POWER ENGINEERING

#10 TRANSFORMERS

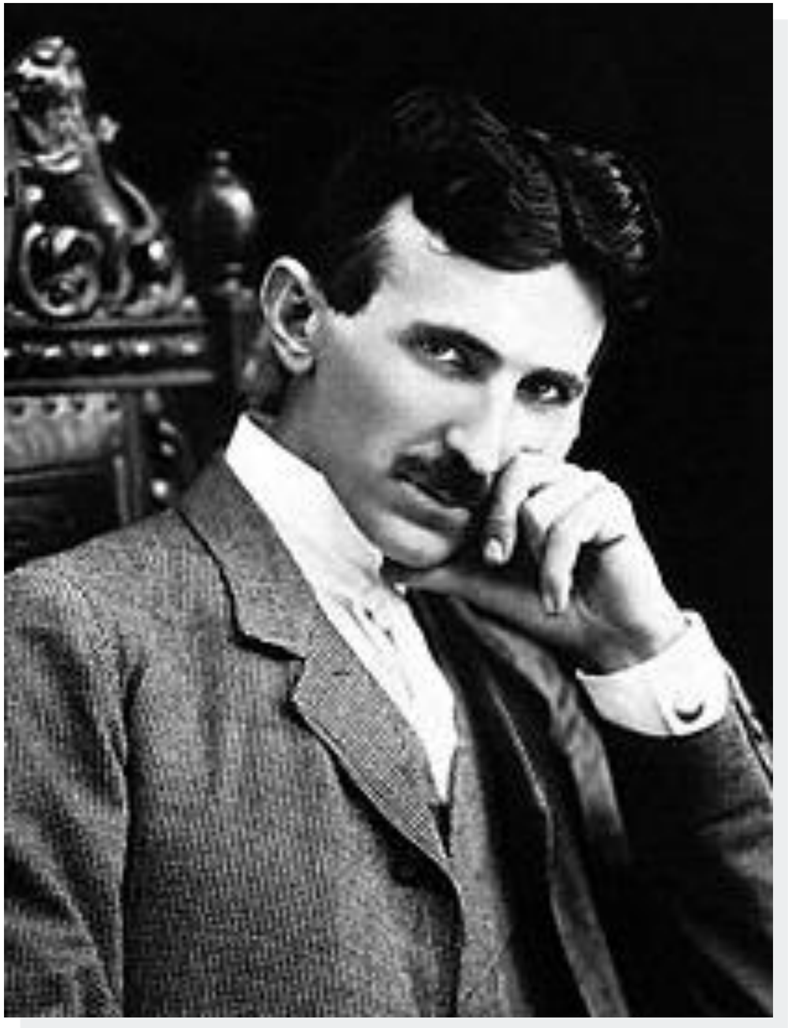
EQUIVALENT CIRCUIT (2)

2018

University of Glasgow

Tesla Quote of the Day

"It is paradoxical, yet true, to say, that the more we know, the more ignorant we become in the absolute sense, for it is only through enlightenment that we become conscious of our limitations. Precisely one of the most gratifying results of intellectual evolution is the continuous opening up of new and greater prospects"



Yip – cant argue with that ☺

Transformers

As we saw in lecture 2 the transformer is one of the principal reasons behind the adoption of AC power systems. Its ability to provide a (relatively!) cheap and reliable means of converting AC voltage levels results in high efficiency AC power transmission.

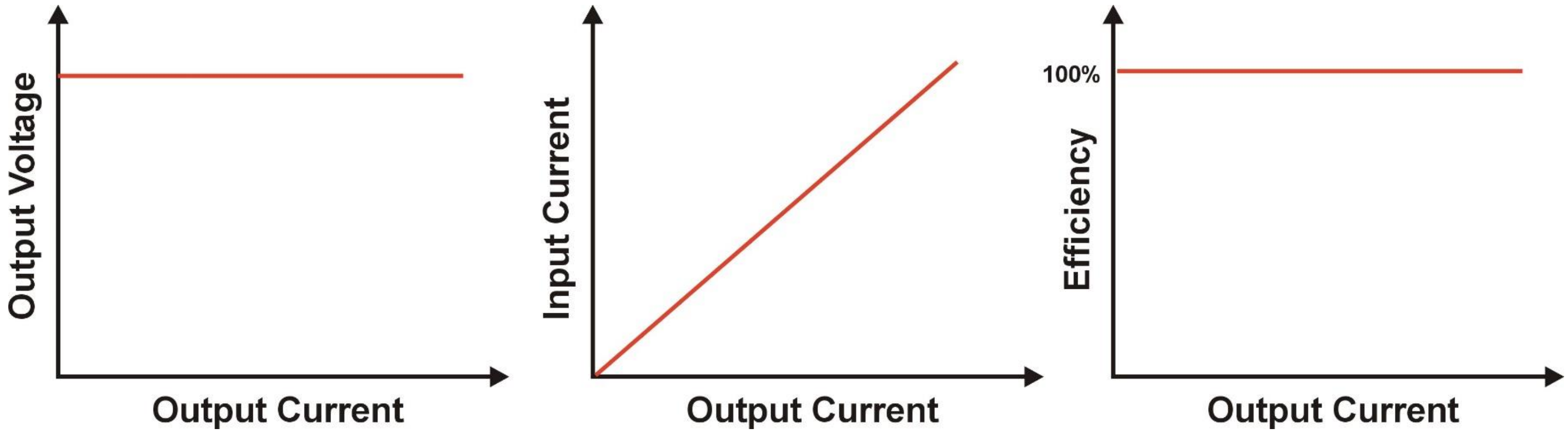
Over the next 4 lectures we will investigate:

