Basic Electrical Engineering KEE101/201

Department of Engineering

Uttar Pradesh Textile Technology Institute

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Post Assignment Lecture on Transformer

Losses in Transformer

There are Two types of Losses:

(1) Core Losses also known as Iron Losses. (Occur in Core)

(2) Copper Losses (Occur in Coil Resistance)

Core Loss

When a transformer core is subjected to an alternating time varying field, this field will cause in turn

- Eddy current and
- Hysteresis losses

These losses occur inside the core of the transformer. The sum of these two losses is known as core loss of the transformer.

Eddy current loss (Part of Core Loss)

It is I^2R loss occurring inside the core. The current is caused by the induced voltage in any conceivable closed path due to time varying field.

To reduce eddy current loss in a material we have to use very thin plates instead of using solid block of material which will ensure very less number of available eddy paths. *Eddy current loss per unit volume of the material directly depends upon the square of the frequency, flux density and thickness of the plate. Also it is inversely proportional to the resistivity of the material.* The core of the material is constructed using thin plates called lamination. Each plate is given a varnish coating for providing necessary insulation between the plates. Cold Rolled Grain Oriented, in short CRGO sheets are used to make transformer core.

Hysteresis loss (Part of Core Loss)

Hysteresis Loss occurs in magnetic material due to frequent magnetization and demagnetization of core. Steinmetz proposed the following empirical formula for quick and reasonable estimation of the hysteresis loss of a given material.

$$P_h = k_h B^n_{max} f$$

The value of n will generally lie between 1.5 to 2.5. Also we know the area enclosed by the hysteresis loop involving B-H characteristic of the core material is a measure of hysteresis loss per cycle.

The core losses are accumulation of Eddy Current losses and Hysteresis Losses

These losses normally depend upon supply voltage and frequency.

In a single phase transformer, supply voltage and frequency are usually constant and hence these (Core Losses or iron Losses) are assumed constant here.

Copper Losses:

There is some resistance in transformer windings of a practical transformer. The losses in primary winding are $I_1^2R_1$ and in secondary winding $I_2^2R_2$. Total copper losses are $I_1^2R_1 + I_2^2R_2$. It clearly shows that Copper losses depend upon winding current. Winding current depend upon Load and hence it is variable. Copper Losses P_{cu}, are therefore variable losses.

Total Transformer Losses

= Iron Losses + Copper Losses

$= P_i + P_{cu}$

Power Loss (Wattmeter Reading) measured during Open circuit test is loss at rated voltage and is equal to iron Loss P_i

Power Loss (Wattmeter Reading) measured during Short circuit test is loss at rated Current and is = Copper Loss P_{cu}

ट्रांसफार्मर में दो तरह के लॉसेस होते हैं एक तो कोर लॉसेस और दूसरा कॉपर लॉसेस। कॉपर लॉसेस वेरिएबल (परिवर्तनीय) लॉसेस होते हैं ये ट्रांसफार्मर वाइंडिंग के रेजिस्टेंस में ट्रांसफार्मर की करंट के बहने से होते हैं।

ट्रांसफार्मर में जब लोड कनेक्ट किया जाता है तो करंट बहती है। उस करंट का स्क्वायर कर के वाइंडिंग की रेजिस्टेंस से मल्टीप्लय करने पर कॉपर लॉसेस प्राप्त होते हैं। लोड परिवर्तनशील है अतः वाइंडिंग करंट भी परिवर्तनशील है। इसलिए इस करंट पर निर्भर होने वाले कॉपर लॉसेस परिवर्तनीय हैं।

कोर लॉसेस को आयरन लॉसेस भी कहते हैं। ये लॉसेस ट्रांसफार्मर की कोर में होते हैं। ये लॉसेस दो तरह के लॉसेस से मिल कर बनते है। पहला eddy करंट लॉस और दूसरा हिस्टेरेसिस लॉस।

ट्रांसफार्मर के कोर मटेरियल में विभिन्न स्थानों पर फ्लक्स डेंसिटी में वेरिएशन होने के कारण विभिन्न छोटे छोटे क्लोज्ड लूप करंट बहते हैं जिसके परिणाम स्वरुप एड्डी करंट लॉसेस होते है। हिस्टेरिसिस लॉसेस आयरन कोर में लगातार मैग्नेटिज़ेशन रिवर्सल के परिणाम स्वरुप उत्पन्न होते है।

