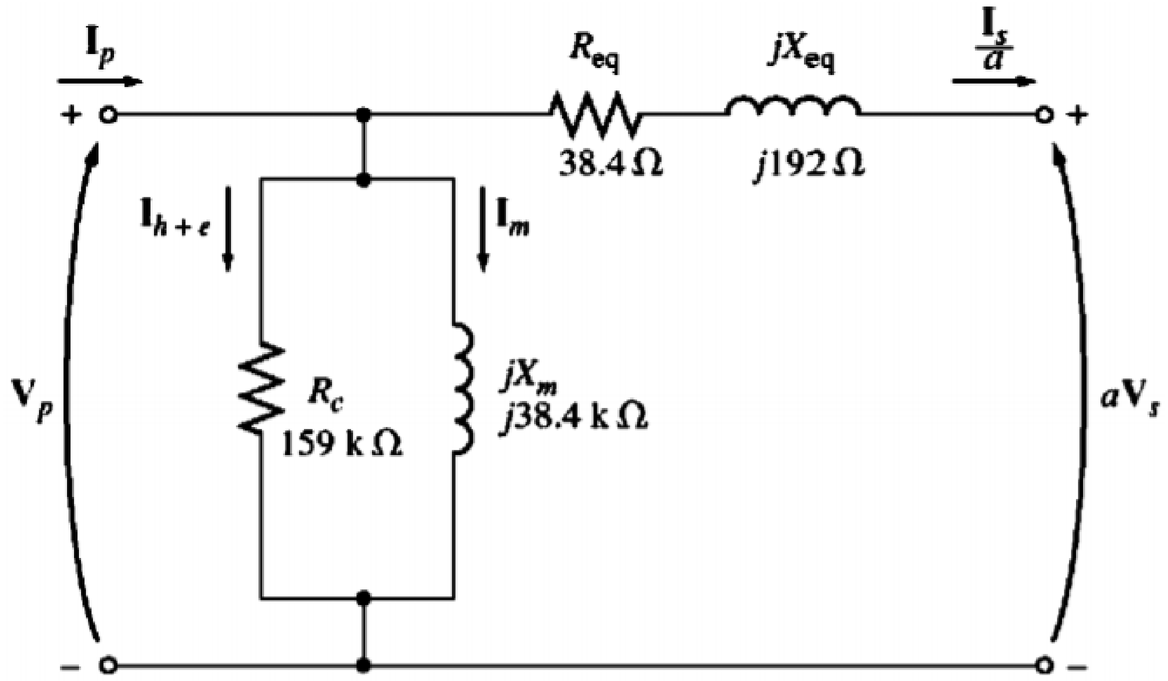
$$\cos\theta = \frac{P_{SC}}{V_{SC} I_{SC}} = \frac{240 \text{ W}}{(489 \text{ V})(2.5 \text{ A})} = 0.196$$

$$|Z_{SE}| = \frac{V_{SC}}{I_{SC}} = \frac{489 \text{ V}}{2.5 \text{ A}} = 195.6\ \Omega$$

$$P_{sc} = I_{sc}^2 . R_{eq}$$ Thus, $$R_{eq} = \frac{P_{SC}}{I_{SC}^2} = 38.4\ \Omega$$

$$X_{eq} = \sqrt{Z_{SE}^2 - R_{eq}^2} = 191.8\ \Omega$$

Eqv ckt ref to **Primary**



What will be the equivalent circuit referred to Secondary?

Problem # 2

Example 2–4. Sketch the approximate per-unit equivalent circuit for the transformer in Example 2–2. Use the transformer's ratings as the system base.