- Types of Transformers
- The Ideal Transformer
- Basic Electromagnetics
- Transformer Limits
- The Equivalent Circuit for a practical Transformer
- Transformer performance under load: Efficiency & Regulation
- Tests to determine the Equivalent Circuit

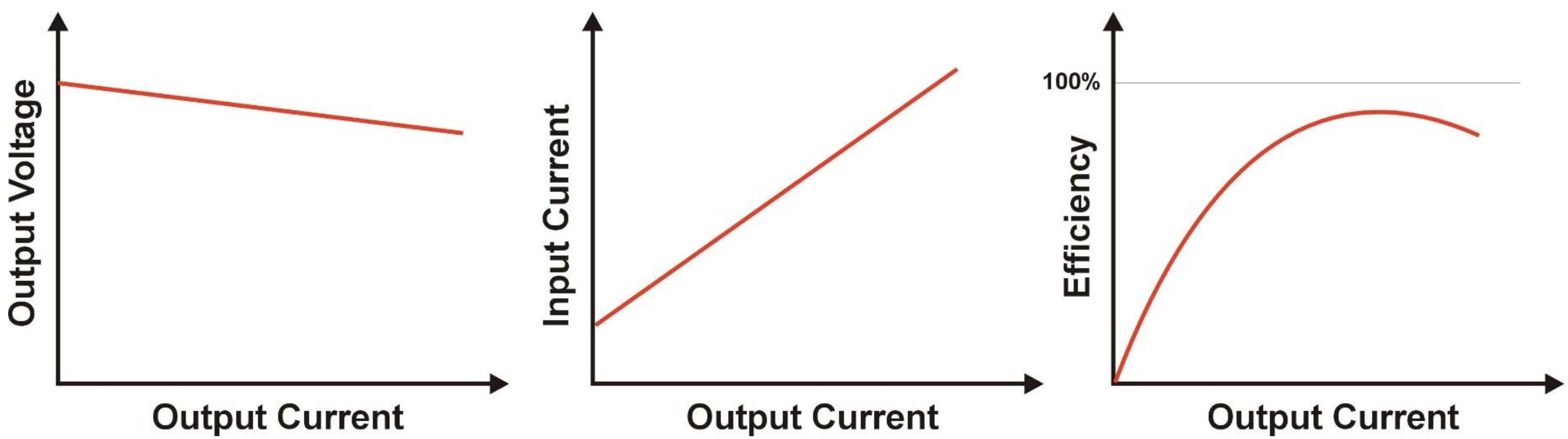
Today

- Three Phase Transformers

Ideal:



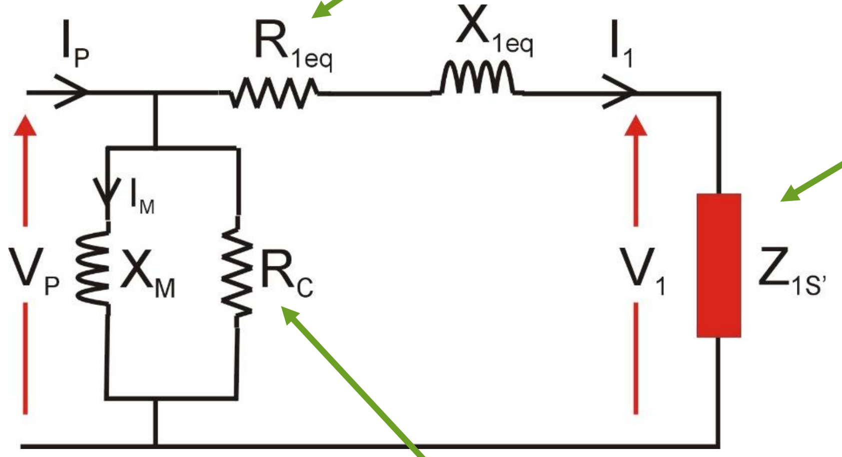
Practical:



