**Chapter 1: Introduction to Machine Principles**

* 1. Electromagnetic field

Magnetic Fields (MF) are mechanisms for energy conversion from one form to another i.e. in transformers, motors, generators… etc. Four basic principles describe how magnetic fields are used in these devices:

It is a must to establish a magnetic field before the conversion process

1. A current-carrying straight wire produces a magnetic field in the area around it.

Right hand rule (R.H.R.)

direction of the

magnetic field Conductor perpendicular to the plane.

I get a series of concentric circle of magnetic lines around the conductor.

1. A time-changing magnetic field induces a voltage in a coil of wire if it is located in the field (this is the basis of transformer action )

ф

I It should be AC to have a MF

Magnetic core

Mean path length (lc)

1. A current –carrying wire when subjected to a magnetic field will experience a force acting on it (This is the basis of motor action)

When there is a current interaction Magnetic bar is current

interaction

1. A moving wire when subjected to a magnetic field has a voltage induced across its terminals (this is a basis of generator action)
   1. Production of magnetic field:

The basic law governing of Magnetic Field is by Ampere’s law

=Inet

Inet : current (A)

H: magnetic field intensity (Amp.turns/m)

For better understanding of the formula we have a rectangular core with a winding of N turns around one leg. Consider all the field remains in the core:

Ф

I

Only mean core

Length (lc)

When an alternating current passes by this coil we have a flux produced in Weber.

NI=Hlc

Nl: Ampere Turns produced

H: Magnetic Field intensity

lc : mean core length(path)

Ф: is the flux produced

How much magnetism I have in the wire

B flux density (Wb/m2 or Tesla) =

A: the net cross sectional area (m2)

B=µH

B (Tesla or wb/m2): Flux density

µ: Permeability: the ability of the core medium to be magnetized

H: Magnetic field intensity

µ = µrµ0

µ0= 4π×10-7 H/m (in free air)

for air µr=1.0

µr can reach up to 6000 for certain materials.

B=

Ф= BA=

* 1. Magnetic circuits:

paths for magnetic flux.

1. Flux lines never intersect
2. Flux lines follow paths of permeability (least reluctance to magnetism)
3. Once a loop is established ф is constant in it

I ф

EMF

R

R (reluctance)

V=iR mmf=Ni

mmf = NI

magnetomotive force ф = F/R

permeance = 1/R

Ф = F×P

Ф = µNIA/lc

* Ф = F(µA/lc)

R (reluctance AT/wb) = lc/µA for a single medium to be magnetized AT/wb

* 1. Composite magnetic circuits

Ф constant (if A changes and B changes)

RAg = g/Agµ0 ф

Ag: Area of the gap

Nig Fringing effect at air gap i.e. Ag increases

Rcore= lc/µAcore

Rair gap= g/µ0Ag

The cross sectional area is increased which leads to a decrease in flux density. When we neglect fringing effect the flux density remains constant.

NB.As the flux is constant in a loop, when the cross sectional area changes the flux density changes.

Series elements in magnetic circuits

When elements are connected in series, then the total reluctance is the sum of individual reluctances of the elements.

RAC1

Rg

RAC2

The total reluctance of elements that are in series is equal to the sum of individual reluctances.

NB. B varies when the element area varies.

Parallel elements in magnetic circuits:

ф

Ni

RAC1 RAC2 Rg

Example:

An iron ring of square of 2×2 cm cross sectional area having an external diameter of 14 cm and an internal diameter of 10 cm. A radial saw cut through the ring forms an air gap of 1 mm. If the ring has a coil uniformly wound round it. With 500 turns calculate the current in the wire of the coil required 1mm to produce a flux of 3.5×10-4 Wb in the Air gap. Neglect flux leakage and fringing.

1mm

14 cm

10 cm

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| B(tesla) | 0.65 | 0.89 | 1.06 | 1.18 |
| H(AT/m) | 200 | 300 | 400 | 500 |

The values are:

Total mmf =Hclc + Hglg

lc = πDmean =

Plot of Graph

B(tesla)

0.875

H AT/m

295

2. A uniform area core of 25 mm2 has the following shape

Ф1 ф2

i Ф3

lg1=0.5mm lg2=1mm

i = 0.25 A N= 1000 Turns

µp of therefore Rc =0

Calculate ф and B in each leg.

The only source of reluctance is in the gaps.

Ag1 = Ag2 = 25×25×10-6

* 1. Faraday’s law

If a flux passes through a wire, therefore a voltage (emf) will be induced. This voltage is proportional to the rate of change of the flux.

N S

The emf induced in a loop of wires with N-turns; therefore the emf induced is:

Lenz’s law gives us the sign needed of the voltage induced which represents the direction of the emf induced.