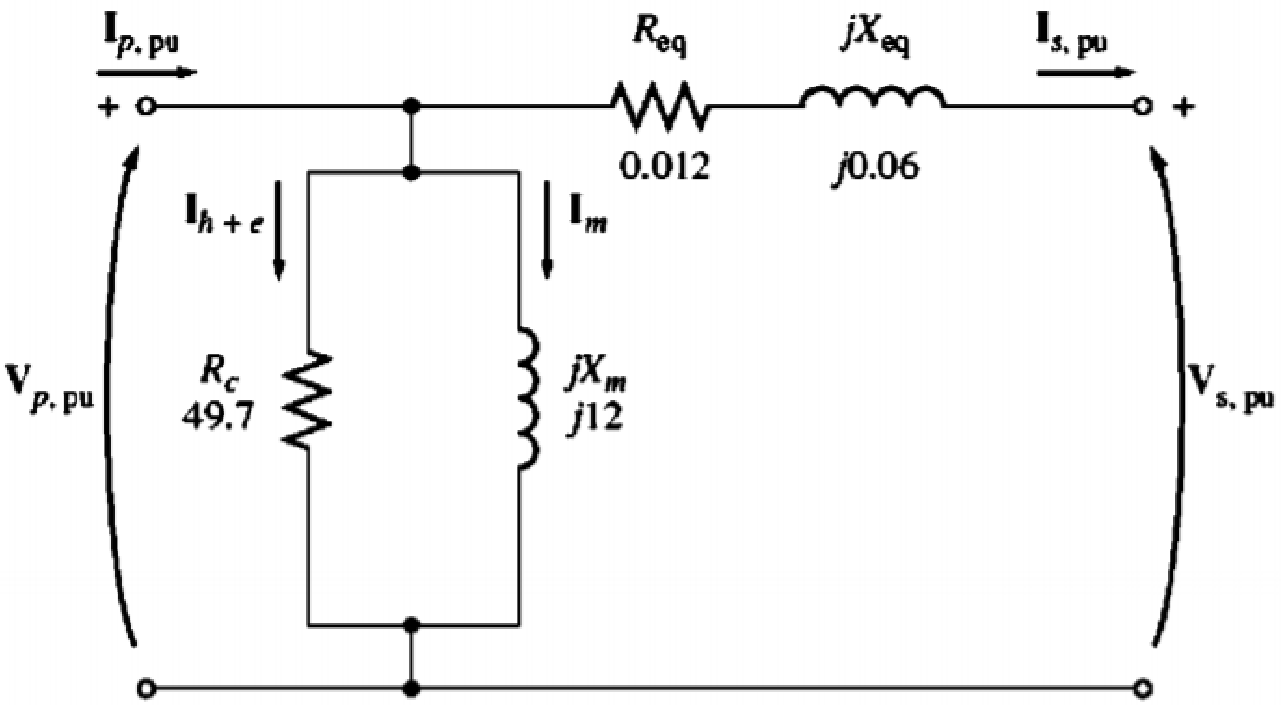
$$V_{\text{base }1} = 8000\text{ V} \qquad S_{\text{base }1} = 20{,}000\text{ VA}$$

$$Z_{\text{base }1} = \frac{(V_{\text{base }1})^2}{S_{\text{base }1}} = \frac{(8000\text{ V})^2}{20{,}000\text{ VA}} = 3200\ \Omega$$

$$Z_{SE,pu} = \frac{38.4 + j192\ \Omega}{3200\ \Omega} = 0.012 + j0.06\text{ pu}$$

$$R_{C,pu} = \frac{159\text{ k}\Omega}{3200\ \Omega} = 49.7\text{ pu}$$

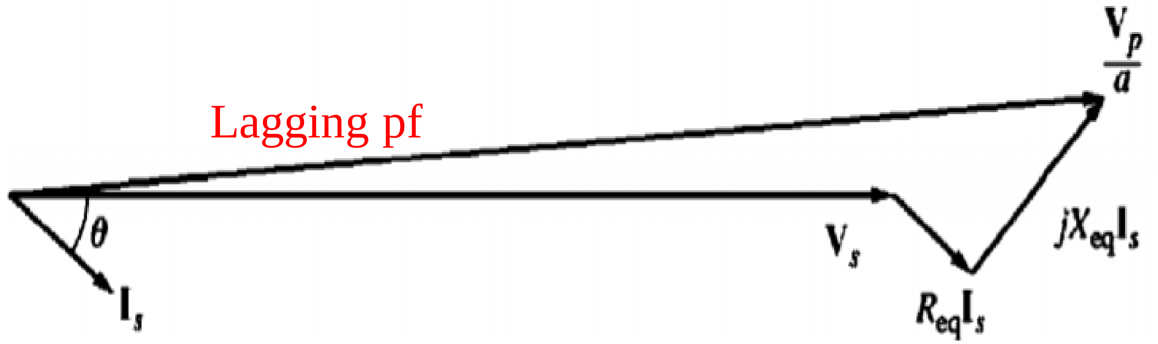
$$Z_{M,pu} = \frac{38.4\text{ k}\Omega}{3200\ \Omega} = 12\text{ pu}$$

