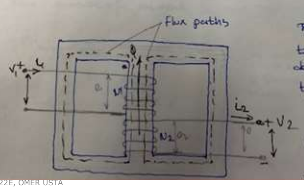
ELK322E Transformer Chapter 2

Chapter 2: POWER TRANSFORMERS
(Modelling of Power Transformers)

2.1. Ideal Transformer:

In a power transformer the coils are placed on an iron core in order to confine the flux so that almost all of the flux linking any one coil links all the other.

- Generators' rated voltage $V = 13.2 \div 24$ kV
- Step up transformers
- Step down transformers
- Transmission voltage level 154 kV, 380 kV, 500 kV, 765 kV
- 750 MVA → 525/22.8 kV for instance



By assuming that the flux varies sinusoidally in the core and that the transformer is ideal, which means that

a) the permeability of the core μ is infinite

confined to the core
flux leakage → 0

c) core losses and winding resistance are zero.

In this case, according to the Faraday's Law

$$v_1 = e_1 = N_1 \frac{d\phi}{dt}$$

$$v_2 = e_2 = N_2 \frac{d\phi}{dt}$$

where, ϕ is the instantaneous value of the flux, and N_1 and N_2 are the number of turns on the windings 1 and 2.

Since we have assumed sinusoidal variation of the flux, from V_1/V_2, in phasor form:

$$\frac{V_1}{V_1} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$$

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If an impedance Z_2 is connected across winding 2

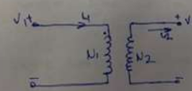
$$Z_2 = V_2 / I_2 = \frac{(N_2/N_1) V_1}{(N_1/N_2) I_1}$$

the impedance as measured across the primary winding is then

$$Z_2' = \frac{V_1}{I_1} = \left(\frac{N_1}{N_2}\right)^2 Z_2$$

Since it is assumed that transformer is an ideal transformer, $S_1 = S_2 = V_1 I_1^* = V_2 I_2^*$

the model of ideal power transformer

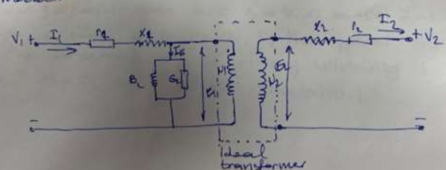


$\mu \to \infty$
$r \to 0$
ϕ sinusoidal
then $\frac{V_1}{V_2} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1}$

2.2. ~~The~~ Practical Model of a transformer

In practice, μ is not infinite
$r \neq 0$ and iron loss is not zero
Flux ~~[illegible]~~ leakage is not zero.

If these are considered, the practical transformer model:



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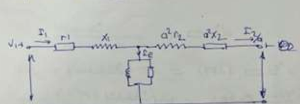
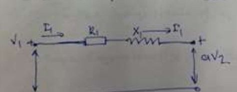
where; X_1 and X_2 are the series leakage reactances
ωL_1, ωL_2
B_L is the shunt magnetizing susceptance
G_L is the shunt magnetizing conductance

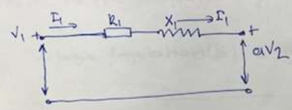
If $a = N_1/N_2$



Since the I_0 is very small compared to rated current, it can be assumed to be zero. Then the transformer model will be:



where $R_1 = r_1 + a^2 r_2$
$X_1 = X_1 + a^2 X_2$



where $R_1 = r_1 + a^2 r_2$

$X_1 = x_1 + a^2 x_2$

Example: A single-phase transformer has 2000 turns on the primary winding and 500 turns on the secondary. Winding resistance are $r_1 = 2\,\Omega$ and $r_2 = 0.125\,\Omega$. The leakage reactances are $x_1 = 8\,\Omega$ and $x_2 = 0.5\,\Omega$. The resistance load Z_2 is $12\,\Omega$. If the applied voltage at the terminals of the primary winding is 1.2 kV, find ~~the~~ V_2 and voltage regulation.

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solution:

$a = N_1/N_2 = 2000/500 = 4$

$R_1 = 2 + 0.125(4)^2 = 4\,\Omega$

$X_1 = 8 + 0.5(4)^2 = 16\,\Omega$

$Z_2' = 12 \times (4)^2 = 192\,\Omega$

Then

$$I_1 = \frac{1200\angle 0^\circ}{192 + 4 + j16} = 6.10\angle{-4.67^\circ}\ A$$

$$aV_2 = 6.10\angle{-4.67^\circ} \times 192 = 1171.6\angle{-4.67^\circ}\ V$$

$$V_2 = (1171.6\angle{-4.67^\circ})/4 = 292.9\angle{-4.67^\circ}\ V$$

$$\text{Voltage regulation} = \frac{|V_{2,NL}| - |V_{2,FL}|}{|V_{2,FL}|} \times 100$$