ट्रांसफार्मर में ओपन सर्किट टेस्ट प्राइमरी (लौ वोल्टेज) साइड में रेटेड वोल्टेज की आपूर्ति की जाती है और सेकेंडरी (हाई वोल्टेज वाइंडिंग) के टर्मिनल्स को ओपन रखा जाता है। इस टेस्ट में प्राप्त वाटमीटर रीडिंग आयरन लॉसेस के बराबर होती है।

शार्ट सर्किट टेस्ट में सेकेंडरी (लौ वोल्टेज) वाइंडिंग के टर्मिनल्स को शार्ट कर दिया जाता है और प्राइमरी (HV) वाइंडिंग को बहुत थोड़ा सा वोल्टेज सप्लाई किया जाता है जब तक सेकेंडरी वाइंडिंग में रेटेड करंट न बहने लगे । जब सेकेंडरी वाइंडिंग में रेटेड करंट का फ्लो होने लगे तो रीडिंग्स ली जाती हैं । इस समय प्राप्त वाट मीटर की रीडिंग कॉपर लॉस के बराबर होती है। ये लॉसेस रेटेड करंट पर हो रहे हैं इसलिए ये फुल लोड कॉपर लॉसेस होते हैं।

यह समझना आवश्यक है की ओपन सर्किट टेस्ट से कोर लॉसेस के अतिरिक्त शंट ब्रांच के पैरामीटर्स भी प्राप्त होते हैं ।

ट्रांसफार्मर इक्विवैलेन्ट सर्किट (समतुल्य परिपथ) में यह बताया गया था। शंट ब्रांच में दो पैरामीटर्स होते हैं, पहला mangetizing reactance Xm और दूसरा कोर लॉस रेजिस्टेंस Rc इन्हें प्राप्त करने के लिए पहले टेस्ट से प्राप्त रीडिंग्स पर ध्यान दें ।

तीन रीडिंग मिलती हैं Pi, Io और Vo इसके आगे सबसे पहले

(१) पावर फैक्टर कैलकुलेट करना है फिर

(2) magnetizing करंट और कोर लॉस करंट कैलकुलेट करनी हैं फिर

(3) वोल्टेज को मैग्नेटीज़िंग करंट से डिवाइड करने पर Xm प्राप्त होगा और

वोल्टेज को कोर लॉस करंट से डिवाइड करने पर Rc प्राप्त होगा।

इसी प्रकार शार्ट सर्किट टेस्ट से कॉपर लॉसेस के अतिरिक्त सीरीज ब्रांच के पैरामीटर (Req और Xeq) (लो वोल्टेज साइड की तरफ) प्राप्त होंगे । Supplied वोल्टेज को रेटेड शार्ट सर्किट करंट से डिवाइड करने पर शार्ट सर्किट impedance Zeq प्राप्त होगा।

प्राप्त पावर को करंट के स्क्वायर से डिवाइड करने पर Req प्राप्त होगा। और Zeq तथा Req प्राप्त होने पर आप Xeq स्वयं कैलकुलेट कर सकते हैं।

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

जिनको पहले की क्लास में पढ़ाया गया उपरोक्त टॉपिक समझ नहीं आया वह अब पुनः नीचे दिए गए लेक्चर नोट्स को ध्यान से पढ़ें । इसके पश्चात् दिए गए न्यूमेरिकल्स को सॉल्व करने का फिर से प्रयास करें और अगेली क्विज के लिए तैयार रहे।

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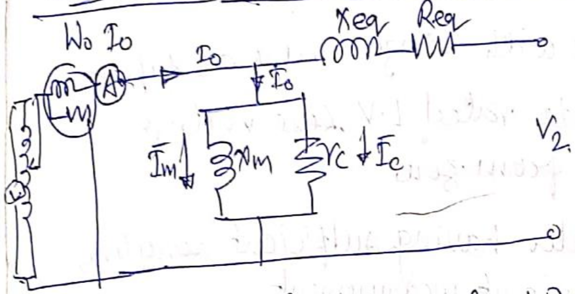
जिनको पहले की क्लास में पढ़ाया गया उपरोक्त टॉपिक समझ नहीं आया वह अब पुनः नीचे दिए गए लेक्चर नोट्स को ध्यान से पढ़ें । इसके पश्चात् दिए गए न्यूमेरिकल्स को सॉल्व करने का फिर से प्रयास करें और अगेली क्विज के लिए तैयार रहे।

Open ckt or No load Test on single phase T/R ①



Test is done (measurements etc) at L.V. side because:—

(1) At L.V. side Instrumentation is easier as compared to that at H.V. side

(2) No load current is normally less than 5% of rated voltage (very less). Further, in transformer the H.V. winding carry lesser current as compared to that of H.V. side. In this case to get the better current reading we must measure at L.V. side

(3) At No load test, one coil is to be given full rated voltage. And it is easier to provide rated voltage of L.V. as compared to that of H.V. (say 220/11000 V. T/R)

②

For test we need.