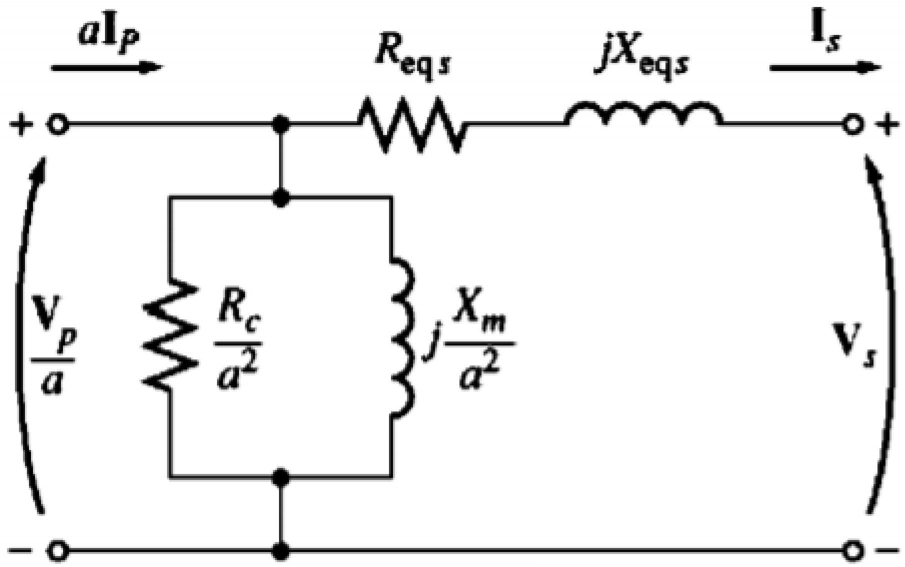


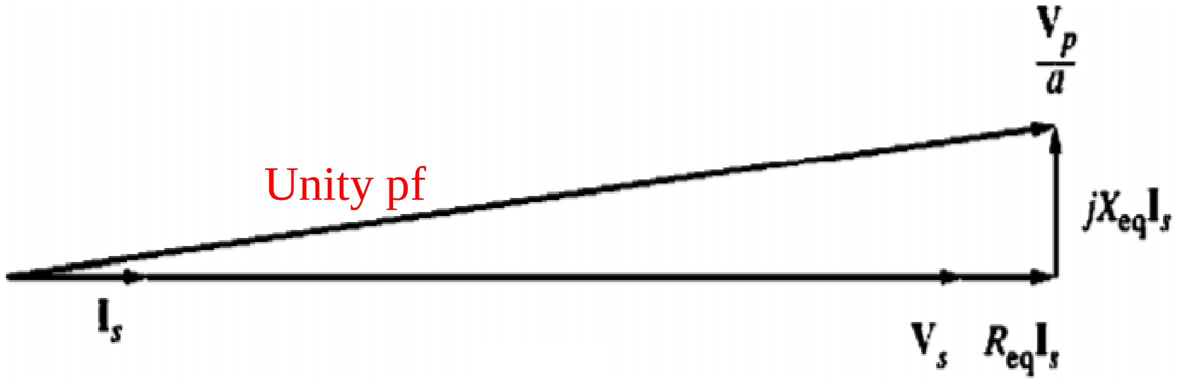
PU equivalent circuit

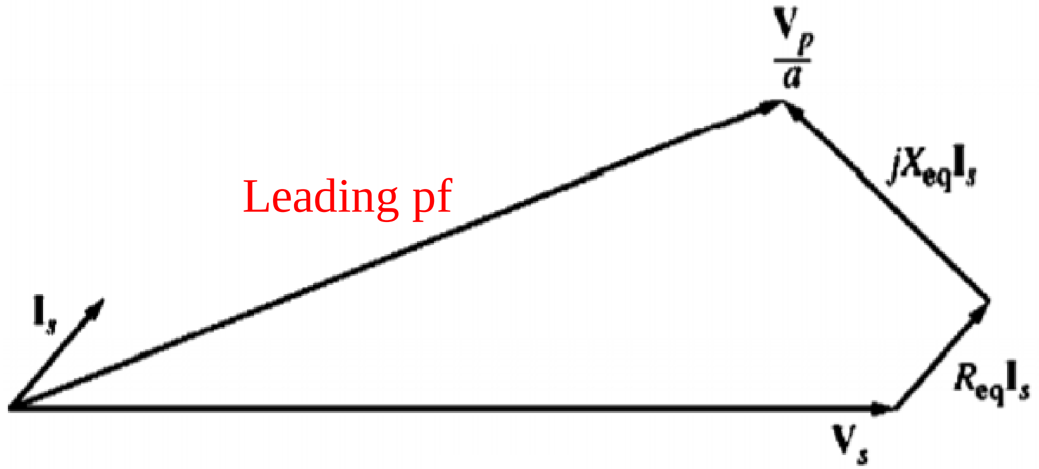
Transformer Phasor Diagram

$$\frac{V_P}{a} = V_S + R_{eq}.I_S + j\,X_{eq}.I_S$$









Transformer Voltage Regulation

Full-load voltage regulation is a quantity that compares the output voltage of the transformer at no load with the output voltage at full load.