Transformer performance under load: Efficiency

Copper Loss (W): $I_1^2.R_{1eq}$

Input Power (W): $V_p.I_p.Cos\Phi_p$



Output Power (W):

$V_1.I_1.Cos\Phi_1$

$V_s.I_s.Cos\Phi_s$

Iron (Core) Loss (W): V_p^2/R_c

Note: we generally have a purely resistive load connected to Secondary hence $Cos\Phi_1$ and $Cos\Phi_s = 1$

$$\text{Input Power (W)} = \text{Output Power (W)} + \text{Losses (W)}$$

Efficiency Equations:

1

$$\text{Efficiency (\%)} = \frac{\text{Output Power (W)}}{\text{Input Power (W)}} \times 100\%$$

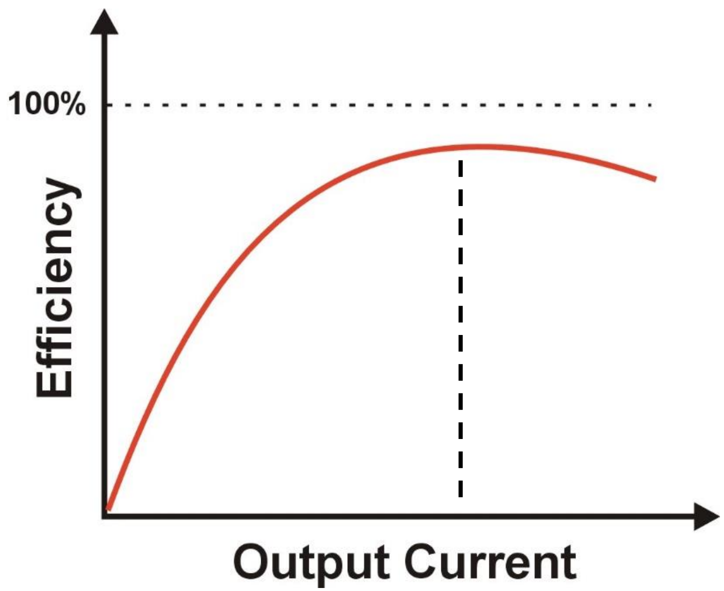
2

$$\text{Efficiency (\%)} = \frac{\text{Output Power (W)}}{\text{Output Power (W)} + \text{Losses (W)}} \times 100\%$$

3

$$\text{Efficiency (\%)} = \frac{\text{Input Power (W)} - \text{Losses (W)}}{\text{Input Power (W)}} \times 100\%$$

Determining Maximum Efficiency Point as a function of Output Current:



$$Efficiency = \frac{V_1 I_1 Cos\phi_1}{V_1 I_1 Cos\phi_1 + P_i + I_1^2 R_{1eq}}$$

(where P_i = Iron Loss)

Divide top and bottom by I_1:

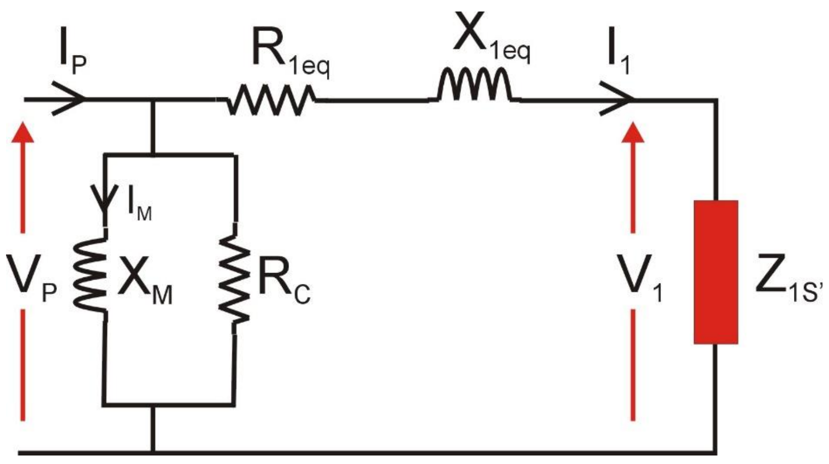
$$Efficiency = \frac{V_1 Cos\phi_1}{V_1 Cos\phi_1 + \frac{P_i}{I_1} + I_1 R_{1eq}}$$

