MACHINES I SUMMARY

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POWER UNIT
ELECTRICAL ENGINEERING

Revision of magnetic circuits

* Principles of operation of Electrical Machines:-

1- Any current carrying conductor or coil generate magnetic field (ϕ) or (H) around it.

2- A time varying field (ϕ) will induce a voltage in any coil cutting the field. (Principle of operation of Transformer)

3- If a conductor cut ϕ, then a voltage will be induced in that conductor. (this is principle of operation of Generator.)

4- If a current carrying conductor is located in ϕ, then it will develop a tourqe. (principle of operation of Motor)

* Magnetic Circuits:-

N: # of turns.
i: Applied current.
ϕ: generated flux (ϕ) wb.

From Amper's law

$$HL_c = Ni$$

$$H = \frac{Ni}{L_c} \quad (A.t/M) \quad \text{---} \boxed{1}$$

Field strength ↳ H; L_c → Mean length of flux path

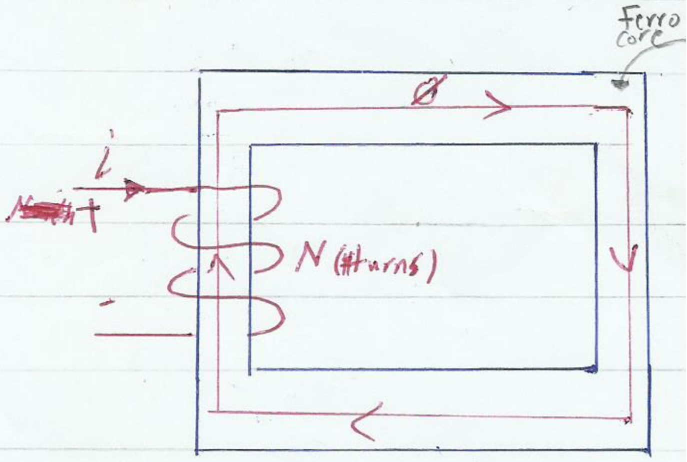


Fig 1

Note:-
$M = M_o M_r$
M_r → relative Permeability
M_o ↳ Permeability of free space $= 4\pi \times 10^{-7}$

* $B = \frac{\phi}{A}$ (Tesla = wb/m2) --- $\boxed{2}$

and $B = M H$ $\boxed{3}$
M ↳ permeability

* From $\boxed{1}$, $\boxed{2}$ and $\boxed{3}$

$$Ni = \frac{L_c}{AM} \phi$$

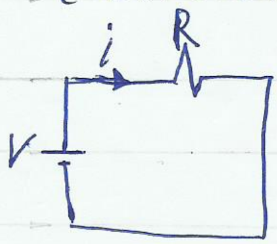
MMF ↲ Ni

* Analogy between Electrical and Magnatic circuits:

Electrical	Magnatic
1. emf, V	MMF (Ni), A.t
2. i, A	ϕ, wb
3- Resistance, Ω	Reluctance, A.t/wb

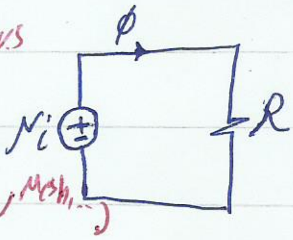
* Equivlant circuts:

electrical



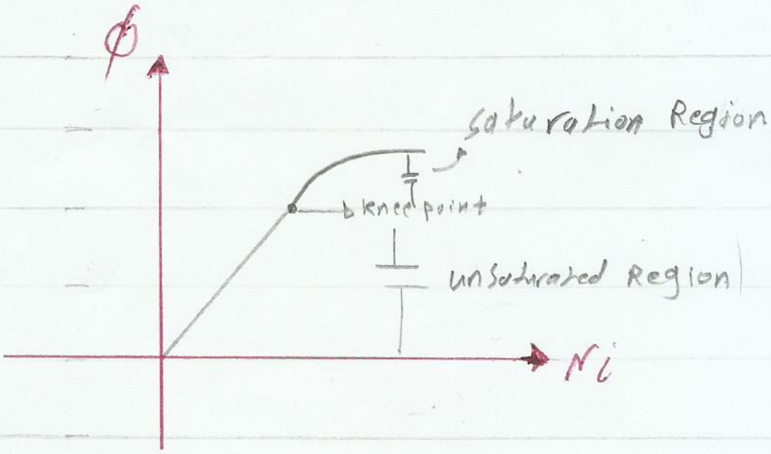
All ele. CKT laws are applicaple to Magnatic (KCL, KVL, Mesh, ...)

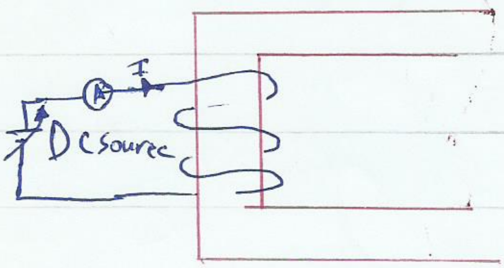
Magnatic



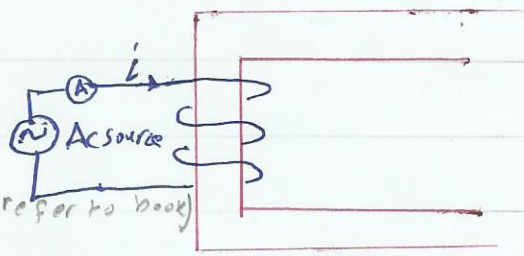
* Magnetization curves:- (The Relation between ϕ or B Vs Ni Vs H)

1- For DC Case:-





2- For AC Source:-



* the Magnetization Curve cuts the tips of Hysteresis loop (More about Hysteresis refer to book)

* There are 2-types of losses through the core:-
  1- hysteresis loss /
  2 eddy current losses

* Examples (Magnetic circuits) :-

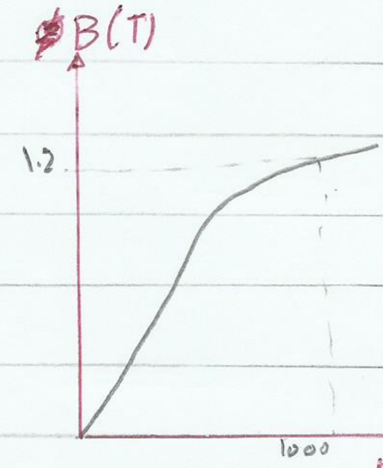
EX1:- The toroidal (Circular cross section) core shown below is Made from cast steel. (Magnetization curve given below)

a) Calculate the coil current required to produce a core density of 1.2 T at the mean radius of the toroid?

Sol:- Mean length of Core, $l_c = 2\pi \frac{(10+6)}{2} \times 10^{-2} m$

$l_c = 0.503 m$, From M.C $H = 1000\ A.t/m$ at $B = 1.2$

$i = \frac{H_c l_c}{N} = \frac{1000 \times 0.16\pi}{200} = 2.51\ A$



M.C

b) what is the core flux?