$$\boxed{\mathrm{VR} = \frac{V_{S,\mathrm{nl}} - V_{S,\mathrm{fl}}}{V_{S,\mathrm{fl}}} \times 100\%}$$

$$\boxed{\mathrm{VR} = \frac{V_P/a - V_{S,\mathrm{fl}}}{V_{S,\mathrm{fl}}} \times 100\%}$$

$$\frac{V_P}{a} = V_S + R_{eq}.I_S + j\,X_{eq}.I_S$$

$$\boxed{\mathrm{VR} = \frac{V_{P,\mathrm{pu}} - V_{S,\mathrm{fl},\mathrm{pu}}}{V_{S,\mathrm{fl},\mathrm{pu}}} \times 100\%}$$

Problem # 3

Example 2–5. A 15-kVA, 2300/230-V transformer is to be tested to determine its excitation branch components, its series impedances, and its voltage regulation. The following test data have been taken from the primary side of the transformer:

Open-circuit test	Short-circuit test
$V_{OC} = 2300$ V	$V_{SC} = 47$ V
$I_{OC} = 0.21$ A	$I_{SC} = 6.0$ A
$P_{OC} = 50$ W	$P_{SC} = 160$ W

(a) Find the equivalent circuit of this transformer referred to the high-voltage side.

(b) Find the equivalent circuit of this transformer referred to the low-voltage side.

(c) Calculate the full-load voltage regulation at 0.8 lagging power factor, 1.0 power factor, and at 0.8 leading power factor.

(e) What is the efficiency of the transformer at full load with a power factor of 0.8 lagging?

$$\theta_{SC} = \cos^{-1}\frac{P_{SC}}{V_{SC}I_{SC}} = \cos^{-1}\frac{160\text{ W}}{(47\text{ V})(6\text{ A})}$$

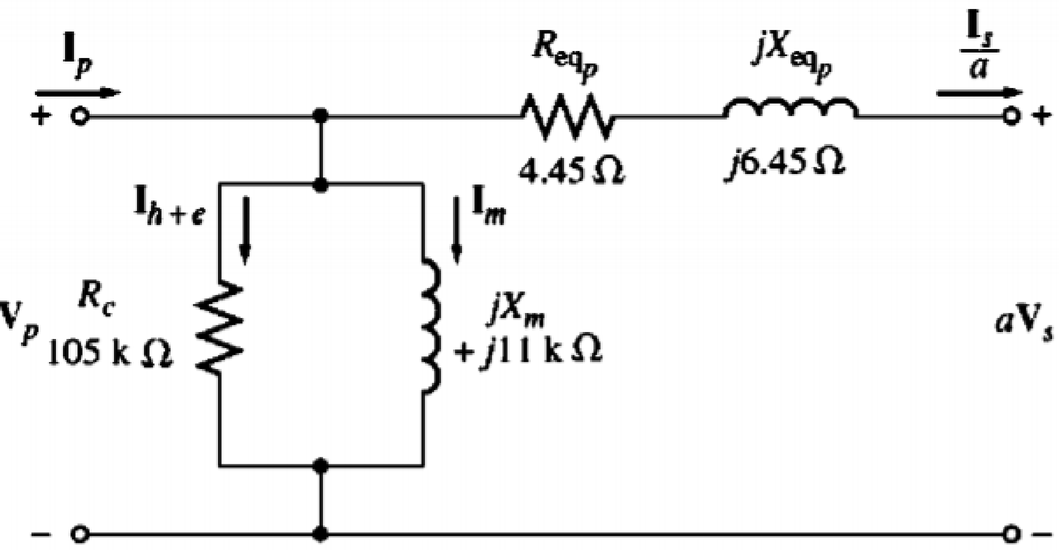
$$\theta_{OC} = \cos^{-1}\frac{P_{OC}}{V_{OC}I_{OC}} = \cos^{-1}\frac{50\text{W}}{(2300\text{ V})(0.21\text{ A})} = 84°$$

$R_{eq} =$?