Maximum Efficiency is when denominator is at a MINIMUM value (ie $d/dI_1 = 0$):

$$\frac{\partial}{\partial I_1}\left(V_1 Cos\phi_1 + \frac{P_i}{I_1} + I_1 R_{1eq}\right) = 0 \longrightarrow -\frac{P_i}{I_1^2} + R_{1eq} = 0 \longrightarrow P_i = I_1^2 R_{1eq} = P_{cu}$$

Ie when IRON LOSS = COPPER LOSS

Lecture 8 Example:



R_{1eq}	30Ω
X_{1eq}	100Ω
R_C	8kΩ
X_M	1kΩ

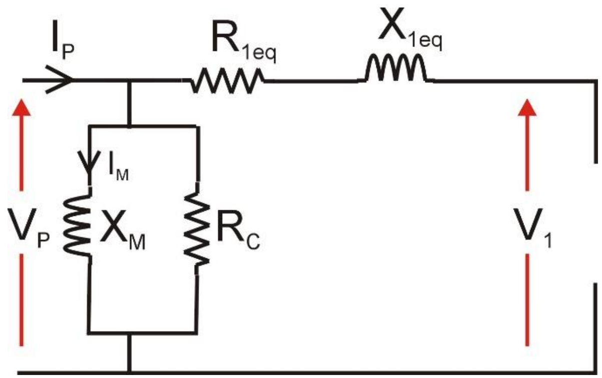
Calculate:

1. The efficiency of the transformer for the 680Ω load resistance
2. The value of load resistance which results in the transformer operating at its maximum efficiency point

Solution done on whiteboard during lecture

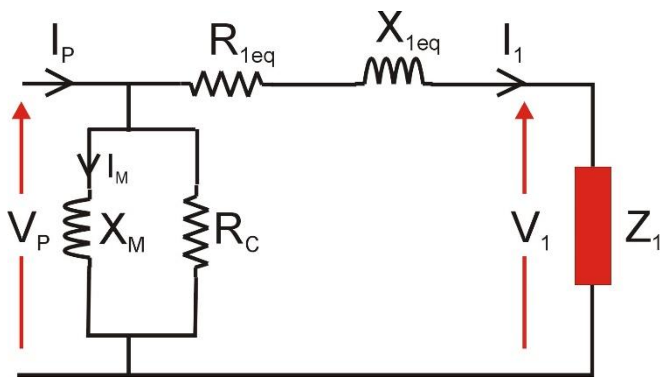
Transformer performance under load: Voltage Regulation

Case 1: No Load connected to Secondary (Open Circuit)