(1) A variac with single phase ac supply to provide rated L.V. side voltage starting from zero

(2) An ammeter having sufficient sensitivity for low current measurement

(3) A voltmeter to measure rated voltage of coil terminals.

(4) A wattmeter with
  (A) current coil sensitive enough for low circuit current
  (B) Meter should be Low power factor type as circuit power factor is very low at No load and is nearly zero.

Connect the instruments and supply rated voltage to the L.V. side of transformer.

Measure

$W_0 = \checkmark$ (P_0)

$I_0 = \checkmark$ Excitation or No load current when secondary is open

$V_1 = \checkmark$ Rated primary voltage (ensure it is reached to rated value).

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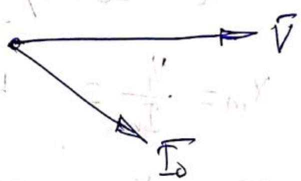
(3)

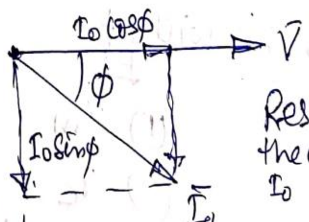
phasor diagram

only supply voltage



Voltage with No load current and secondary winding open.

ϕ is angle between voltage and current I_0
so $\cos\phi$ is power factor.



Resolve the current I_0

$I_0 \cos\phi$ = Active component of current $= I_c$
$I_0 \sin\phi$ = Reactive Component of current $= I_m$

(4)

From readings of W_0, V_1 and I_0

$$W_0 = P_0 = V_1 I_0 \cos\phi$$

so $\cos\phi = \dfrac{W_0}{V_1 I_0}$ (All are known and measured)

Now $I_m = I_0 \sin\phi = I_0 \sqrt{1-\cos^2\phi}$

$I_c = I_0 \cos\phi$ known.

$$X_m = \frac{V_1}{I_m} = \text{known}$$

$$r_c = \frac{V_1}{I_c} = \text{known} = \frac{V_1}{I_0 \cos\phi}$$

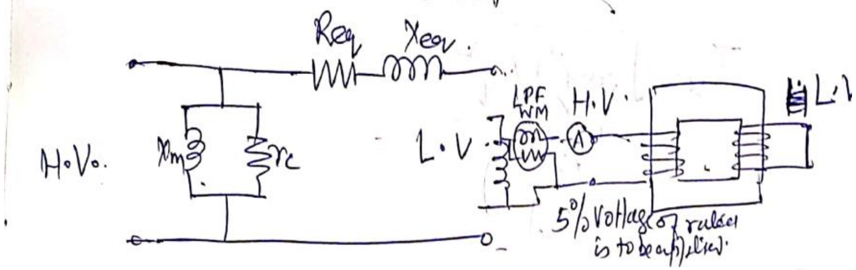
$$r_c = \frac{V_1}{I_0} \frac{V_1 I_0}{W_0} = \frac{V_1^2}{W_0}$$

So we will get

(1) X_m
(2) r_c
(3) Core losses $P_i = W_0$

Note that due to very less current the losses in winding are so less as compared to $W_0 = P_i$ that these are ignored.

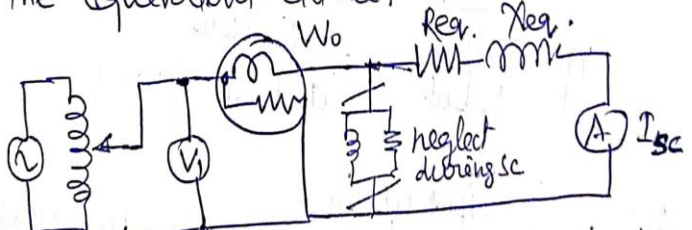
Short Circuit test on Single phase Transformer



To conduct the test L.V. side is short circuited and a little voltage is applied at H.V. side till the rated current flows through short circuited L.V. coil.