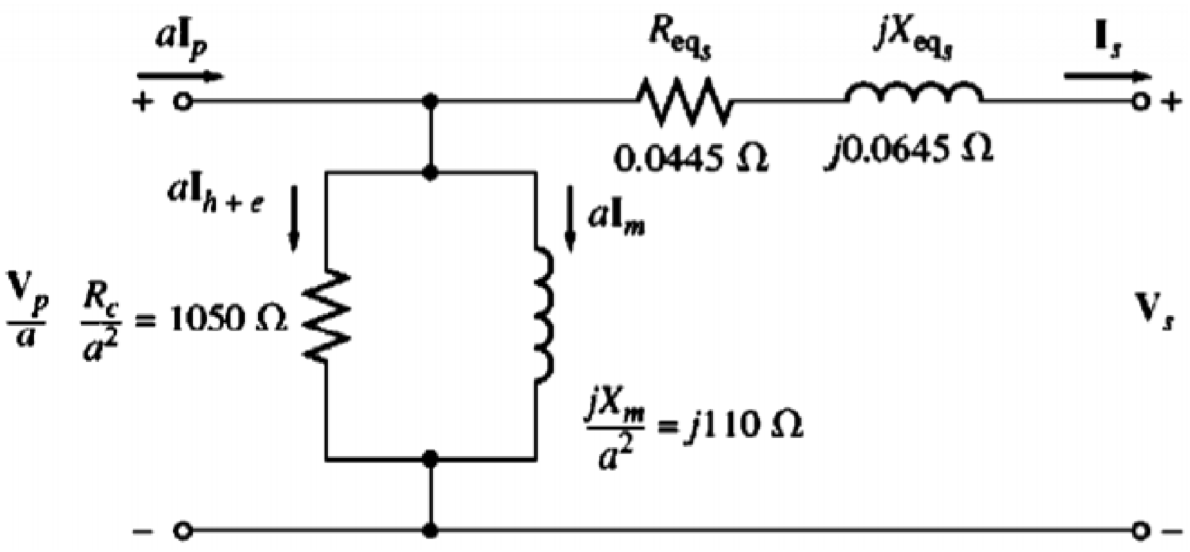
$X_{eq} =$?

$R_C =$? and $X_M =$?

Problem # 3 contd...



Eqv ckt referred to *primary*



Eqv ckt referred to *secondary*

Problem # 3 contd…

Regulation calculation at *Lagging power factor*

$$I_{S,\text{rated}} = \frac{S_{\text{rated}}}{V_{S,\text{rated}}} = \frac{15{,}000 \text{ VA}}{230 \text{ V}} = 65.2 \text{ A}$$

$$\frac{V_P}{a} = V_S + R_{eq}.I_S + j\,X_{eq}.I_S$$

At PF = 0.8 lagging, current $\mathbf{I}_S = 65.2 \angle -36.9° \text{ A}$.

$$\begin{aligned}\frac{\mathbf{V}_P}{a} &= 230\angle 0° \text{ V} + (0.0445\ \Omega)(65.2\angle -36.9° \text{ A}) + j(0.0645\ \Omega)(65.2\angle -36.9° \text{ A})\\ &= 230\angle 0° \text{ V} + 2.90\angle -36.9° \text{ V} + 4.21\angle 53.1° \text{ V}\\ &= 230 + 2.32 - j1.74 + 2.52 + j3.36\\ &= 234.84 + j1.62 = 234.85\angle 0.40° \text{ V}\end{aligned}$$

Voltage Regulation, $\text{VR} = \frac{V_P/a - V_{S,\text{fl}}}{V_{S,\text{fl}}} \times 100\% = \frac{234.85 \text{ V} - 230 \text{ V}}{230 \text{ V}} \times 100\% = 2.1\%$

Problem # 3 contd…

Regulation calculation at *Unity power factor*

At PF = 1.0, current $\mathbf{I}_S = 65.2\angle 0^\circ$ A.

$$\frac{\mathbf{V}_P}{a} = 230\angle 0^\circ \text{ V} + (0.0445\ \Omega)(65.2\angle 0^\circ \text{ A}) + j(0.0645\ \Omega)(65.2\angle 0^\circ \text{ A})$$

$$= 230\angle 0^\circ \text{ V} + 2.90\angle 0^\circ \text{ V} + 4.21\angle 90^\circ \text{ V}$$

$$= 230 + 2.90 + j4.21$$

$$= 232.9 + j4.21 = 232.94\angle 1.04^\circ \text{ V}$$

$$\text{VR} = \frac{232.94 \text{ V} - 230 \text{ V}}{230 \text{ V}} \times 100\% = 1.28\%$$