$$\text{Secondary Voltage} = Vp.\frac{Ns}{Np}$$

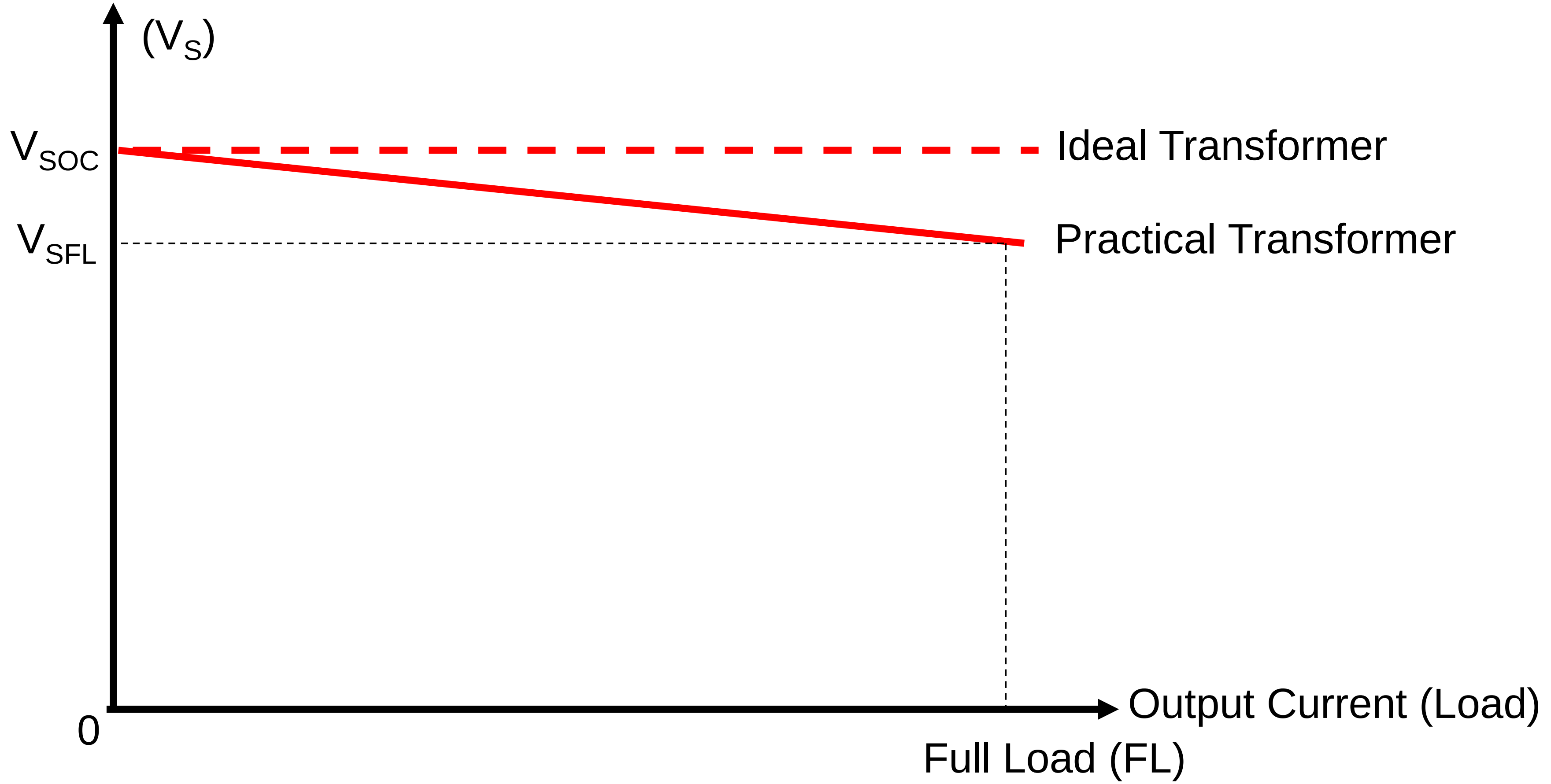
Case 2: Load connected to Secondary



$$\text{Secondary Voltage} < Vp.\frac{Ns}{Np}$$

Output Voltage as a function of Output Current

Secondary (Output) Voltage



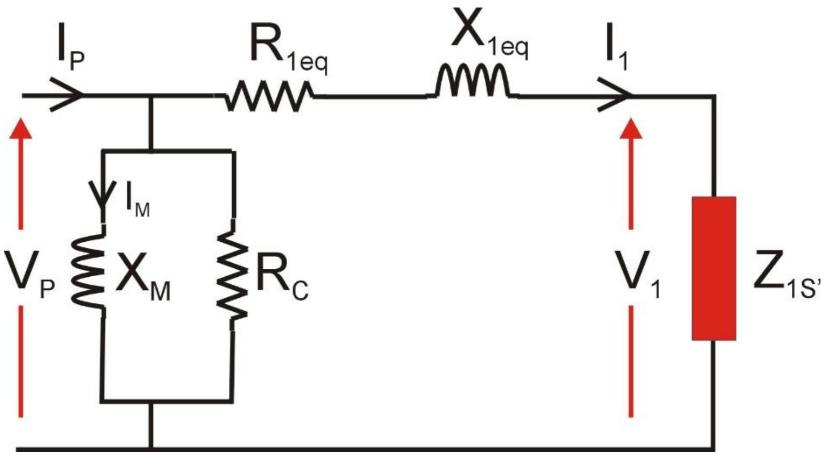
$$\text{Voltage Regulation (\%)} = \frac{V_{SOC} - V_S}{V_{SOC}} \times 100\%$$

Notes:

1] V_S is the Secondary Voltage under load

2] V_{SOC} is the Secondary Voltage under OPEN CIRCUIT conditions (no load)

3] The lower the value for Voltage Regulation the better (typically <5%)