Sol:- $A = (2 \times 10^{-2})^2 \pi = 1.26 \times 10^{-3} m^2$

$\phi = BA = 1.2 \times 1.26 \times 10^{-3} = 1.52 \times 10^{-3}\ wb$

c) If a 2-mm wide air gap is made in the troid (across A-A'), determine the new coil current required to maintain a core flux density of 1.2 Tesla

Sol:- $Ni = H_c l_c + H_a l_a = H_c l_c + \frac{B}{\mu_o} l_g$

$i = \frac{1000 \times 0.503}{200} + \frac{1.2 \times 2 \times 10^{-3}}{4\pi \times 10^{-7} \times 200} = 98\ A$

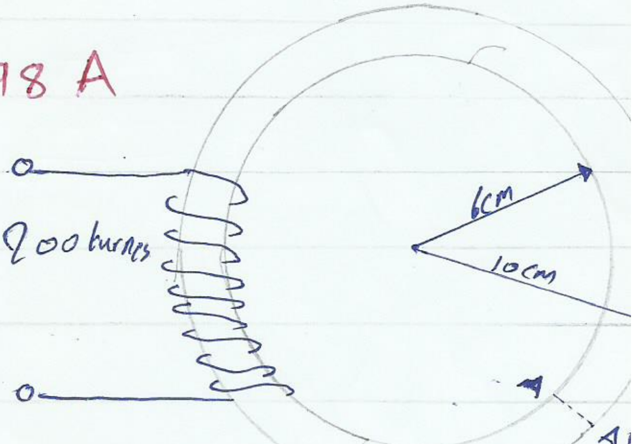


Fig 2

EX2:- In the magnetic circuit shown below, the relative permeability of the ferromagnetic material is 1200. Neglect magnetic leakage and fringing. All dimensions are in cm, and the core has a square cross-sectional area. Determine the air gap flux, the air gap density, and the magnetic field intensity.

Sol: $F_1 = N_1 i_1 = 5000\,A\cdot t$

$F_2 = N_2 i_2 = 5000\,A\cdot t$

$\mu_c = 1200\mu_0 = 1.51 \times 10^{-3}\ (T\cdot m/A\cdot t)$

$R_1 = \frac{l_c}{\mu_c A_c} = \frac{3 \times 52 \times 10^{-2}}{1.51 \times 10^{-3} \times 4 \times 10^{-4}}$

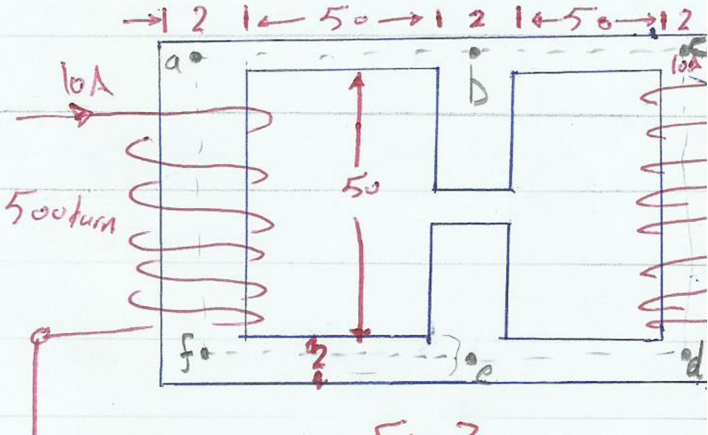


Fig 3

$R_1 = 2.58 \times 10^{6}\ At/wb$

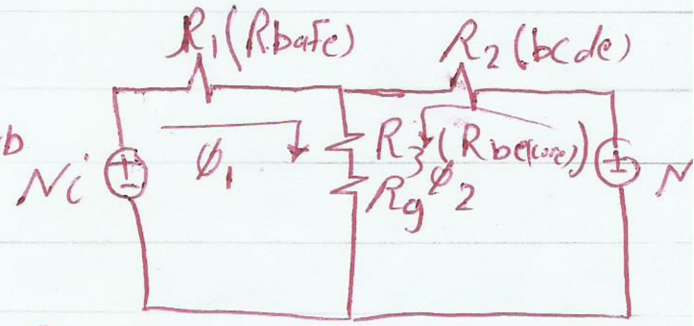
From symmetry

$R_1 = R_2 = 2.58\ M\,At/wb$

$R_g = \frac{l_g}{\mu_0 A_g} = \frac{5 \times 10^{-3}}{4\pi \times 10^{-7} \times 4 \times 10^{-4}}$

$R_g = 9.94\ M\,At/wb$

$R_3 = \frac{51.5 \times 10^{-2}}{1.51 \times 10^{-3} \times 4 \times 10^{-4}} = 0.82\ M\,At/wb$



Equ*CKT

Mesh:-

$\phi_1(R_1 + R_3 + R_g) + \phi_2(R_g + R_3) = F_1$ ---[1]

$\phi_2(R_2 + R_3 + R_g) + \phi_1(R_g + R_3) = F_2$ ---[2]

solving [1],[2] ---

$\phi_1 = \phi_2 = 2.067 \times 10^{-4}\ wb$

$\phi_g = \phi_1 + \phi_2 = 4.134 \times 10^{-4}\ wb$

$B_g = \frac{\phi_g}{A_g} = 1.034\,T$

$H_g = \frac{B_g}{\mu_0} = 0.822 \times 10^{6}\ A\cdot t/m$

Transformes.

*** Classification:-**

1) Power transformer
2) Instrument transformer
3) Impedence matching transformers.

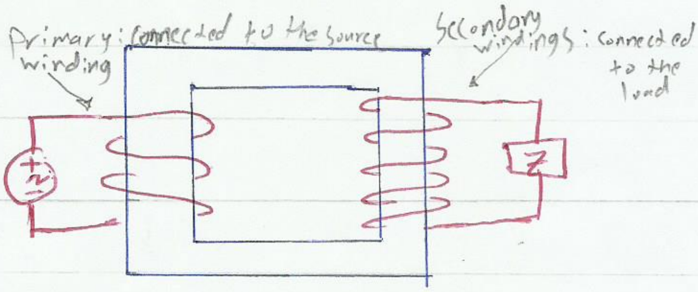
*** Construction :-**

It consists of the following two part:-

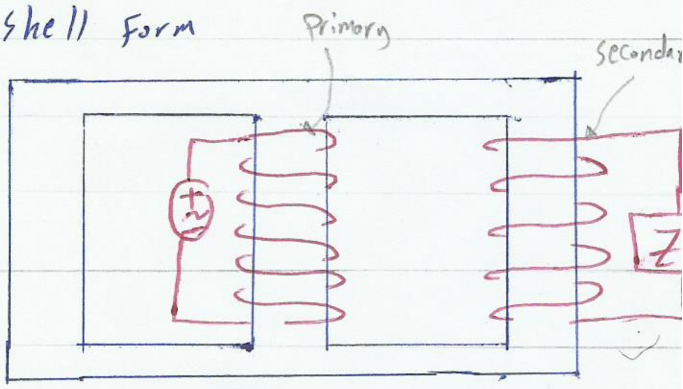
i) Core :- to carry the windings

two types of cores:-

1) core form



2) shell form



ii) windings or coils :- 1) Primary winding 2) Secondary windings

*Note:- The principle of operation is based on faraday's law. $\left(e = -N\frac{d\phi}{dt}\right)$

*** Ideal Transformers:-**

assume the following:-

1. No losses → Core losses (eddy current and hysteresis)
   → electrical losses (resistance and self Inductance)

2. No leakage flux.

3. Core has Very high μ_r. $(\mu_r = \infty)$

Cont. Ideal transformers

* we will find the V, I, Z relations of primary and secondary windings.

$N_p, N_s \equiv$ # of primary and secondary turns.

$V_p \equiv$ primary applied voltage

$e_p, e_s \equiv$ the induced voltages

$i_s =$ secondary current.

$V_s \equiv$ secondary voltage.

