Energy conversion I

Lecture 7

Topic 2: Transformers & its performance (S. Chapman, ch. 2)

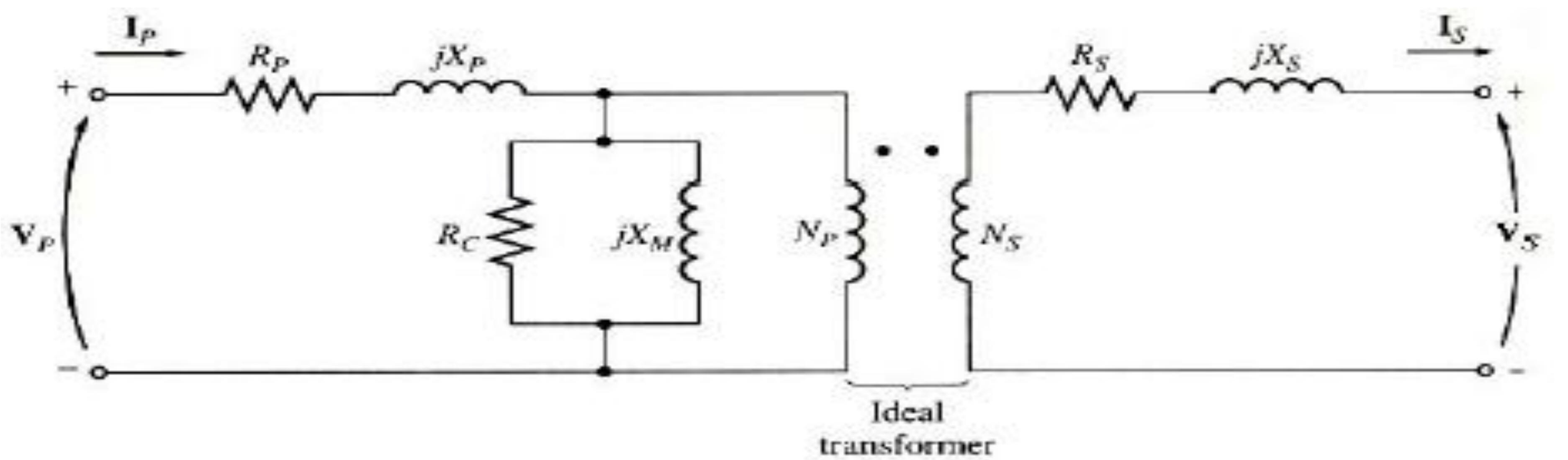
- Introduction
- Types and Construction of Transformers.
- Ideal Transformer.
- Theory of operation of real single-phase transformers.
- **The Equivalent Circuit of a Transformer.**
- The Per-Unit System of Measurement
- Transformer voltage regulation and efficiency
- Autotransformers
- Three phase transformers

Equivalent circuit of a real Transformer

- Copper (winding) loss: R_p, R_s
- Leakage flux: Xp(Lp), Xs(Ls)
- Core loss: R_c
- Magnetizing current (X_M)
- Transformer Turns ratio: Ideal transformer
- Electrical Isolation: Ideal transformer