As losses in copper winding are full load losses due to flow of rated current, the fixed losses P_i can be ignored (being very little as compared to P_{cu}).

The equivalent ckt be:—



Approximate equivalent circuit for finding out series branch parameters R_{eq} & X_{eq} Referred to HV side.

$$Z_{sc} = \sqrt{R_{eq}^2 + X_{eq}^2}$$

$$= \frac{|V_s|}{|I_{sc}|}$$

$$W_{sc} = I_{sc}^2 R_{eq}$$

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

$$X_{eq} = \sqrt{Z_{sc}^2 - R_{eq}^2}$$

The test is done at full load current so the value of Power loss $W_{sc} = P_{cu}$ is full load copper loss.

Efficiency

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{losses}}$$

$$= \frac{\text{Output}}{\text{output} + P_i + P_{cu}}$$

$$\eta = \frac{V_2' I_2' \cos\phi}{V_2' I_2' \cos\phi + P_i + P_{cu}} = \frac{V_2 I_2 \cos\phi}{\ldots}$$

P_i → depends upon applied voltage and frequency; it is constant because normally 1φ T/R operates at const Volts & freq.

$P_{cu} = I_2'^2 R_{eq}'$
$= I_2^2 R_{eq}'$

$$= \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + P_i + I_2^2 R_{eq}'} = \frac{V_2 \cos\phi}{V_2 \cos\phi + \frac{P_i}{I_2} + I_2 R_{eq}'}$$

Efficiency at any given load condition

$$\eta_{(nu)} = \frac{\text{Output Power}}{\text{Input power}} = \frac{\text{Output Power}}{\text{Output power} + \text{Losses}}$$

$$= \frac{\text{Output Power}}{\text{Output Power} + P_i + P_{cu}}$$

KVA load on a transformer is $V_2 I_2$ | Copper loss $= I_2^2 R_{eq_2} = P_c$ (at x fraction of load)

Full load Copper loss $P_{cu} = I_{2fl}^2 R_{eq}$

$$\frac{P_{cux}}{P_{cu}} = \left(\frac{I_2}{I_{2fl}}\right)^2 = \left(\frac{V_2 I_2}{V_2 I_{2fl}}\right) \times x^2$$

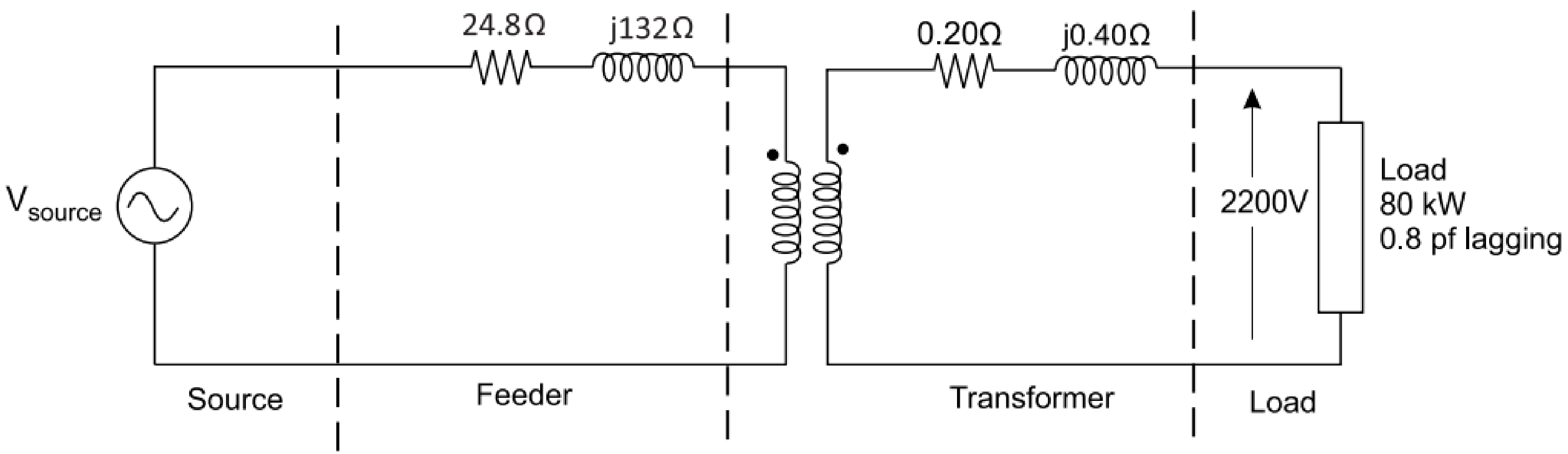
$$\eta_x = \frac{x\,(KVA)_{rated} \cdot \cos\phi}{x\,(KVA)_{rated} \cos\phi + P_i + x^2 P_{cu}}$$