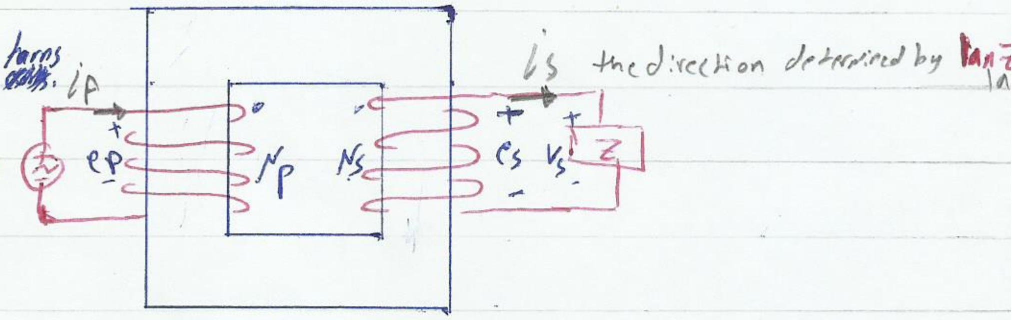


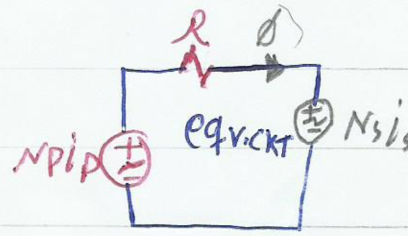
Fig 4

$V_p = e_p = N_p \frac{d\phi}{dt}$ $\quad V_s = e_s = N_s \frac{d\phi}{dt}$

Note:

$\frac{N_p}{N_s} = a$ (turns Ratio)

$$\boxed{\frac{V_p}{V_s} = \frac{N_p}{N_s}} \quad (a) \quad --- [1]$$



From equivalent CKT:

$-N_p i_p + \phi R + N_s i_s = 0$

$R = 0$ (Ideal)

$\therefore N_p i_p = N_s i_s$

$$\boxed{\frac{i_p}{i_s} = \frac{N_s}{N_p} = \frac{1}{a}} \quad --- [2]$$

*Note:

1) If $a > 1 \Rightarrow$ Step up transfomer

2) If $a < 1 \Rightarrow$ Step down transformer

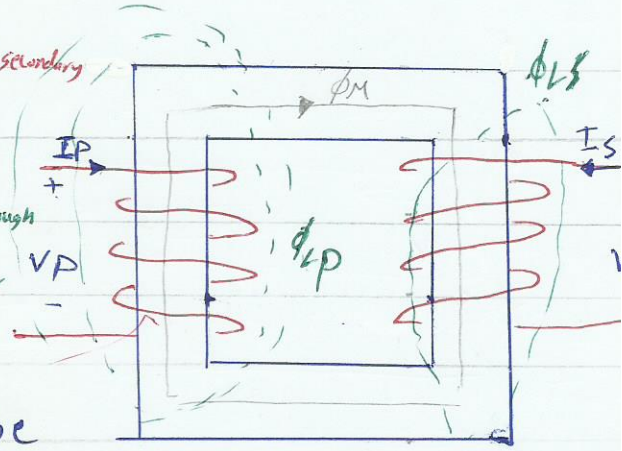
(A) ∴ $Z_p = \frac{V_p}{I_p}$, Since $\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s} = a$ -- (B) From (A) and (B)

$Z_p = a^2 \frac{V_s}{I_s} \Rightarrow \boxed{Z_p = a^2 Z_L}$ --- [3]

Practical OR Real Single-Phase transformer

* operation:

ϕ_M:- Flux Component linking both primary and secondary coils (mutual flux)



ϕ_{LS}:- secondary leakage flux.
ϕ_{Lp}:- primary leakage flux.
} passes through one winding and the air

* from Fig 5 the flux in both coils can be divided into 2 Components; mutal flux and leakge flux. Fig 5

$\therefore \phi_p = \phi_{Lp} + \phi_M$ .... [1] and $\phi_s = \phi_{LS} + \phi_M$ ... [2]

* From fraday's law:-

$e_c = \frac{d\lambda}{dt}$ .... [3] where λ :- is the flux linkage in the coil $\lambda = \sum_{i=1}^{N} \phi_i$ (Flux passing through the ith coil)

* the average flux/turn can be determined:-

$\bar{\phi} = \frac{\lambda}{N}$; the eq [3] become $e_c = N \frac{d\bar{\phi}}{dt}$ ... [4]

Note:- in Real transformer the total flux is not N because Not every turn has the same flux.

Now plug [1] in [4]

$e_P = N_P \frac{d\bar{\phi}_P}{dt} = N_P \frac{d\phi_M}{dt} + N_P \frac{d\phi_{LP}}{dt} = e_{PM} + e_{PL}$ ... [5]

(In ideal transformer No e_{PM})

also plug [2] in [4]

$e_s = N_s \frac{d\phi_M}{dt} + N_s \frac{d\phi_{LS}}{dt} = e_{SM} + e_{SL}$ ... [6]

* Now we need to model both Primary and Secondary CKTs taking leakge flux in account

Cont. Practical 1-ϕ transformer

* The losses that occur in real transformer that have to be accounted

A. Copper losses, Copper losses are resistive heating losses in both coils. These losses propotinal to I^2 (I^2R)

B. Eddy Current losses. also resistive heating that propotinal to the square of voltage square that applied to the transformer

Note:- Copper losses represented by R series with the leakage flux Inductance

C. Hysteresis losses (explaind previous).

D. leakage flux : represented as Inductance ??!! why??

*as shown previous :- (eq [5] and [6] at 7th page)

$$e_{PL} = N_P \frac{d\phi_{LP}}{dt} \quad [1] \text{ and } \quad e_{SL} = N_S \frac{d\phi_{LS}}{dt} \quad [2]$$

*Note: much of leakage flux path is through air and air has constant relactance higher than the core, $\phi_{PL} \propto i_P$ and $\phi_{SL} \propto i_S$

So: $\phi_{LP} = (P N_P) i_P$ [3] and $\phi_{LS} = (P N_S) i_S$ [4]

(N_P: Number of turns in primary; N_S: Number of secondary turns; P: Permeance of flux path)

From [1], [2], [3] and [4]:

$$e_{PL} = \frac{N_P^2}{R} \frac{di_P}{dt} \text{ and } e_{SL} = \frac{N_S^2}{R} \frac{di_S}{dt}$$

($\frac{N_P^2}{R} = L_P$, $\frac{N_S^2}{R} = L_S$)

Note:- $P = \frac{1}{R}$

* the Magnetization current in a Real transformer:-

at No-load (secondary circuit is open): the Primary current has 2 Components

1.) The Magnetization Current i_m (the current Required to produce the flux in the core)

Note: $i_m + i_{h+e} = i_{exc}$

2) The core - losses current i_{h+e}. (the current which is required to make up for hysteresis and eddy current losses)

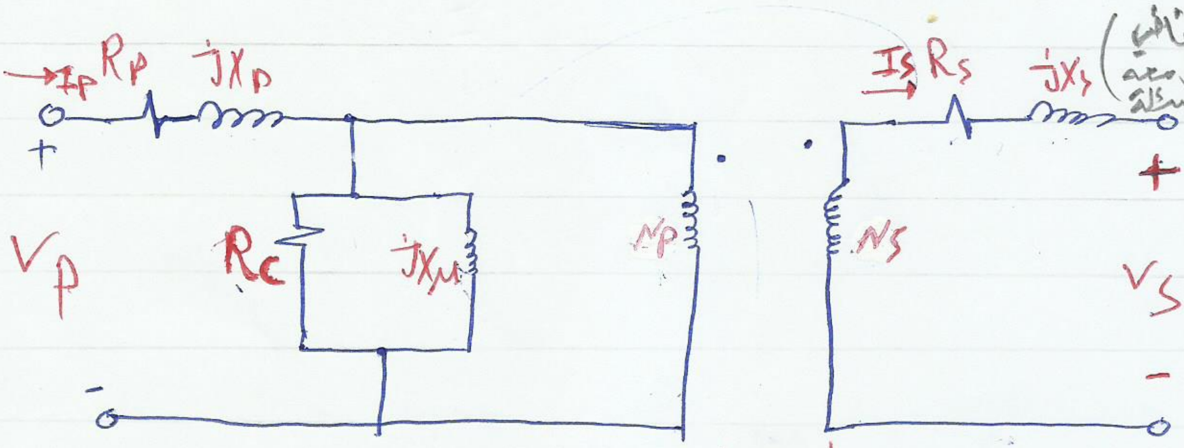
For more details reffer to your book (electric machinary fundamentals by Chapman 5th edition pages (81, 82, 83).