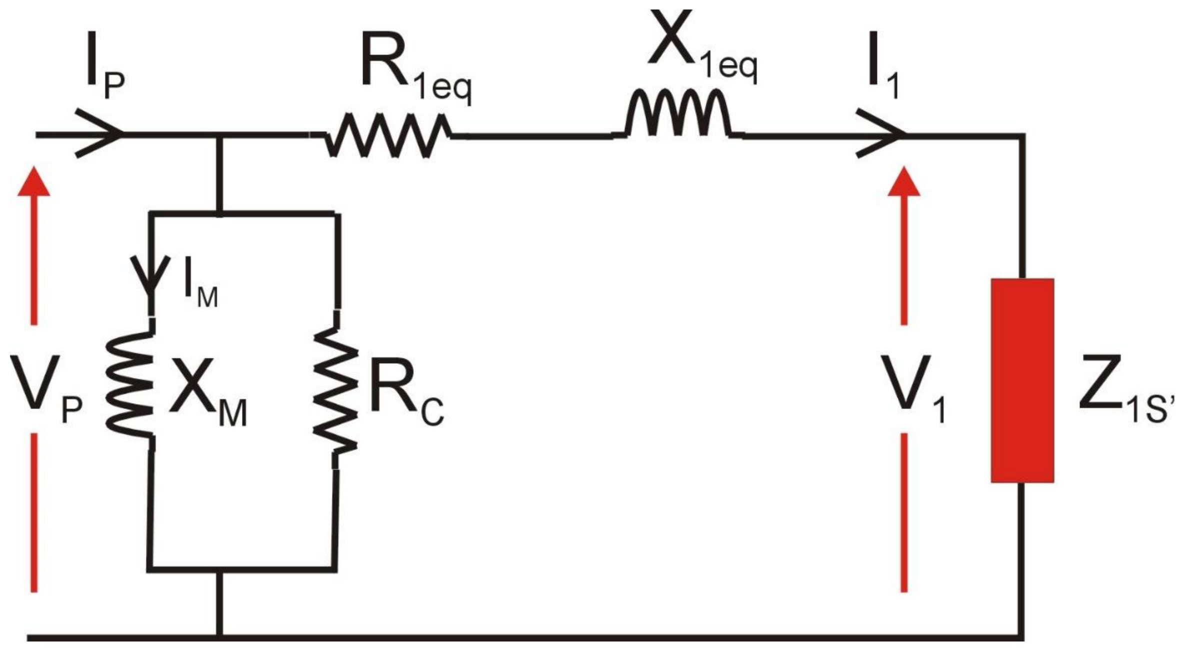


V_P	120V
R_{1eq}	2Ω
R_C	3kΩ
$Z_{1s'}$	144Ω
I_1	0.8A

Calculate:

1. **The transformer efficiency (%)**
2. **The transformer regulation (%)**

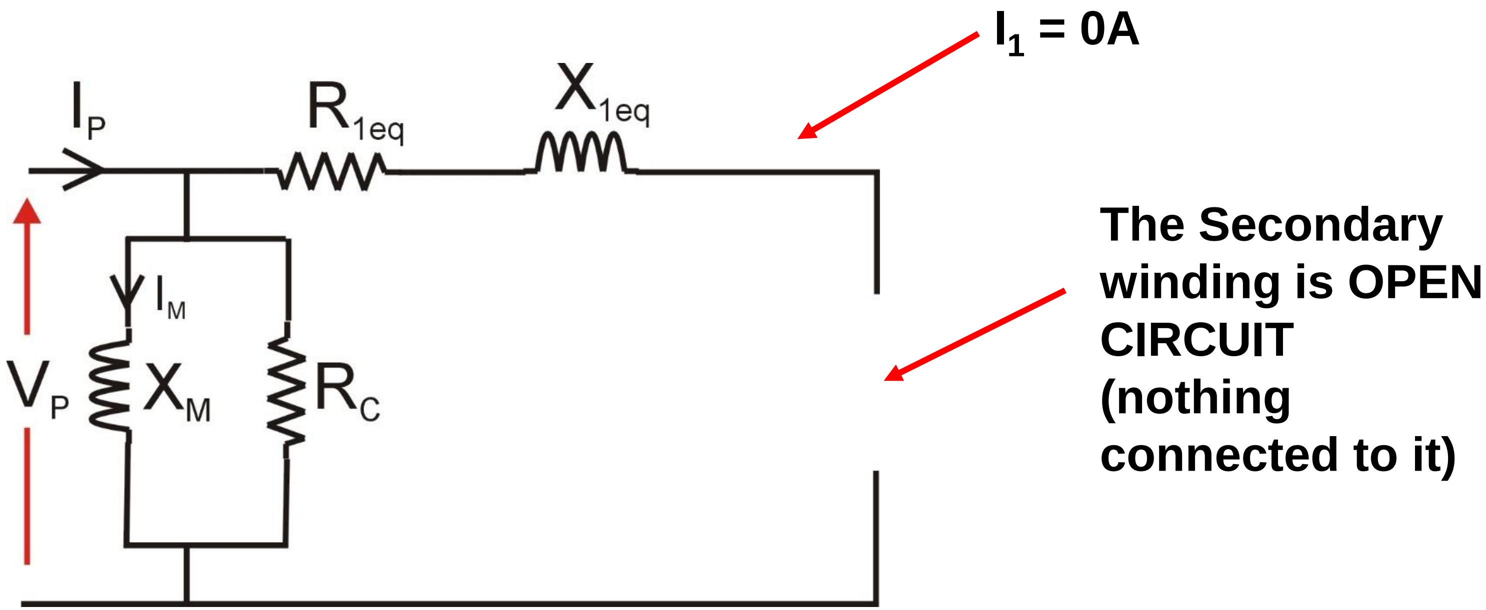
Tests to determine Equivalent Circuit Parameters