$$P_i = x^2 P_{cu}$$

$$x = \sqrt{\frac{P_i}{P_{cu}}}$$

A 100-kVA, 24/2.4 kV single-phase transformer is connected to a power source through a feeder of impedance 24.8 + j132 Ω. The equivalent series impedance of the transformer referred to its low voltage side is 0.20 + j0.40 Ω. The load on the low-voltage side of the transformer is 80 kW at 0.8 pf lagging and 2200V. What is the voltage regulation of transformer in percentage?

Solution: Make this Equivalent circuit first



The secondary current I_2 is given by

$$|I_2| = \frac{80k}{(2200)(0.8)} = 45.45A$$

The power factor 0.8 lagging, corresponds to an impedance angle of $36.87\,^o$.

Hence, the secondary current phasor is given by

$$I_2 = 45.45\angle - 36.87\,^o A$$

To find the voltage-regulation of the transformer, we have to find the primary side voltage of the transformer referred to the secondary side

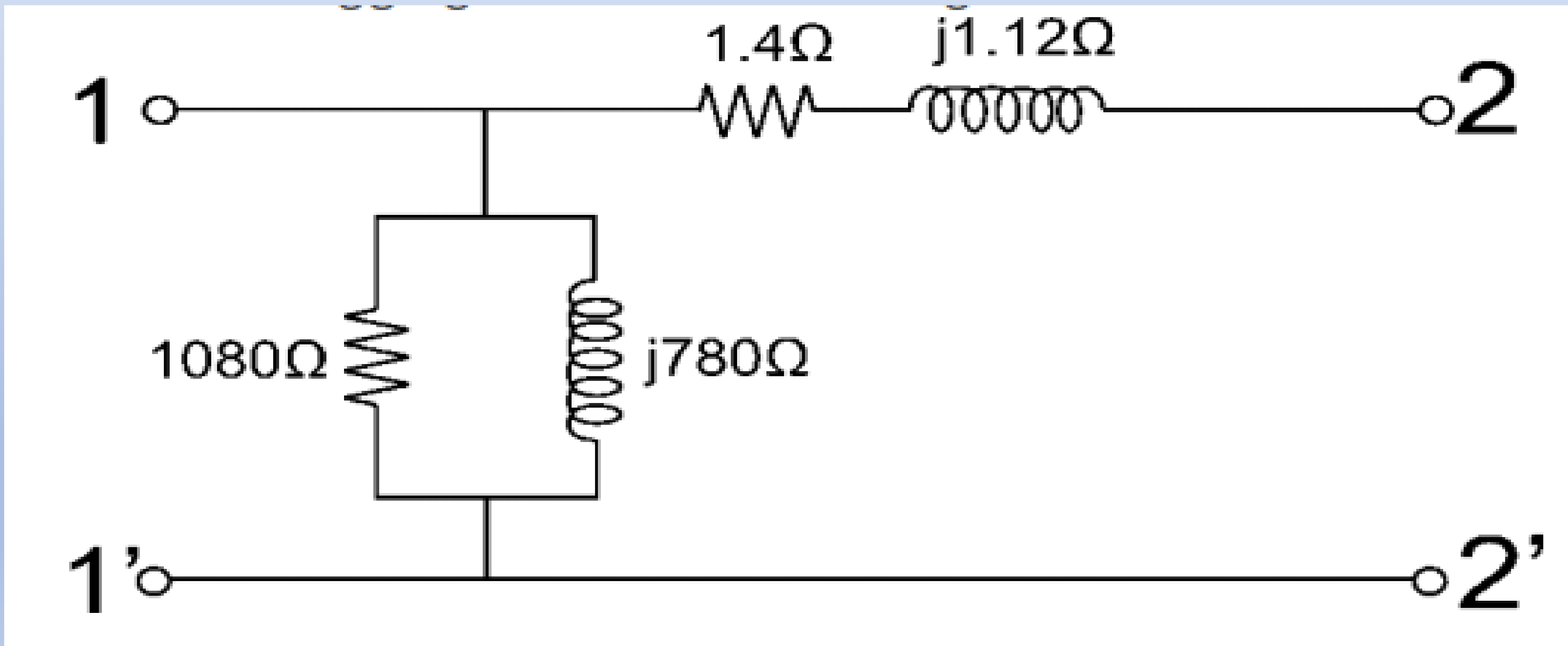
$$V'_{source} = 2200 + 45.45\angle - 36.87(0.2 + j0.40)$$