Equivalent circuits of Transformer

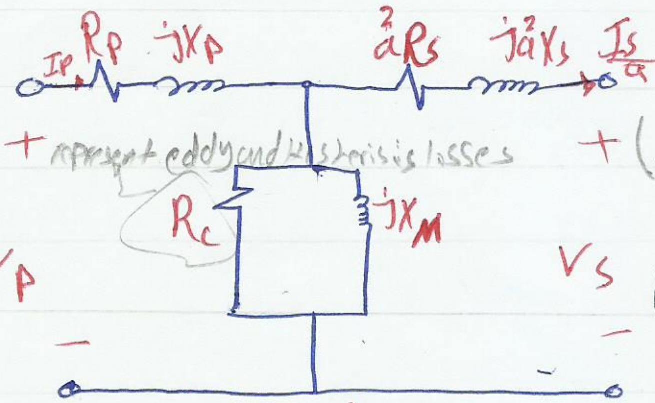
Now we can Construct our model :- (هسع بنقدر نبلش الحفلة)

1) Exact equivalent circuit :-

(هالشكل على الفاينل بنقدر نتعامل معه بحل الأسئلة)



(a) Ideal Transformer

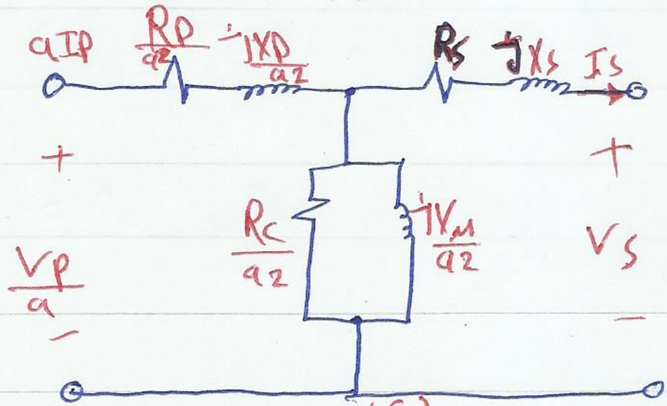


(هاذا الشكل الالطف)

(هون $a = \frac{N_P}{N_S}$)

(referred to Primary voltage)

(b)



(هون $a = \frac{N_P}{N_S}$)

(referred to Secondary voltage)

(C)

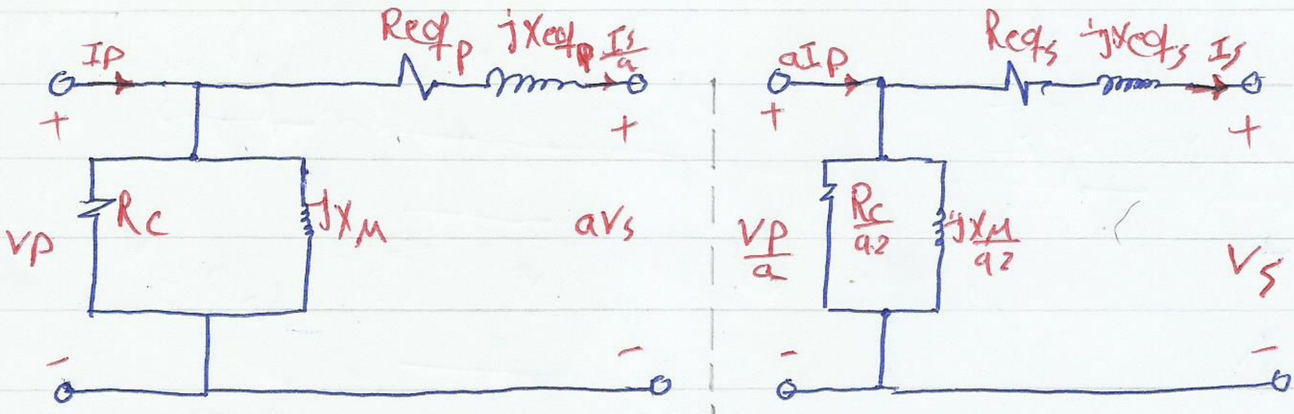
Fig 6

2) Approximate equivalent circuit :-

(هاظ السركيت منستعمله بحل الأسئلة)

* The exact form is complex than necessary.
* Since the excitation current (I_{exc}) is only about 2% - 3% of full current so the excitation branch is moved to front of transformer and primary and secondary impedances are left in series with each other

So the Approximate equivalent C.K.T:



$R_{eq\,p} = R_p + a^2 R_s$

$X_{eq\,p} = X_p + a^2 X_s$

(a)

$R_{eq\,s} = \frac{R_p}{a^2} + R_s$

$X_{eq\,s} = \frac{X_p}{a^2} + X_s$

(b)

Fig 7

* Notes:

1) $N_p : N_s \Rightarrow \frac{N_p}{N_s} : 1 \Rightarrow$ (a)

1) a:1 If we referred 1 to a then we multiply Z by a^2, V by a and divide I by

2) a:1 If we referred a to 1 then we divide Z by a^2, v by a and multiply I b

2) $R_{eq\,p} \neq R_{eq\,s}$ and $X_{eq\,p} \neq X_{eq\,s}$ | So we will use pu system as will be explained late

* Evaluation of transformers parameters: (هاذا الموضوع سهل بس بدنا نتنبه ونركز منيح)

- We want measure the parameters RC, XM and Zeq experimentaly

How??!!

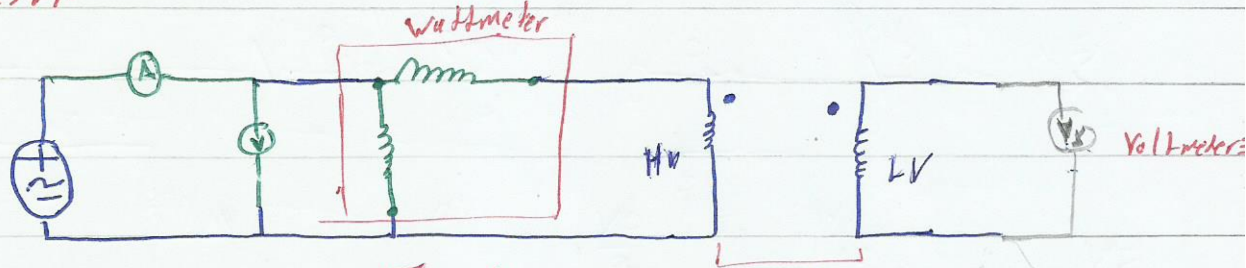
→ by performing 2 tests:-

1) open CKT test :- Used to measure RC and XM (o/c)

2) Short CKT test :- It is used to measure Zeq (s/c)

Evaluation of Transformer Parameter

1) O/C Test:



Transformer

Fig 8

*Procedure:

A) Apply open circuit at secondary by keeping the terminal o/c or by connecting voltmeter.