This sign is obtained as follows:

If the coil is short-circuited at its terminals a current will flow.

This current will produce a flux opposing the original flux of the coil.

Self-inductance

The self-inductance of a coil affects its ability to stop changes in the corresponding magnetic field.

Flux linkage: The flux that is cutting the coil. (Maximum flux linkage of a coil with N turns coils)

The energy stored in the magnetic circuit.

Work done equals to energy stored

by replacing

Example:

A 2 pole shunt motor has a flux per pole 0.01 Wb when the exciting-current is 2 A the number of turns in each pole equals 2000. Calculate the energy stored in the magnetic field.

Find L and then ф then the flux linkage.

Ф = 0.01 Wb

I field

Supply Armature

Number of turns =2×2000= 4000 we have 2 poles

The energy stored is magnetizing the field so the motor functions.

* 1. Characteristics of ferromagnetic material

Important in the transformation of energy.

Magnetic circuit is a necessity but it has losses for the same B=µH

If µ increases H will decrease

Those with high permeability materials are more expansive than the ones with low permeability.

With higher µr we obtain small H, hence less magnetizing current i.e. lower losses.

µr can go up to 6000 when changing from one material to another.

Magnetic behavior of ferromagnetic materials:

In electromechanical energy conversion devices, these materials have 2 important roles to be played:

1. From B=µH, we have to obtain large B from smaller levels of H; as µ increases H will decrease . Large B leads to an increase in the magnetic forces and energy density. This plays a major role in the performance of energy conversion devices. When we decrease H=NI/l, as H decreases I will decrease.
2. Magnetic materials can be used to constrain and direct magnetic fields in a well defined path i.e. in a transformer, it maximize the coupling λ between windings and lower I excitation for transformer operation. In rotating machines they shape the field to obtain the desired torque characteristics. Ferronmagnetics are iron, iron alloys with silicon, cobalt, mg, nickel etc…

µ0 is constant; µr varies up to 6000 µ0

saturation

B Tesla

knee

linear

H (AT/m)

The field is more contained in the magnetic material we have less leakage and better λ and hance smaller excitation I is needed or lower N (number of turns)

In the machines the torque is affected greatly by the magnetic field therefore we have:

* How to decrease a B H curve? B

i decrease (1)

* Have magnetic material
* coil has N turns core length
* increase the current
* coil is fully unmagnetized reverse the current (2) increase i

H AT/l

(4) The hysteresis loop

(3)

saturation

From (1) (2) we start to decrease the current, B doesn’t follow the same path because the core is magnetized. (Residual flux or magnetism) Then at (2) we reverse the direction of the current and start increasing it until saturation. It will produce a magnetic field in the opposite way to (3)

At (3) we start decreasing that current until it reaches 0 value at (4)

At (4) we reverse the current and start increasing it until saturation reaching (1)

The hysteresis loop is the representation of the loss which has to be taken care of. This loss is due to the formation of flux.

The smaller the hysteresis loop for the material the smaller are the losses hence the better material.

Flux density varies between 1.5 2.5

For cast-steel flux density= 0.025

The hysterisis losses are proportional to the frequency and not linearly proportional, the ability of the material to be magnetized.

Pe (eddy current losses) due to emf induced in the core itself which will cause circulating current in it which results in any current losses

To minimize these losses: of the core increase R by lamination in thin sheets insulation these sheets from each other then I tight them. Any current losses formula:

V: induced emf

R: Electric resistance of the core

Kl: Constant of material

f: frequency

Bmax: Flux density

A group of e- that has certain magnetic direction form the domain

* 1. Magnetic domains

This happens due to an mmf they are being lined up.

The alignment ends at the saturation, any addition is a waste.

We need the domain to be aligned. Any extra mmf will be a loss.

The hysteresis losses are used to produce theses domains> I want them aligned to produce the magnetic field.

Ampere-turn is used to align them.

* 1. Motor and generator action due to magnetic field

Motor action:

Assume we have a magnetic field and in the surrounding then it will induce a current-carrying conductor which will produce a force.

If a current I is flowing B

F (force)

I

L: length of conductor

B: Flux density conductor

N.B. in series magnetic circuit ф is constant; B is not necessarily constant if we have composite circuits with different cores if we consider fringing A changes.

Generator action:

Induces an emf and then current. V B

Induced voltage in a conductor +++

Moving in a magnetic field

No movement no emf induced L

B: flux density \_\_\_

V: velocity of the wire

L: length of the conductor in the magnetic field

The product VB is not constant but we take it as maximum.

Ф is the angle between V and B

Consider ф to be 90°, and their position with respect to the position of the conductor.

Generator action: Its relative mvt between the conductor in a flux density of B(T) with a velocity v.