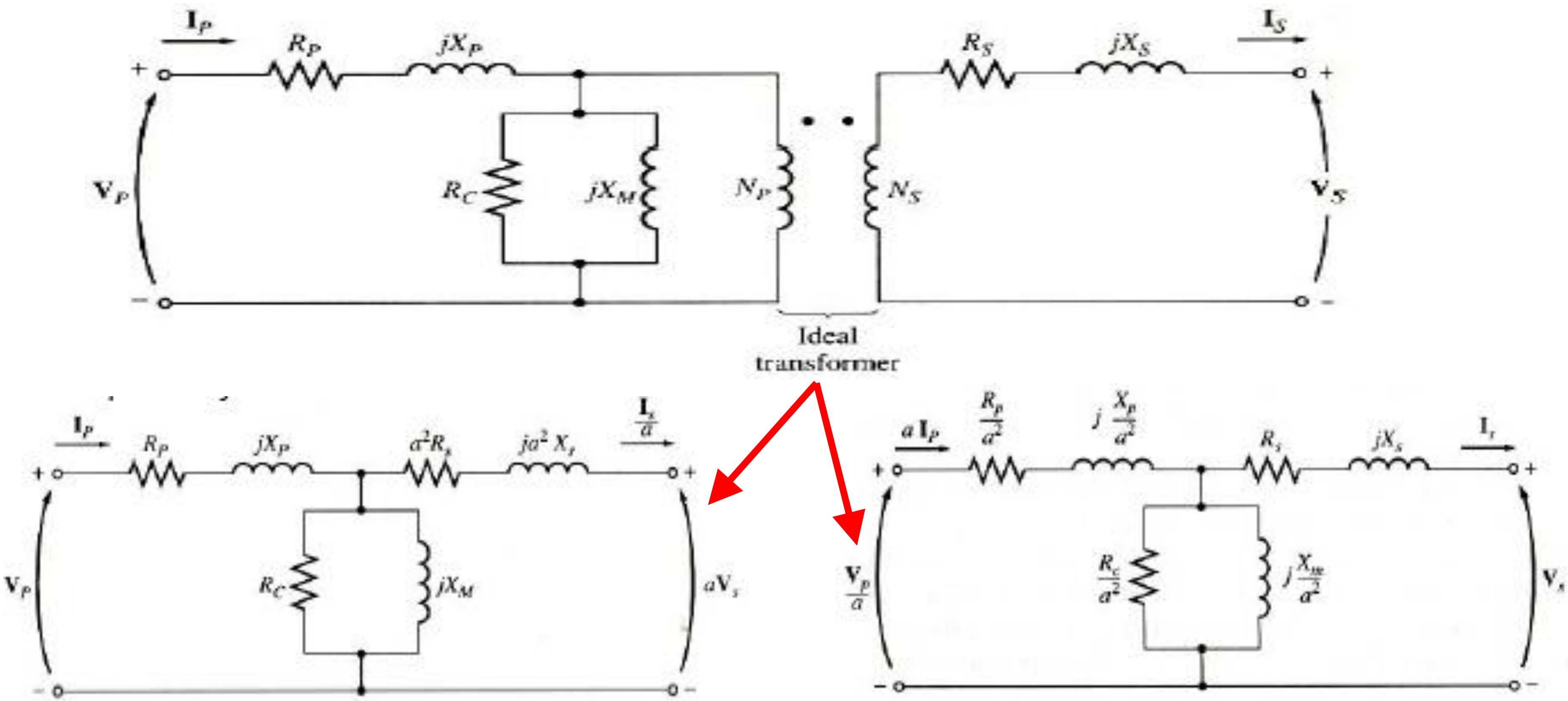
$$\frac{V_p}{V_s} \approx \frac{N_p}{N_s} = a$$

$$\frac{I_p}{I_s} \approx \frac{N_s}{N_p} = \frac{1}{a}$$



Other equivalent circuits of a real transformer

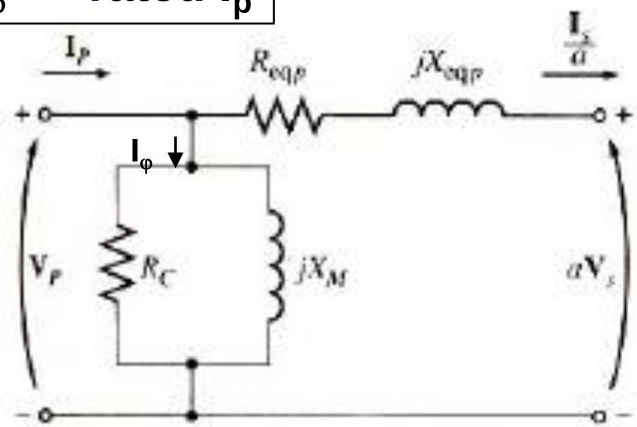
Having ideal transformer in the Model different models can be considered:

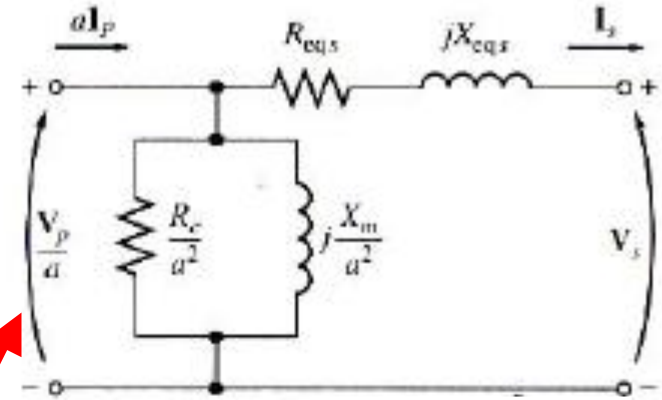


Referred to primary **Referred to secondary**

Approximate equivalent circuits of a real transformer

rated I_φ << rated I_p





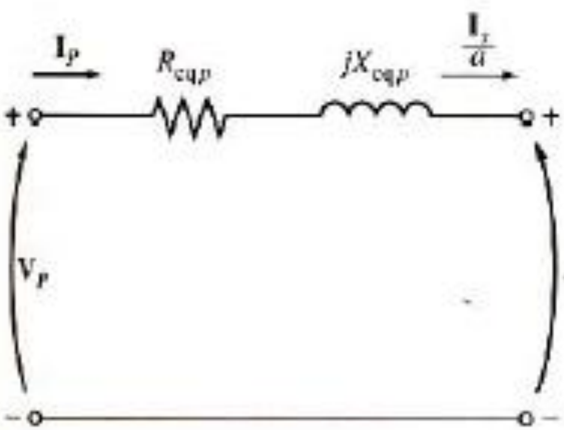
$R_{eqp}=R_p+a^2R_s$

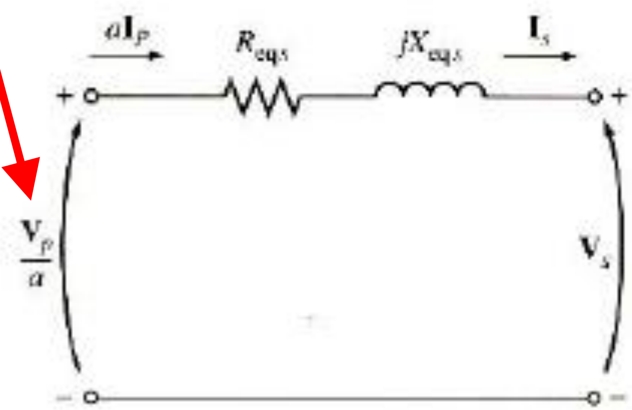
$X_{eqp}=X_p+a^2X_s$

$R_{eqs}=R_s+R_p/a^2$

$X_{eqs}=X_s+X_p/a^2$

Ideal Transformer





Equivalent circuit of a real Transformer

Example:

Approximate equivalent circuit parameters of a 20kVA, 8000/240V, 60Hz transformer are listed:

$R_{c,HV}$ = 160 kΩ, $X_{m,HV}$ = 38.4 kΩ, $R_{eq,HV}$ = 38.4 Ω, $X_{eq,HV}$ = 192 Ω

What is the ratio of magnetizing current to rated current?
What is the ratio of voltage drop across the transformer series impedance to rated voltage?

Solution:

Rated high-voltage winding current is:

$I_{HV,n} = 20000/8000 = 2.5$ A

$I_{\varphi} = 8000(1/160 - j1/38.4) = 50 - j208.3 = 214.2e^{-j76}$ mA (small lagging power factor)