B) Apply rated voltage at the primary, then measure Voc / Ioc an[d]

* Calculations:

$$Y_F = \frac{1}{R_C} - \frac{j}{X_M} = G_C - jB_X \quad --- [1]$$

(conductance, susceptance)

(XM, Rc طلع بكون Referred to LV)

$$|Y_F| = \frac{I_{oc}}{V_{oc}} \quad --- [2]$$

Note: Here
- It's better to us[e] Low voltage as p[rimary]

$$PF = \cos\theta = \frac{P_{oc}}{V_{oc} I_{oc}} \Longrightarrow \theta = \cos^{-1} \frac{P_{oc}}{V_{oc} I_{oc}} \quad --- [3]$$

$$Y_F = \frac{I_{oc}}{V_{oc}} \angle -\theta \quad --- [4]$$

plug [4] in [2] to find Rc, XM

2) S/C test:

(Connection as Fig 8 but we connect ameter instead the voltmeter)

* Procedure:-

(Zeq referred to HV طلع بكون)

A) Apply S/C at secondary or connect ameter

B) Apply rated current to (S/C)...

$$|Z_{SF}| = \frac{V_{SC}}{I_{SC}} \quad --- [1]$$

$$Z_{SF} = R_{eq} + jX_{eq} \quad --- [2]$$

$$PF = \cos\theta = \frac{P_{SC}}{I_{SC} V_{SC}} \qquad \theta = \cos^{-1} \frac{P_{SC}}{V_{SC} I_{SC}} \quad --- [3]$$

Here, it's better to u[se] High Voltage as primar[y]

$$Z_{SF} = \frac{V_{SC}}{I_{SC}} \angle\theta \quad --- [4]$$

Plug [4] in [2] to find Req, Xeq

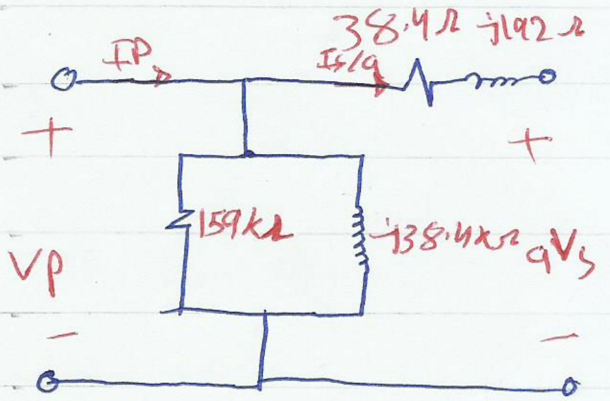
EX:- 20 KVA, (8000/240), 60 HZ transformer has the following Parameters refferred to HV side:

$R_C = 159\,k\Omega$ $X_M = 38.4\,k\Omega$ $R_{eq} = 38.4$ $X_{eq} = 192\,\Omega$

IF an o/c test was performed with LV as the primary, what would be the Reading of its measuring instruments

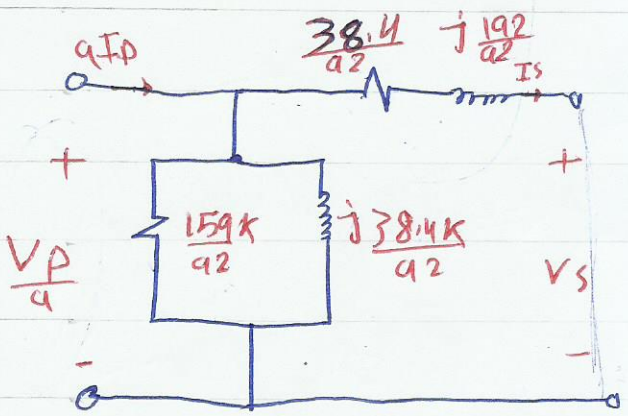
هذا السؤال فيرست فصل أول (2013 / 2014)

sol: First of all we will referred the parameters to LV:-



a
33.34:1

referred to H.V side



a
33.34:1

referred to L.V side

Fig(9)

$V_{o/c} = 240\,V$ because we applied rated voltage at primary

$I_{o/c} = I_C + I_M$

$I_C = \frac{V_{o/c}}{R_C} = 1.68\,A$

$I_M = \frac{V_{o/c}}{jX_M} = 6.95 \angle -90$

Note:- Example 2-2 page 92

عشان الله تحله

$I_{o/c} = 7.15 \angle -76.41°$

$P_{o/c} = |I_{o/c}|\,|V_{o/c}| \cos(\theta_{V_{oc}} - \theta_{I_{o/c}})$

$P_{o/c} = 403.2\,W$

Per-unit (pu) system

Definition: insted of expressing the basic quantites of voltage, (cu…
Impedence and power by thier units of (V, A, Ω, VA), they
are expressed as a fraction of Base value.

$$Pu\ value = \frac{actual\ value}{Base\ value}$$

why we use it!!

* we use pu system because the following advantages:
1) it simplifies the analysis of power system.
2) the Resistance oR Reactance of transformers or generators in pu fall…
a certain Narrow Range, Hence this may help in checking answers

* Base value selected for S and V (S_B, V_B) then I_B, Z_B
Calculated as follow:-

$$I_B = \frac{S_B}{V_B} \qquad Z_B = \frac{(V_B)^2}{S_B}$$

Transformer voltage Regulation:

* voltage Regulation:- is a quantity that compares the output voltage of the transformer at no-load with the output voltage at full loads.

$$VR = \frac{\frac{V_P}{a} - V_{S,FL}}{V_{S,FL}} \times 100\%$$

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

Transformer efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$= \frac{P_{out}}{P_{out} + P_{losses}} \times 100\%$$

$$\eta = \frac{V_S I_S \cos\theta}{P_{cu} + P_{core} + V_S I_S \cos\theta}$$

Example 2-5 page 102

(حل حلو)

The auto transformer

* we use this transformer to change voltage levels by small amount.
* It's to expensive to build conventional transformer with windings almost having the same voltage rating → use auto transformer

* Construction

the coils are connected in series. (additive manner) as follows:-

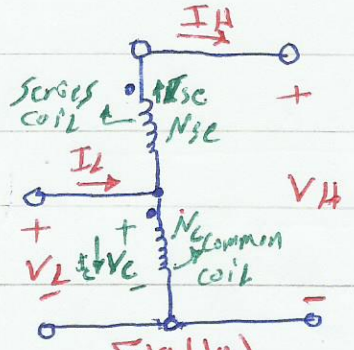


Fig (10)

Note:
$I_L = I_c + I_{se}$
$I_H = I_{SE}$
$V_L = V_C$
$V_H = V_C + V_{SE}$

* analysis:-

voltage - current relation ship:-

A) Voltage relation:-

$$\frac{V_C}{V_{se}} = \frac{N_C}{N_{se}} \quad \text{---} \boxed{1} \quad \text{(From previous note)}$$

$V_C = V_L$

$$V_H = V_C + \frac{N_{se}}{N_C} V_C \quad \text{---}$$

$$* \quad \boxed{\frac{V_H}{V_L} = \left(1 + \frac{N_{se}}{N_C}\right)} \quad \text{----} \boxed{2}$$

* B) Current relation:-

$$\frac{I_C}{I_{se}} = \frac{N_{se}}{N_C} \quad \text{---} \boxed{3}$$

$I_{se} = I_H$

$$I_L = \frac{N_{se}}{N_C} I_{se} + I_{se}$$

$$* \quad \boxed{\frac{I_L}{I_H} = \left(1 + \frac{N_{se}}{N_C}\right)} \quad \text{---} \boxed{4}$$

* Apparent power advantage of Autotransformer:-

* If a Conventional transformer is Connected as autotransformer, then the apparent power of auto will be greater than the apparent Power of the conventional

input apparent power $S_I = V_L I_L$ --- [5]

output apparent power $S_O = V_H I_H$ --- [6]