Problem # 3 contd…

Regulation calculation at *Leading power factor*

At PF = 0.8 leading, current $\mathbf{I}_S = 65.2 \angle 36.9° \text{ A}$.

$$\frac{\mathbf{V}_P}{a} = 230 \angle 0° \text{ V} + (0.0445 \,\Omega)(65.2 \angle 36.9° \text{ A}) + j(0.0645 \,\Omega)(65.2 \angle 36.9° \text{ A})$$

$$= 230 \angle 0° \text{ V} + 2.90 \angle 36.9° \text{ V} + 4.21 \angle 126.9° \text{ V}$$

$$= 230 + 2.32 + j1.74 - 2.52 + j3.36$$

$$= 229.80 + j5.10 = 229.85 \angle 1.27° \text{ V}$$

$$\text{VR} = \frac{229.85 \text{ V} - 230 \text{ V}}{230 \text{ V}} \times 100\% = -0.062\%$$

Problem # 3 contd…

Calculation of efficiency

$$P_{\text{Cu}} = (I_S)^2 R_{\text{eq}} = (65.2\text{ A})^2(0.0445\ \Omega) = 189\text{ W}$$

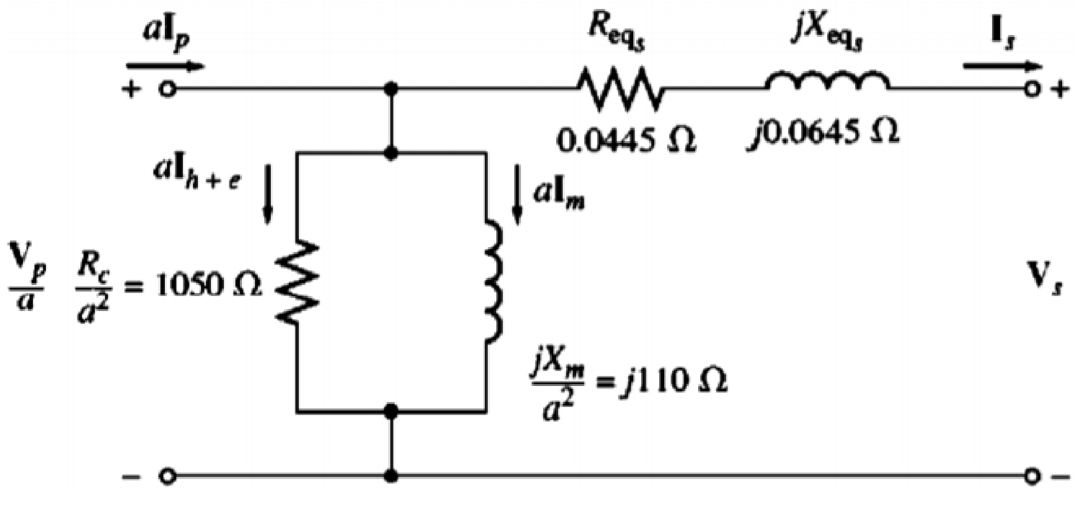
$$P_{\text{core}} = \frac{(V_P/a)^2}{R_C} = \frac{(234.85\text{ V})^2}{1050\ \Omega} = 52.5\text{ W}$$

$$P_{\text{out}} = V_S I_S \cos\theta = (230\text{ V})(65.2\text{ A})\cos 36.9^\circ = 12{,}000\text{ W}$$

$$\eta = \frac{V_S I_S \cos\theta}{P_{\text{Cu}} + P_{\text{core}} + V_S I_S \cos\theta} \times 100\%$$

$$= \frac{12{,}000\text{ W}}{189\text{ W} + 52.5\text{ W} + 12{,}000\text{ W}} \times 100\%$$

$$= 98.03\%$$



Condition for maximum efficiency

Cu loss $= I_1^2 R_{01}$ or $I_2^2 R_{02}$ where I_1 = Primary current I_2 = Secondary current

Iron loss = Hysteresis loss + Eddy current loss $= W_h + W_e = W_i$

Primary input $= V_1 I_1 \cos\phi_1$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

For η to be maximum, $\frac{d\eta}{dI_1} = 0.$

Thus, $\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1}$ → $W_i = I_1^2 R_{01}$ or $I_2^2 R_{02}$ → $\boxed{W_i = I_1^2 . R_{eqp} = I_2^2 . R_{eqs}}$

Why transformer rating in VA?