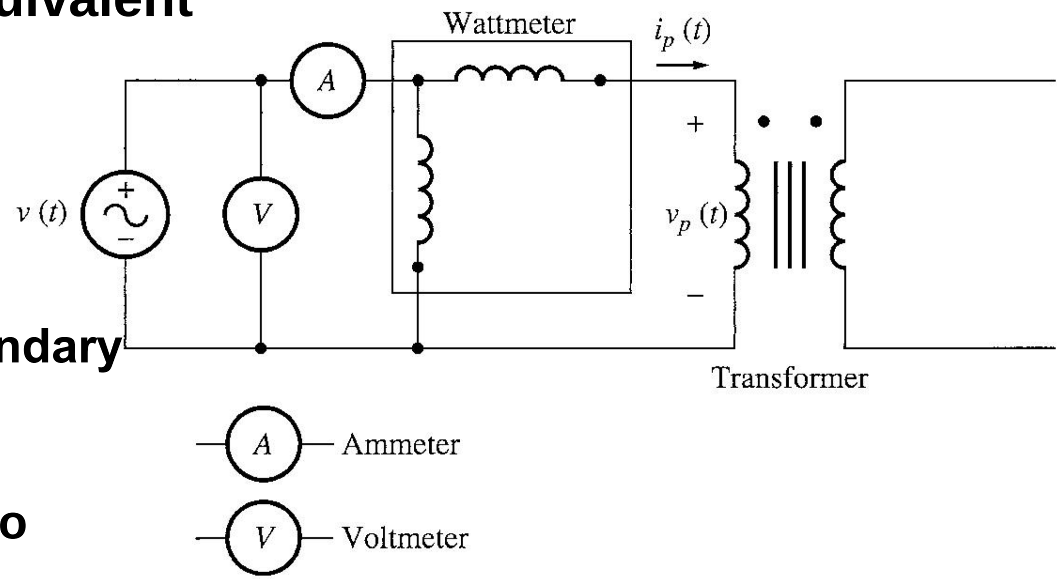
$I_m / I_{HV,n} = 214.2 * 10^{-3}/2.5 = 0.085 =$ **8.5%**

Voltage drop: $V = 2.5*(38.4+j192) = 96 + j480 = 489e^{j78.7}$ V

$V / V_{HV,n} = 489/8000 = 0.061 =$ **6.1%**

Determination of Equivalent circuit components

Experimental test to get the equivalent Circuit parameters:



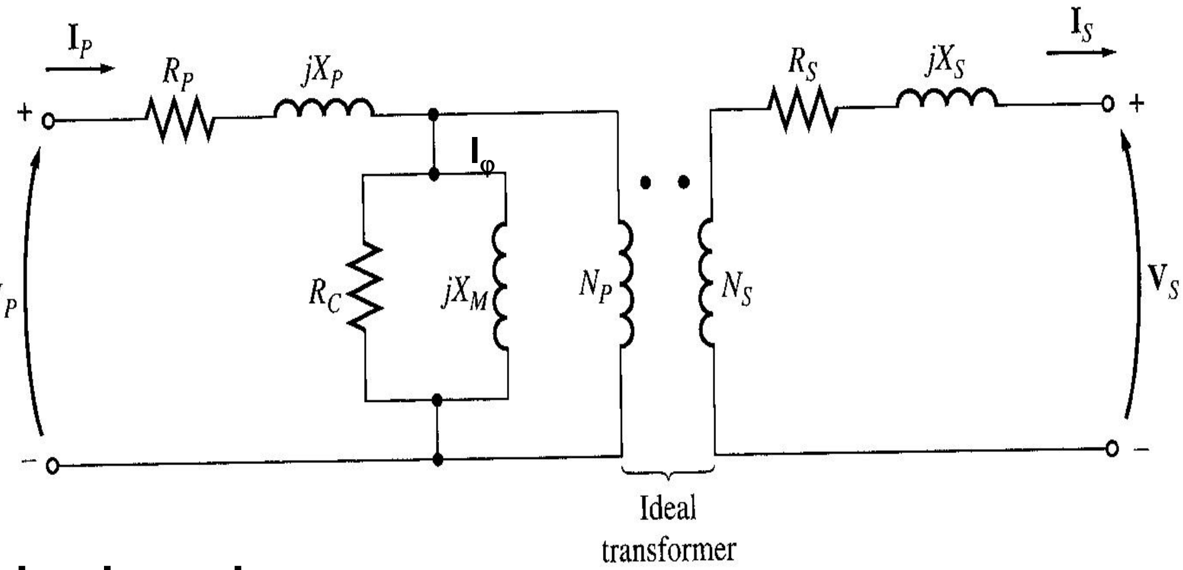
Open Circuit test:

open-circuited transformer's secondary winding (high voltage)

connecting full-rated line voltage to primary winding (low voltage)