→ assuming step-up

Now sub into [5] OR [6]

$$S_O = V_L\left[\frac{N_{SE}+N_C}{N_C}\right] \times I_L\left[\frac{N_C}{N_L+N_{SE}}\right] = V_L I_L = S_I$$

$$S_I = S_O = S_{IO}$$

* S_W (apparent power of the windings) = the apparent power of conventional

$$S_W = V_C I_C = V_{SE} \cdot I_{SE}$$

$$S_W = V_{SE} I_{SE} \qquad (V_{SE} = V_H - V_L \text{ and } I_{SE} = I_H)$$

$$S_W = (V_H - V_L) I_H$$

$$S_W = V_H I_H - V_L I_H \qquad \left(V_L = \frac{N_C}{N_{SE}+N_C} V_H\right)$$

$$S_W = \underbrace{V_H I_H}_{S_{IO}}\left(1 - \frac{N_C}{N_{SE}+N_C}\right)$$

$$S_W = S_{IO}\left(\frac{N_{SE}}{N_{SE}+N_C}\right)$$

$$\frac{S_{IO}}{S_W} = \frac{N_C+N_{SE}}{N_{SE}} \quad \text{--- [7]}$$

→ >1

Notes: the increase of S is due to:
- transformation action
- conduction action

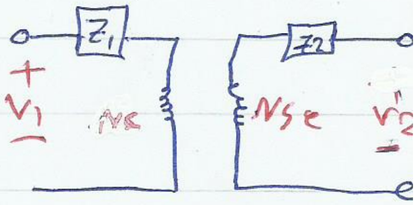
* Compared to a given transformer connected in the conventional manner, the effective per-unit impedance of an autotransformer is smaller by a factor equal to the reciprocal of the power advantage of the autotransformer (why??!!)

(problem 2-16)

Ex: prove that $Z_{eq}' = \frac{N_{se}}{N_{se}+N_c}$, If a (conventional) transformer having a series impedance Z_{eq} is connected as autotransformer, Z_{eq}' it's per-unit impedence of autotransformer

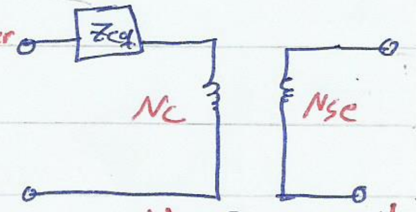
Sol: For the transformer connected as conventional, the impedence reffered to the primary (N_c) is:

$$Z_{eq} = Z_1 + \left(\frac{N_c}{N_{se}}\right)^2 Z_2 \quad \text{---} \boxed{1}$$



(a)

when this transformer connected as an autotransformer the circuit is shown at fig (11,c).



b) equivalent of (a)

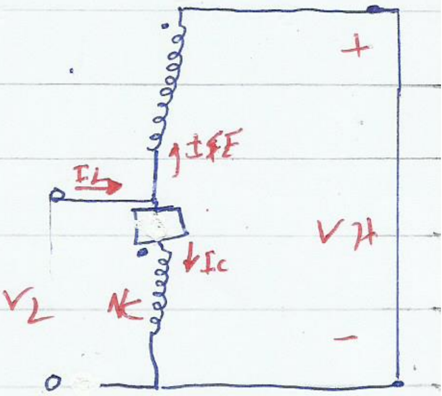
If the output windings of the are shorted, the voltage $V_H = 0$, and the voltage V_L will be

$$V_L = I_c Z_{eq} \quad \text{----} \boxed{2}$$

$$I_L = I_c + I_{se} = I_c + \frac{N_c}{N_{se}} I_c$$

$$I_L = \frac{N_{se}+N_c}{N_{se}} I_c \quad \text{---} \boxed{3}$$

$$Z_{eq}' = \frac{V_L}{I_L} = \frac{N_{se}}{N_{se}+N_c} Z_{eq}$$ #.



(C)

Fig (11)

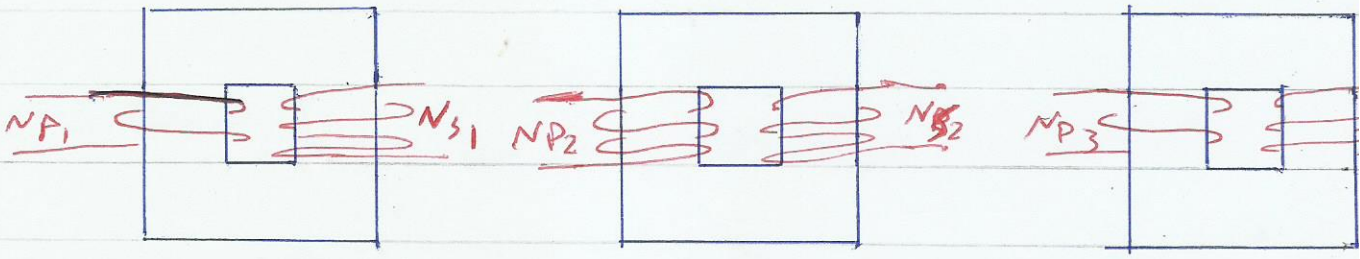
Example 2.8 page 116
(لبحكي كن اخواوة)

Three-Phase Transformer

(...ا الموضوع أهم موضوع بالمادة
...وم بنحل عليه اسئلة كثير)

* There are 2 basic constructions:-

1) using 3-single phase transformers as Fig (12):



Bank of 3.Ø transformer

More reliable (each unit could be replace individ...

Fig (12)

2) Three sets of windings wrapped on common core as shown in Fig (13)

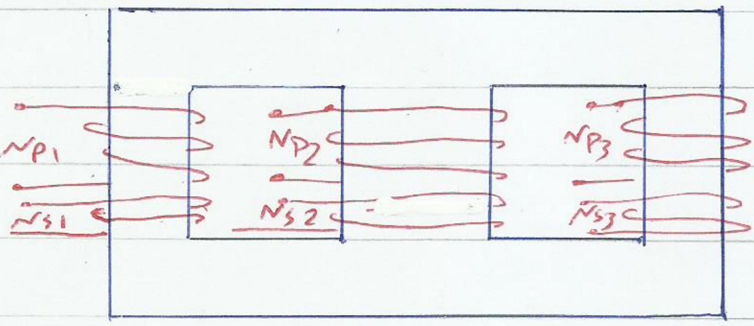


Fig (13)

(lighter, cheaper, more economical and smaller)

* Three-Phase transformer connection:

* The primaries or secondaries of any 3-Ø transformer can be independently connected in either a wye (Y) or a delta (Δ) This give 4 possi...

1) Y-Y 2) Y-Δ

3) Δ-Y 4) Δ-Δ

1) Y-Y Connection:

Y-Y Connection is shown in Fig (14)

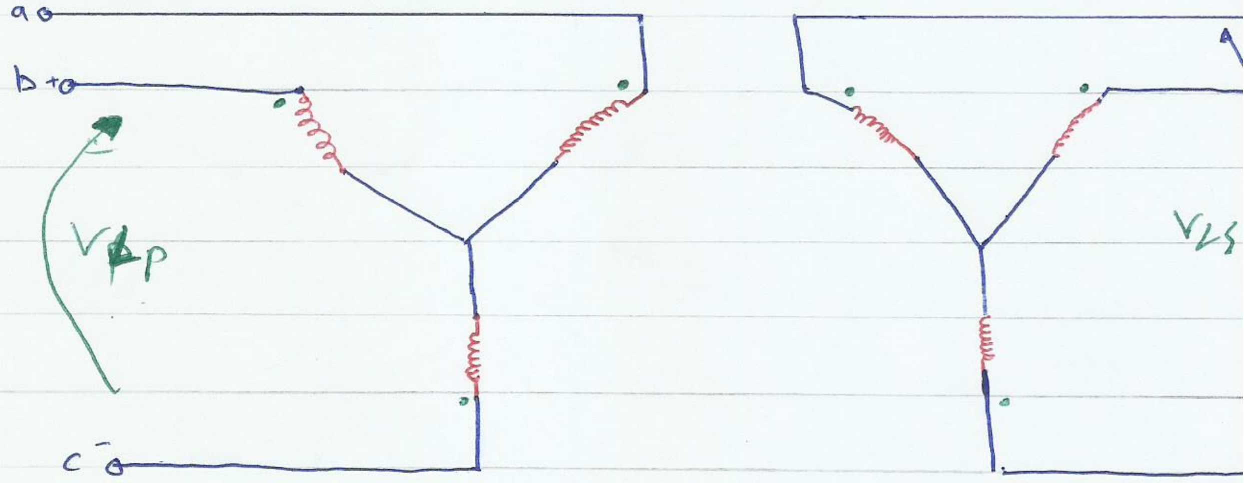


Fig 14

$V_{LP} = \sqrt{3} V_{\phi P}$

$V_{LS} = \sqrt{3} V_{\phi S}$ → $\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3} V_{\phi P}}{\sqrt{3} V_{\phi S}} = a$