$$V'_{source} = 2218.19\angle 0.23$$

Therefore, the voltage regulation of the transformer is

$$VR = \frac{2218.19 - 2200}{2200} \times 100 = 0.83\%$$

The equivalent circuit of a 5.5 kVA, 220V/440V, 50 Hz transformer referred to HV side is shown in figure. What should be the applied voltage to the LV side when the transformer delivers rated current at 0.7 power factor lagging at a terminal voltage of 400V?



Sol^n Parameters are given at H.V. side it means we have to find out $\bar{V}_{NL}$ at H.V. side or V_1'.

Once we get it we have to convert it to L.V. side by

$$V_1 = \left(\frac{N_1}{N_2}\right) \times V_1'$$

Rated current $I_2 = \frac{5.5 \times 10^3}{440} = 12.5$ A

it is at 0.7 lag means $\cos\phi = 0.7 \Rightarrow$
$\phi = (-45.57°)$

So $\bar{I}_2 = 12.5 \angle -45.57°$

Now $V_1' = V_{2NL} = \bar{I}_2 Z_2 + 400\angle 0°$

$= (12.5 \angle -45.57°)(1.4 + j1.12) + 400\angle 0°$

$= (12.5 \angle -45.57°)(\sqrt{1.4^2 + 1.12^2} \angle 38.65 + 400\angle 0°$

$= 1.79 \times 12.5 \angle -6.9° + 400\angle 0°$

$= 22.41(0.99 + j0.12) + (400 + j0)$

$= 422.18 + j2.689 = \sqrt{422.18^2 + 2.69^2} \angle 0.37$

$= 422.19 \angle 0.37°$ V

So $V_1 = \frac{220}{440} \times 422.19 = 211$ V.

Practical Transformer

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The following data were obtained for a 5 kVA, 50 Hz, 200/1000 V single phase transformer:

O.C. Test (L.V. Side) : 200V, 1.2 A, 90W

S.C. Test (H.V. Side): 50 V, 5A, 110W.

(1) Find Shunt Branch Parameters at LV side

(2) Find Shunt branch parameters referred to high voltage side

(3) Find Series Branch parameters

(4) Find No Load Transformer Voltage (V_{NL}) and the voltage regulation of the transformer in percentage, with full-load on the HV side at rated voltage, The load power factor being 0.8 lagging?

The detailed solution is being presented for your understanding.

Solution

(1)

O.C test (L.V) 200V (V_{oc}), 1.2A (I_o), 90W (P_i)

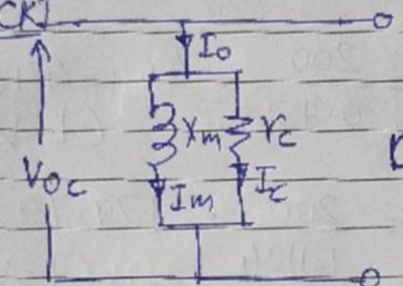
You know Power $P = VI\cos\phi$ (in ac – 1ph)

$\Rightarrow$

$$\cos\phi = \frac{P}{VI} = \frac{P_i}{V_{oc} I_o} = \frac{90}{200 \times 1.2} = 0.375$$

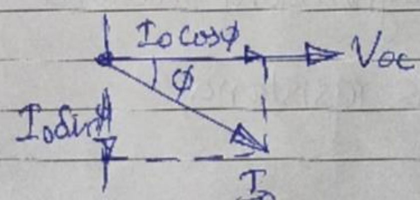
$$\sin\phi = \sqrt{1-\cos^2\phi} = \sqrt{1-0.375^2} = 0.927$$

Now CKT



L.V. Side

phasor



$I_c = I_o\cos\phi$ Core loss current (A)