In this section we will investigate two tests which determine values for the Equivalent Circuit components:

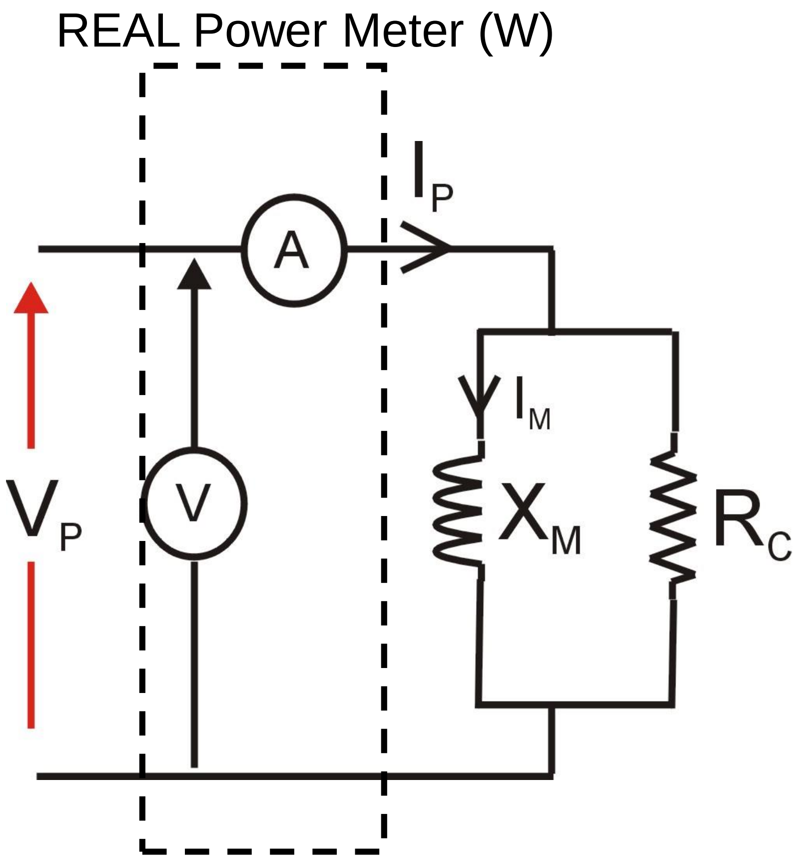
X_M R_C R_{1eq} X_{1eq} & Turns Ratio

Test 1: Open Circuit Test (X$_M$, R$_C$ & Turns Ratio)



As a result the equivalent circuit simplifies to that shown on the following slide:

Open Circuit Test



Note: REAL Power (P) is associated with Resistive components, REACTIVE Power (Q) Is associated with inductive components

Measurements:

V_P	Primary Voltage (V)
I_P	Primary Current (A)
P_P	Primary REAL Power (W)
V_{SOC}	Secondary OPEN CIRCUIT Voltage (V)

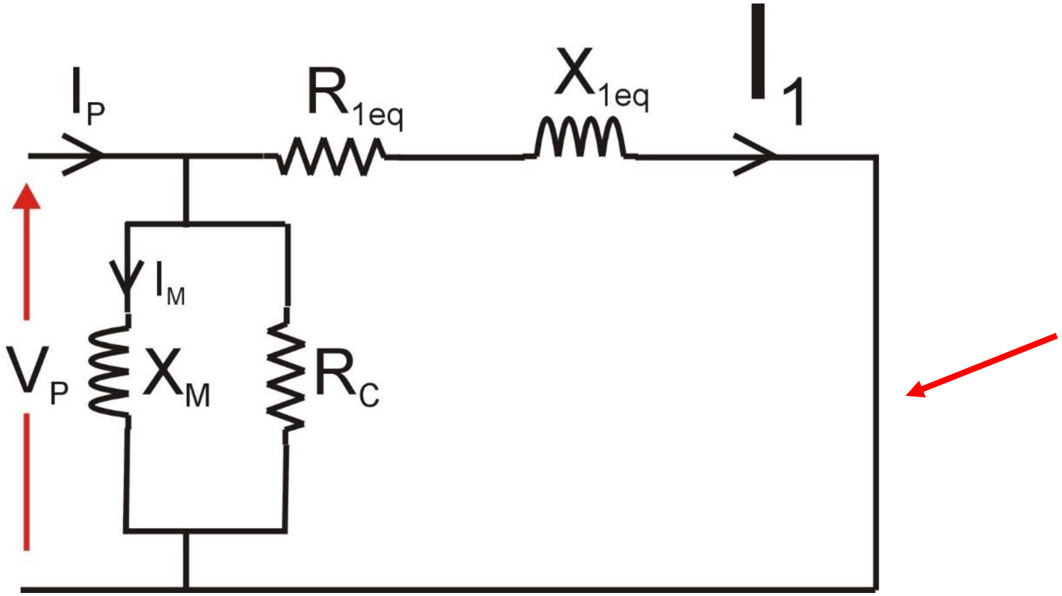
Calculations:

$$R_C = \frac{V_P^{\,2}}{P_P} \qquad S_P = V_P . I_P$$

$$Q_P = \sqrt{\left(S_P^{\,2} - P_P^{\,2}\right)} \qquad X_M = \frac{V_P^{\,2}}{Q_P}$$

$$Turns\_Ratio = \frac{V_P}{V_{SOC}}$$

<u>Test 2: Short Circuit Test</u> (X_{1eq}, R_{1eq})

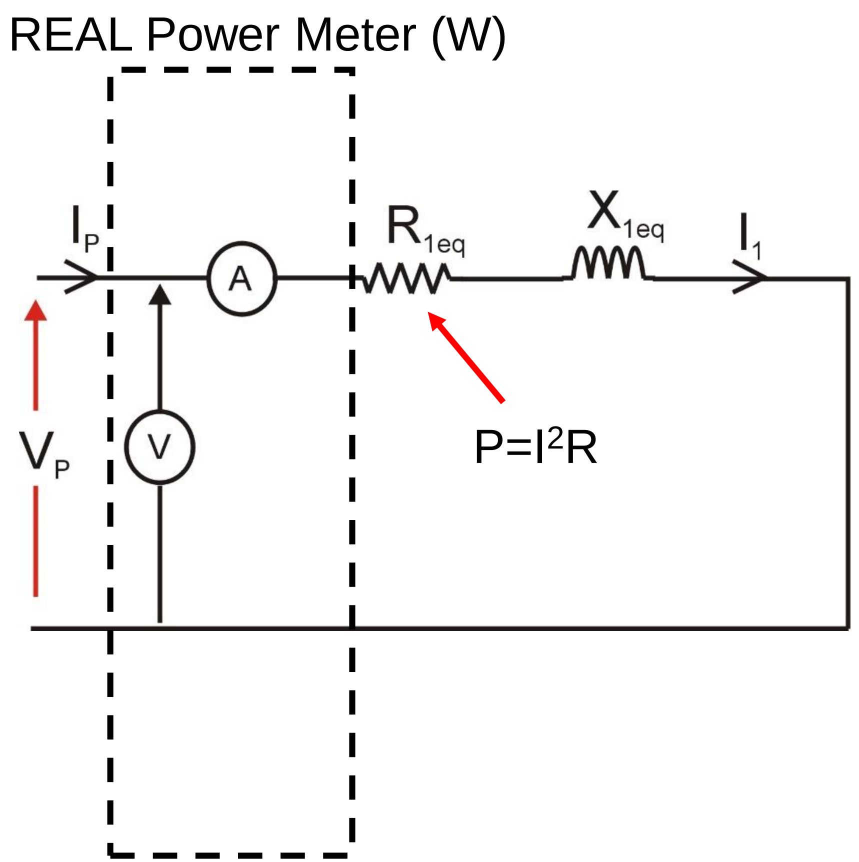


The Secondary Winding is Short Circuited (Z_S=0), and as a result I_1 flows through R_{1eq} and X_{1eq}

Note: We perform the test such that full load current flows in primary winding. Because the secondary winding is short circuit this requires a very much smaller primary voltage.

It turns out that I_1 is significantly bigger than I_M (&I_C) and therefore we can simplify the Equivalent Circuit to that shown on the following slide:

Short Circuit Test



Note: REAL Power (P) is associated with Resistive components, REACTIVE Power (Q) Is associated with inductive components

Measurements:

V_P	Primary Voltage (V)
I_P	Primary Current (A)
P_P	Primary REAL Power (W)

Calculations:

$$R_{1eq} = \frac{P_P}{I_P^{\,2}} \qquad S_P = V_P . I_P$$

$$Q_P = \sqrt{\left(S_P^{\,2} - P_P^{\,2}\right)} \qquad X_{1eq} = \frac{Q_P}{I_P^{\,2}}$$

Example:

The results of a transformer Open Circuit and Short Circuits tests are as follows, from these determine values for the transformer equivalent circuit parameters.

Open Circuit Test

V_p	240V
I_p	0.4A
P_p	20W
V_{SOC}	120V

Short Circuit Test

V_p	15V
I_p	3A
P_p	30W

Solution done on whiteboard during lecture