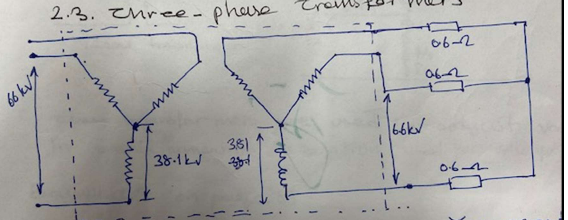
$V_{2,NL}$ (V_1/a): is the magnitude of load voltage V_2 at no load

$V_{2,FL}$ is the magnitude of V_2 at full load.

$$\text{Voltage Regulation}(\%) = \frac{1200/4 - 292.9}{292.9} \times 100 = 2.42\%$$

$$\text{Voltage Regulation}(\%) = \frac{1200/4 - 292.9}{292.9} \times 100 =$$

2.3. Three-phase Transformers



Y-Y connected.

Y-connected Load

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HV side
LV side

Primary voltage $V_1 \rightarrow U_{LL} = 66\,kV$
$\rightarrow U_{LN} = 38.1\,kV$

Secondary voltage (load voltage)

$U_{LL} = 6.6\,kV$

$U_{LN} = 3.81\,kV$

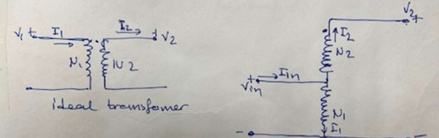
$x = a^2 r = 0.6\left(\frac{38.1}{3.81}\right)^2 = 60\,\Omega$

study: If the load ~~was~~ side was Δ-connected, what would be ~~the~~ x

transformer connection Y–Δ, $x = ?$.

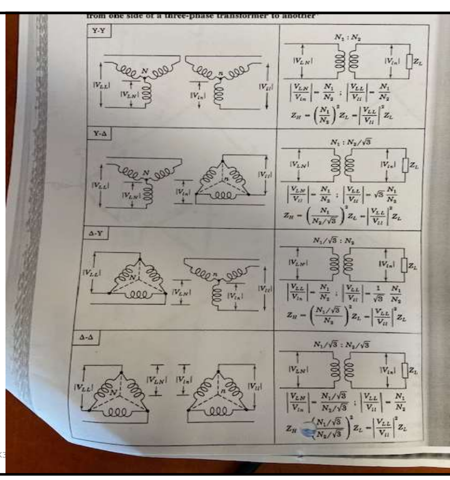
$x = a^2 r = \left(\frac{38.1}{2.2}\right)^2 0.6 = 180\,\Omega$

2.4 The Autotransformer



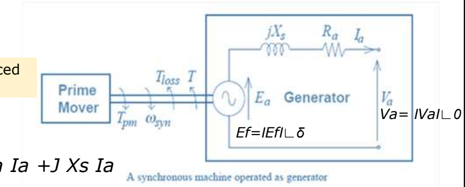
These transformers are used to adjust voltage in small amount. No isolation (used for voltage regulation)

Example 2.9 on page 69



2.1.1. Production and Absorption of Reactive Power

Internal /Produced Voltage



$Ef=Va + Ra\ Ia + J\ Xs\ Ia$

Ef=IEfI∟δ and Va=IVaI∟0

Generator Power Output

$$S = P + jQ = \frac{Va * E_f}{Xs} Sin\delta + J\left(\frac{Va * E_f}{Xs} Cos\delta - \frac{Va^2}{Xs}\right)$$

Real/active Power (W,kW,MW)

Reactive Power (VAR, kVAr, MVAr)

2.1.1. Production and Absorption of Reactive Power

Synchronous Generators:

They can generate and absorb reactive power.

They produce reactive power when they are overexcited.

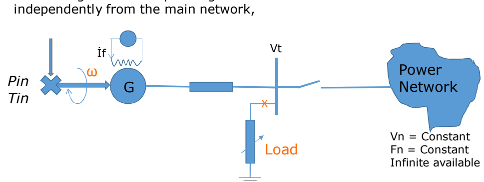
They absorb reactive power when they are under-excited.

Generated by excitation systems

$$S = P + jQ = \frac{Va * E_f}{Xs} Sin\delta + J\left(\frac{Va * E_f}{Xs} Cos\delta - \frac{Va^2}{Xs}\right)$$

Taken from the network

While the generator is operating independently from the main network,



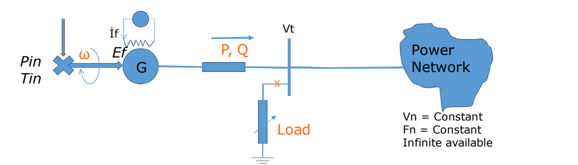
If ↗ then Ef ↗ then Vt ↗
If ↘ then Ef ↘ then Vt ↘

The terminal voltage of the generator can be controlled by changing the excitation current via an AVR

Tin, Pin ↗ then ω ↗ then F ↗
Tin, Pin ↘ then ω ↘ then F ↘

The frequency of the generated voltage can be controlled by changing the input power/torque using a speed governor.