Measuring V, I and P

Open-circuit test



$I_p = I_\varphi$ << rated I_p

⬇

Negligible voltage drop
Across: $R_p + j X_p$

⬇

Rated voltages across magnetizing branch

⬇

Operating close to rated magnetic operating point

⬇

R_c: origin of power loss (core loss)
X_m : origin of lagging power factor

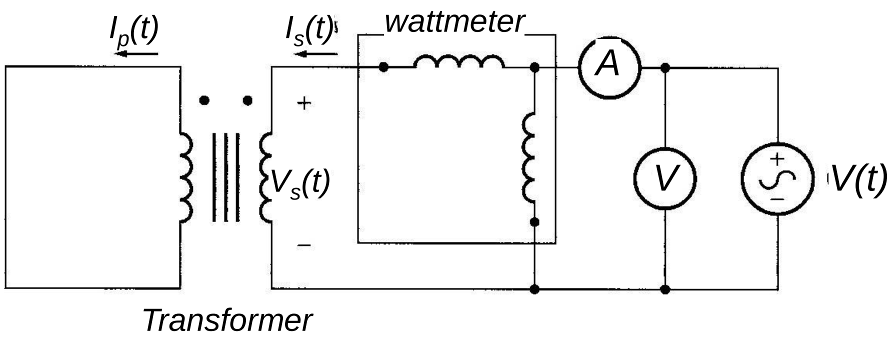
$$R_c = \frac{V_{oc}^2}{P_{oc}}$$

$$\frac{I_{oc}}{V_{oc}} = \sqrt{\frac{1}{R_c^2} + \frac{1}{X_m^2}}$$

Short-circuit test

Short-circuited transformer's primary winding (low voltage)

connecting full-rated-current voltage to secondary winding (high voltage)



Measuring V, I and P

$V_{sc} = V_s$ << rated V_s ➡ Negligible voltage drop across: R_c & j X_m ➡

Negligible magnetizing current ➡ rated current in primary & secondary winding

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2}$$

$$\frac{V_{sc}}{I_{sc}} = \sqrt{R_{eq}^2 + X_{eq}^2}$$

R_{eq}: origin of power loss (winding loss)
X_{eq} : origin of lagging power factor

Determination of Equivalent circuit components

Notes:

Open-circuit and Short-circuit test can be done either in the low-voltage or high-voltage winding.

Based on the measuring winding, the parameters are calculated in that side (Z_{eq} in High voltage side and R_c and X_m in low voltage).

Usually Open circuit test is measured in low voltage (with rated voltage) and Short circuit test is measured in high voltage side (with rated current).

To have the detailed equivalent circuit we can suppose that:

$$R_p = a^2 R_s$$
$$X_p = a^2 X_s$$

Determination of Equivalent circuit components

Example:

The open circuit test and the short circuit test results of a 20kVA, 8000/240V, 60Hz transformer are listed.

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

Find the approximate equivalent circuit referred to the high voltage side.

Solution:

O.C. test is measured in High voltage side! (How can it be found out)

S.C. test is measured in high voltage side. ($I_{hv,\ rated}$ = 20000/8000=2.5 A)

Using O.C. test results:

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

$$R_{c,HV} = \frac{V_{oc}^2}{P_{oc}} = \frac{8000^2}{400} = 160\,k\Omega$$

$$\frac{I_{oc}}{V_{oc}} = \sqrt{\frac{1}{R_c^2} + \frac{1}{X_m^2}} \Rightarrow X_m^2 = \left((\frac{I_{oc}}{V_{oc}})^2 - \frac{1}{R_c^2} \right)^{-1}$$

$$X_{m.HV} = 38.4 k\Omega$$

Using S.C. test results:

$$R_{eq,HV} = \frac{P_{sc}}{I_{sc}^2} = \frac{240}{2.5^2} = 38.4\Omega, \qquad \frac{V_{sc}}{I_{sc}} = \sqrt{R_{eq}^2 + X_{eq}^2} \Rightarrow X_{eq}^2 = \left(\frac{V_{sc}}{I_{sc}} \right)^2 - R_{eq}^2,$$

$$X_{eq,HV} = 192\,\Omega$$

What would be the Open circuit measurement results if done in LV side?

Try to find the detailed equivalent circuit having magnetizing branch in the HV side.