Y-Y connection has 2 problems:

1) If load on the transformer circuit unbalanced, then the voltages on the phases can becomes unbalanced.

2) Third-harmonic voltage can be large

* Harmonics in Y-Connections:

IF 3-φ set of voltages is applied to Y-Y transformer, the vo[ltage] in any phase will be 120° apart from the voltage in any other phase, However the third-harmonic components of each of three phases will be in phase with each other, why!!??

inphase with each other.

$V_A = V_{m1} \sin \omega t + V_{m3} \sin 3\omega t$

$V_B = V_{m1} \sin(\omega t - 120°) + V_{m3} \sin(3(\omega t - 120°))$ → 360°

$V_C = V_{m1} \sin(\omega t - 240) + V_{m3} \sin(3(\omega t - 240°))$ → 720°

Cont. 3-ϕ transformer

So there are three cycle in third harmonic for each cycle of the fundemental freetueny. There are always some third-harmonic Component in a transformer because of the nonlinearity of the core.

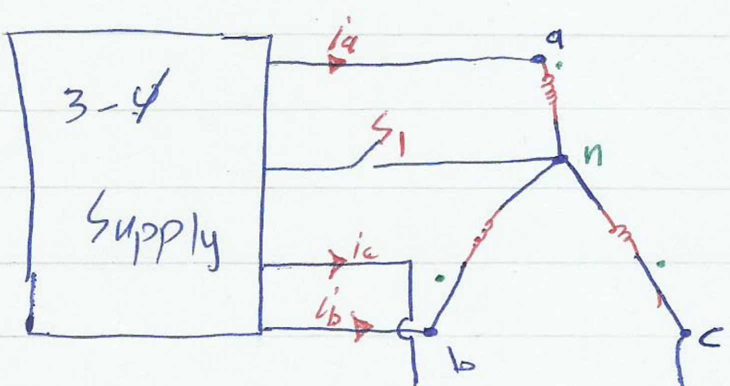
These components add up, and the result is very large third-harmon component of voltage on top of the 50/60 HZ fundamental voltage.

Both of the unbalanced problem and third-harmonic can be solved by using one of the following two techniques:-

1) Solidly ground the neutrals of the transformer; especially the primar winding's neutral. This connection premits the additive third-harmonic compon to cause a current flow in the neutral insted of buildings up large voltage it's also provide a return path for any imbalanced in the load

2) Add third windings connected in Δ to the transformer called tertiary windings; this winding must handle the circulating current so it made about one-third power rating of two main winding.

* these techniques are shown below:



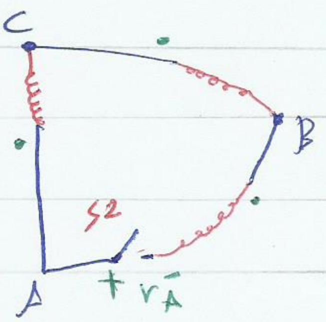


Fig 15

case 1: S_1 closed, S_2 open.

$$i_a = I_{m1}\sin\omega t + I_{m3}\sin 3\omega t$$

$$i_b = I_{m1}\sin(\omega t-120) + I_{m3}\sin 3(\omega t-120)$$

$$i_c = I_{m1}\sin(\omega t-240) + I_{m3}\sin(3(\omega t-240))$$

$$i_n = i_a + i_b + i_c = 3I_{m3}\sin 3\omega t$$

Cont. 3-ϕ transformer

Case 2: S_1 open, S_2 open

in this case the harmonic current can't flow in the primary CKT. so i_a, i_b, i_c will be pure sinusoidal which leads to non-sinusoidal flux so the voltage in Δ windings will be non-sinusoidal.

Phase voltages:

$$V_A = V_{m1}\sin \omega t + V_{m3}\sin 3\omega t$$

$$V_B = V_{m1}\sin(\omega t - 120) + V_{m3}\sin(3(\omega t - 120))$$

$$V_C = V_{m1}\sin(\omega t - 240) + V_{m3}\sin(3(\omega t - 240))$$

$$V_{AB} = V_{m1}\sin \omega t - V_{m1}\sin(\omega t - 120)$$

line voltage sinusoidal !!

Case 3: S_1 open, S_2 closed

* V_Δ will generate 3rd harmonic current, these currents will substitute for the missing 3rd harmonic currents in the prim...

* Y-Δ Connection:

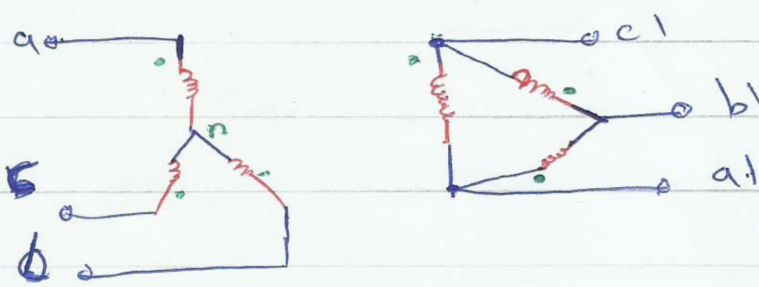


Fig 16

$$\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}\,V_{\phi P}}{V_{\phi S}} = \sqrt{3}\,a$$

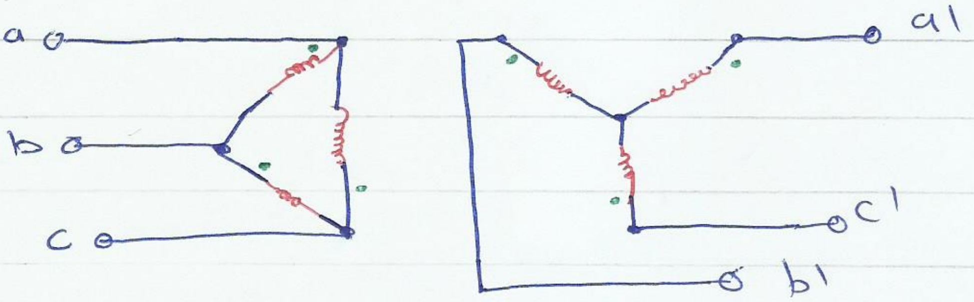
Assuming +ve phase sequence, if $\angle V_{an} = 0°$

$\therefore \angle V_{ab} = \angle V_{LP} = 30°$ since $V_{\phi P}$ and $V_{\phi S}$ are in-phase $\therefore \angle V_{a...}$

$\therefore$ Y-Δ Connection introduce a phase shift $= 30°$

Cont 3-ϕ transformer

3) Δ-Y Connection



$$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{\sqrt{3}\,V_{\phi S}} = \frac{a}{\sqrt{3}}$$