While the generator is operating in parallel with the main network,



If ↗ *then Ef* ↗ *then Vt* ✕ ⟶ *Q* ↗
If ↘ *then Ef* ↘ *then Vt* ✕ ⟶ *Q* ↘

The reactive power generated can be controlled by changing the excitation current of the generator.

Tin, Pin ↗ *then* ω ↗ *then F* ✕ ⟶ δ ↗ *P* ↗
Tin, Pin ↘ *then* ω ↘ *then F* ✕ ⟶ δ ↘ *P* ↘

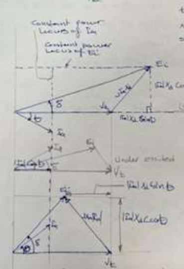
The active power output of the generator can be controlled by changing the input power/torque using a speed governor.

• In order to provide constant power ~~factor~~ P from the generator to the power network;

$P = |V_t|\,\underbrace{|I_a|\cos\theta}$ ⟶ must be constant

$= \frac{|E_i||V_t|\cos\delta}{X_d}$

In this case if we vary the dc field current If the generated (internal) voltage varies proportional so as to keep $|I_a|\cos\theta$ constant.



$Q = \frac{|E_i||V_t|\cos\delta}{X_d} - \frac{|V_t|^2}{X_d}$

$= \frac{V_t}{X_d}(E_i\cos\delta - V_t)$

(a) ⟶ for over excited generator supplies reactive power into the network
$E_i\cos\delta > V_t$

Normal excitation is defined as the condition when

$|E_i|\cos\delta = |V_t|$

• $|E_i|\cos\delta > |V_t|$ over excited

$|E_i|\cos\delta < V_t$ Under excited

Supplying the same amount of real power/load leading current

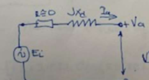
Example: The generator of above example has synchronous reactance $X_d = 1.7241$ pu and is conneted to a very large system. The terminal voltage is $1.0\angle 0°$ pu. and generator supplying to the system a current of 0.8 pu at 0.9 power factor lagging. All pu values are on the machine base. Neglecting the resistance, find the magnitude and angle of the synchronous internal voltage Ei, and P and Q delivering to the infinite bus. If the real power output of the generator remains contstant, but the excitation of the generator is:

a) increased by %20°, find the angle of δ between Ei and the terminal voltage, Q delivered to the bus by the generator

b) decreased %20°, find the angle of δ, ~~again~~ terminal voltage and Q again.

Solution:

$E_i = |E_i|\angle\delta$



$S = 635$ MVA @ 0.9 pf lagging

$V_B = 24$ kV rated voltage

$N = 3600$ rpm

$\bar{X}_d = 1.724$ pu

$I = 15\,275.73$ A
$= 15.276$ kA $= I_B$

$Z_B = \frac{24^2}{635} \cong 0.907\,\Omega$

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$E_i = |E_i| \angle \delta^\circ = V_t + jX_d I_a = 1.0\angle 0^\circ + j\,1.7241 \times 0.8 \angle{-25.842^\circ}$

$= 1.6012 + j\,1.2414 = 2.026 \angle 37.7862^\circ$ (pu)

$S = P + jQ = V I^*$

$P = \dfrac{|V_t||E_i|}{X_d} \sin\delta$ real (average-active) power output of the generator delivered to the power system

$Q = \dfrac{|V_t|}{X_d}(|E_i|\cos\delta - |V_t|)$ reactive power output of the generator.

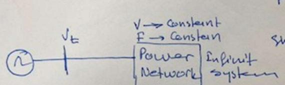
$P = \dfrac{1 \times 2.0261}{1.7241} \sin 37.7862^\circ = 0.72$ (pu)

$Q = \dfrac{1.0}{1.7241}(1.6012 - 1.0) = 0.3487$ (pu)

$Q = \dfrac{1.0}{1.7241}(1.6012 - 1.0) = 0.3487$ (pu)

(a) Increasing excitation by 20% with P and V_t constant

$P = 0.72 = \dfrac{1.0 \times 1.2 \times 2.0261}{1.7241} \sin\delta$



$\sin\delta = 0.[illegible] \Rightarrow \delta = 30.702$

In this case the new value of Q supplied by the generator

$Q = \dfrac{1.0}{1.724}[1.2 \times 2.026 \cos(30.702) - 1.0] = 0.6325$ pu

(34)

(b) with excitation decreased 20%, we obtain

$0.72 = \dfrac{1.0 \times 0.8 \times 2.026}{1.724} \sin\delta \Rightarrow \delta = 49.9827^\circ$

then

$Q = \dfrac{1.0}{1.724}[0.8 \times 2.0261 \cos(49.9827) - 1.0] = 0.0245$ pu