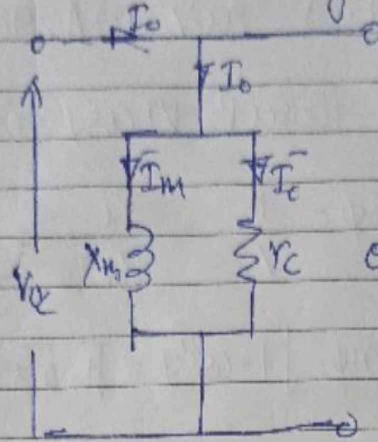
$I_m = I_o\sin\phi$ Magnetizing current (A)

(2)

$I_c = 1.2 \times 0.375 = 0.45\,A$

$I_m = 1.2 \times 0.927 = 1.1124\,A$

From the circuit diagram



Testing L.V Side

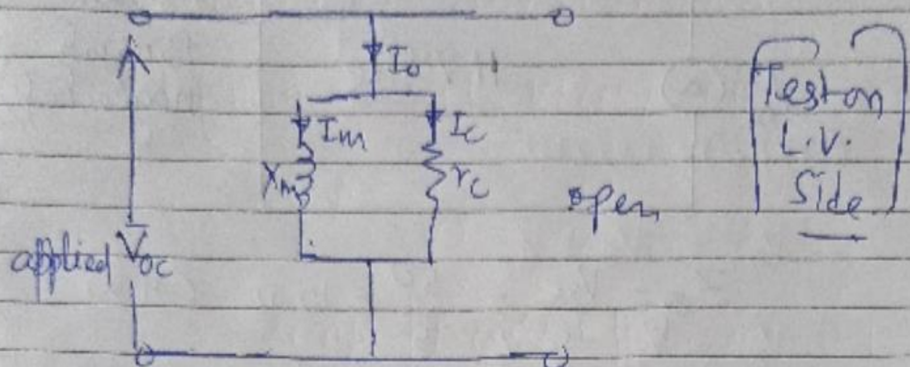
$$r_c = \frac{V_{oc}}{I_c} = \frac{200}{0.45} = 444.44\,\Omega \text{ (L.V)}$$

$$X_m = \frac{V_{oc}}{I_m} = \frac{200}{1.1124} = 179.79\,\Omega \text{ (L.V)}$$

X_m – Magnetizing reactance.

r_c – Core loss resistance

There is another way of finding r_c & X_m without phasor diagram, if you have understanding of the circuit (3)



$P_i = V_{oc} \cdot I_c$ and $I_c = \frac{V_{oc}}{r_c}$

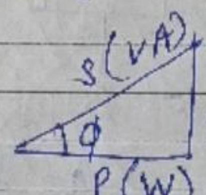
$\Rightarrow r_c = \frac{V_{oc}^2}{P_c} = \frac{200^2}{90} = 444.44\,\Omega$ (L.V.)

Apparent power S = V·I = $V_{oc} \cdot I_o = 200 \times 1.2 = 240$ W

Active power $= P_i = 90$ W (given)

Reactive power $Q = \sqrt{S^2 - P_i^2}$ (from power triangle)

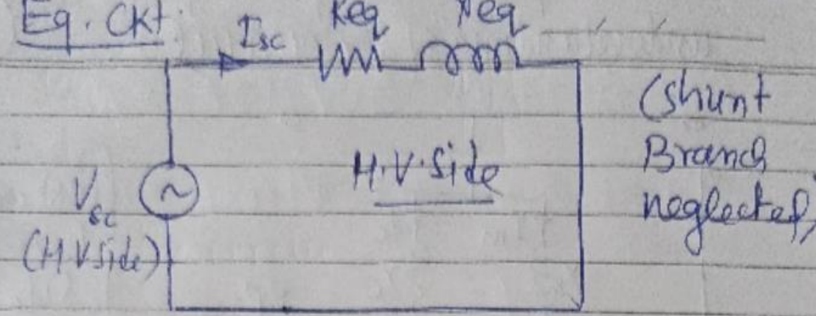
So Q = 222.48 VAR



$X_m = \frac{V_2^2}{Q} = \frac{200^2}{222.48} = 179.79\,\Omega$ (L.V. Side)

S.C Test Result: 50V, 5A, 110W (4)

Eq. Ckt:

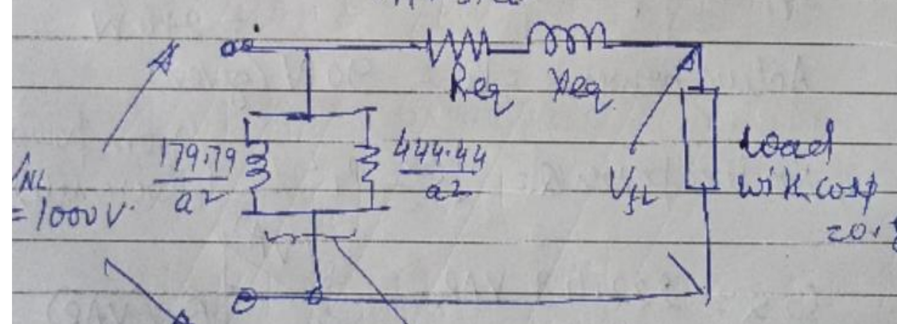


$Z_{eq} = \frac{V_{sc}}{I_{sc}} = \frac{50}{5} = 10\,\Omega$ (H.V.)

$R_{eq} = \frac{P_{sc}}{I_{sc}^2} = \frac{110}{5^2} = 4.4\,\Omega$ (H.V.)

$X_{eq} = \sqrt{Z^2 - R_{eq}^2} = \sqrt{10^2 - 4.4^2} = 8.98\,\Omega$ (H.V.)

Now Approx CKT. (H.V. Side)



$a = \frac{200}{1000}$ referred to H.V. side.

Theory V_{NL} is Voltage across secondary terminal (H.V in this case) without load connected.

(5)

V_{fL} is Voltage across load terminals when load is connected.

We define Voltage regulation as

$$\text{Voltage Regulation} = \frac{V_{NL} - V_{fL}}{V_{fL}}$$

$$\%\text{Voltage Regulation} = \frac{V_{NL} - V_{fL}}{(V_{fL})} \times 100.$$

So in above example what is $V_{NL} = ?$

It is 1000V (given).

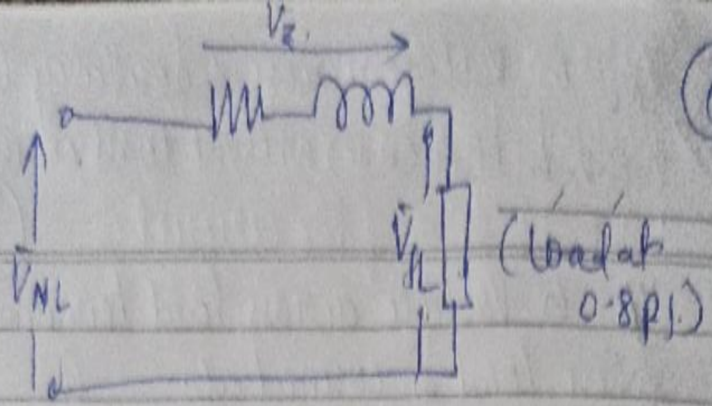
- then current in ckt at fL is 5 A given
- Load p.f is given $\cos\phi = 0.8$ so angle between Voltage & current is $\phi = \cos^{-1} 0.8 = -36.87$ (-ve sign because lagging is given.

So if $V = 1000\angle 0$ Volts

$I = 5\angle -36.89$ A

and $Z_{eq} = R_{eq} + jX_{eq} = 4.44 + j\,8.98\ \Omega$

(6)



from the circuit

$$\bar{V}_{NL} = \bar{V}_z + \bar{V}_{fL}$$

$$\bar{V}_{NL} - \bar{V}_{fL} = \bar{V}_z$$

$$= I \times Z_{eq}$$

$$= 5\angle -36.89 \times (4.44 + j8.98)$$

$$= 5\angle -36.89 \times \sqrt{4.44^2 + 8.98^2}\,\angle \tan^{-1}\theta'$$

Where $\angle \tan^{-1}\theta' = \angle \tan^{-1}\frac{8.98}{4.44} = \angle 63.69$

So we have

$\bar{V}_{NL} = \bar{V}_{FL} + 50.1 \angle 26.8^\circ$

$= 1000 \angle 0 + 50.1 \angle 26.8^\circ$

$= 1000 + j0 + 50.1 (0.893 + j0.451)$

$= 1044.74 + j22.595$

$= \sqrt{1044.74^2 + 22.595^2} \angle \tan^{-1} \frac{22.595}{1044.75}$

$\angle 1.238^\circ$

$|\bar{V}_{NL}| = 1044.98$

$\% V.R. = \frac{1044.98 - 1000}{1000} \times 100 = \frac{44.98}{10} = 4.498\%$