Fig 17

* This connection has same phase shift as Y-Δ Connection (3

4) Δ-Δ Connection

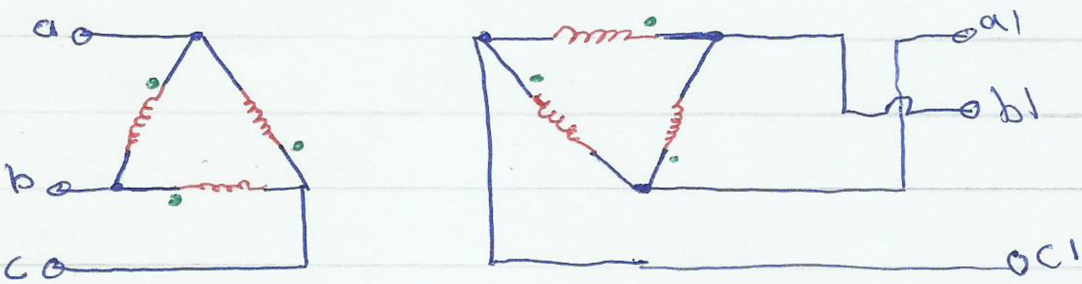


Fig 18

$$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{V_{\phi S}} = a$$ (No-phase shift)

* pu system for 3-ϕ transformer
  * applicable to 3-ϕ transformer, by using per-phase CKT Concept.

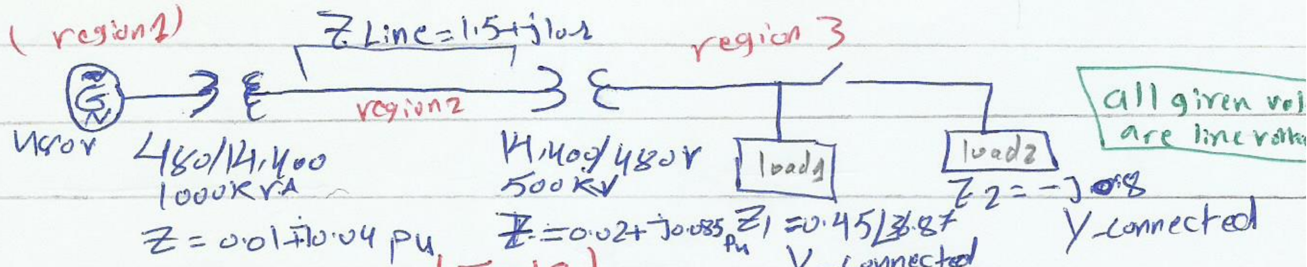
$$S_{1\phi\,base} = \frac{S_{3\phi}}{3}$$

$$Z_{1\phi,b} = \frac{(V_b)^2}{S_{1\phi b}}$$

(problem 2-29)

EX: Power system consisting of 3-ϕ, 480-V, 60HZ generator suppling 2-loads through transmission line with a pair of transformer at either end. as shown in Fig 19

Cont 3-ϕ transformer



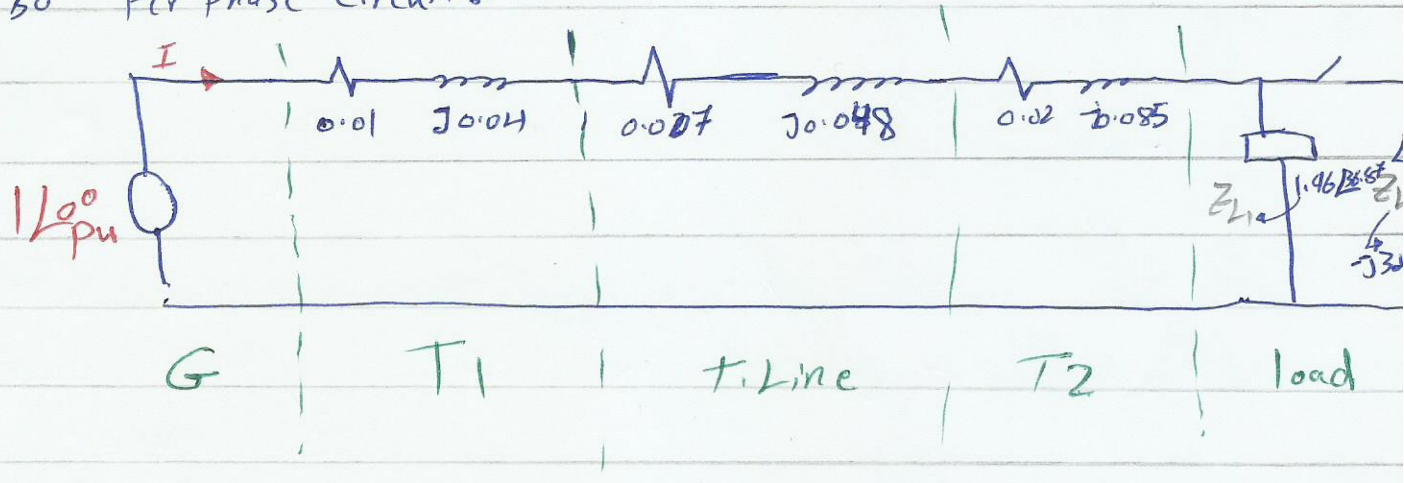
(Fig 1a)

a) sketch the per-phase equivalent circuit of this power system.

- $S_{3\phi,b} = 1000 KVA$

Region	Z base
1	$Z_b = \frac{(480/\sqrt{3})^2}{(1000\times10^3)/3} = 0.23\,\Omega$
2	$Z_b = \frac{(14400/\sqrt{3})^2}{(1000\times10^3)/3} = 207.36\,\Omega$
3	as region 1 $Z_b = 0.23\,\Omega$

so Per phase Circuit:



b) with switch open find P, Q, S and PF for the generator?

KVL to find I

$1\angle0° = (0.01 + j0.04 + 0.007 + j0.048 + 0.02 + j0.085 + 1.96\angle36.87)\,I$

$I = 0.477\angle{-40.05°}$

$S_{pu} = V_{pu} I^*_{pu}$ $\quad S_{pu} = 0.477\angle{+40.05}$ pu

~~S = 175.26 + 147~~ $\quad S = 0.477\angle{+40.05} \times 1000 KVA$

PF = Cos 40.05

PF = 0.765 lag

$S_G = 477 KVA\angle40.05$ $\quad P_G = real\{S_G\} = 365 KW$ $\quad Q_G = 306 KVAR$

c) with switch closed, Find P, Q, S and PF of Generator?

KVL to find I:

$1\angle 0^\circ = (0.01 + j0.04 + 0.007 + j0.048 + 0.02 + j0.085 + (1.568 + j1.176) \cdot I$

$I = 0.4\angle -6.56^\circ$

$S_{pu} = V_{pu} I^*_{pu}$

$S_{pu} = 0.4\angle 6.56$

$S_G = 400\,KVA \quad P_G = 397.4\,Kw \quad Q = 45.7\,KVAR$

$PF = \cos 6.56 = 0.9935$ **Lagging**

d) what are the transmission losses with switch open? with switch closed? what is the effect of adding load 2 to the system?

1) switch open:

$I = 0.477\angle -40.05\,pu$

$P_{pu,losses} = |I|^2 Z_{line+transformers}$

$P_{losses\,pu} = 7.39 \times 10^{-3}\,pu$

$P_{losses} = 7.4\,kw$

2) switch closed:

$I = 0.4\angle -6.56^\circ$

$P_{pu,losses} = |I|^2 Z$

$P_{pu,losses} = 5.92 \times 10^{-3}\,pu$

$P_{losses} = 5.92\,kw$

adding load 2 leads to:

1) decreasing power losses in transmission process

2) increasing power factor