**Chapter 2: Three phase circuits** (Ref. appendix A p. 681)

In single phase circuit we have V, I, R, L, C.

In the basic AC single phase

i j𝝎L 1/𝝎C

Hotline H

Neutral N

The instant power is pulsating => circuit is not working efficiently

The effective power is constant

For single phase

P

S Q leading Q lagging

P S

Q: it is released in the magnetic field of inductor as lagging, or in capacitor as leading,.

Electric field to charge a capacitor: current leading.

For the same power when we reduce Q and thus reducing the angle Φ so to the power factor is improved.

The winding is installed in the magnetic field. When the flux is not cutting the winding, no emf is induced

When the flux is perpendicular to the winding, we have *maximum flux cutting it and emf is induced*

S

N

a

a’

R

j𝝎L

j𝝎L

v(t)

Z Z’

Z X difference of the two reactances

Ф R (resistance) and X (reactance)

R

, Ф: phase angle and Z: impedance

2.1 Generation of 3-phases

N

S

3 coils are Displaced by 120° in space and rotating in a magnetic field

b

c’

a

a’

c

b’

There will be a voltage induced

with an instantaneous value *v* in each phase.

°

This is similar to 3 single phase generator producing equal voltages but displaced by 120°

If these conductors are identical (which they normally are) I have three equal voltages induced but displaced by a 120°.

Phase sequence is the order in which the voltage of each phase reaches its peak value.

va

vb vc

120 240

I have three currents ia, ib, ic are equal in values but displaced by 120°.

When three phases are equally loaded it is called a balanced load.

When we have three single phase loads :

The phases of the loads could be connected in two main ways:

1. The Y-connection
2. The Delta-connection

The Y-connection

va

R

R

R

N (neutral)

vc

vb

Wye (star) connected load: this system may also feed a delta connection

The Delta-connection

a

Va  Va Vb

b

Vc

Vb

c

Vc

Va

N N

Vb

Vc

If the loads are balanced then the current in the neutral IN =0.

A Y-connected supply Feeding a delta connected load:

We don’t need the neutral for the delta connected load.

It is more advantageous to connect the capacitors in delta to get more reactive power from them.

If I put my voltage meter across the neutral and a line I will get a phase voltage value.

V

Vф phase voltage

V

VL line voltage

Relation between phase voltage and line voltage:

Vф

Vc

VL

120° Va

Vb

Remember the Vф and VL are displaced is WYE

If we have a balanced

load then the phases R

are equally loaded . N R

If the phase angle is N

different it is not R

a balanced load.

For balanced, IN =0;having 3 connections and a neutral instead of 6 between the source and the load.

In the normal case: 3 hotlines and a neutral line.

If balanced we don’t need always the neutral wire.

The line current IL =Iф

For delta-connected

IL1

Ia  Ib

Va  Vb

Vc Ic  IL2

IL3

At the point nothing is stored sum of currents is equal to zero

For balanced load: Ic IL

Ia

* Ib

As a result the same apply for the other 2 phase currents

For resistance

S: apparent power

Q: reactive power

If we say power means P unless otherwise said. P in MW, kW, W

ZΔ ZΔ

- ZY

Need to simplify connections

Draw a single line diagram:

The windings are carrying less current.

For pure balanced capacitive load

For the capacitor bank we connect it in delta (use for power compensation)

Ic

P V

ФL Qcomp

S Icomp Q

Scomp

Qc: reactive power drawn by the capacitor

I

V ZL Z

To bring the power factor to less than 1 lagging.

P=constant; as Q decreases, I decreases.

Reduce cross sectional of cable and related conduits ; reduce losses because P is proportional to I2.

P

Qcomp

Q

S

Example:

1

1 0.8

0.9

0.6

Problems

Problem set 1:

1. 4 wire => Y-connected

10Ω

N

10Ω

10Ω

N

**Chapter 3: Transformers**

* 1. Introduction and EMF equations
     1. Construction

1. Windings…
2. Core…
3. Core form…
4. Shell…
5. Tank…
6. Bushings…
7. Oil for insulation and cooling…
   * 1. EMF equations

ϕ

* 1. Principle of operation of Transformer

The voltage at the primary VP produces a current in the windings of the primary IP which induces a flux ϕ in the core. The direction of ϕ is obtained by the right hand rule. The flux cuts the primary and the secondary windings producing an induced voltage EP and ES. If a load is connected across ES a current will flow producing a flux opposing the main flux and reduces it, which reduces EP and ES. As EP is reduced, IP is increased as

which brings back instantly the main flux to its original value. i.e. remains practically constant and hence EP and ES remain at the same value practically.

ϕ

VS

Load

* 1. Ideal Transformer

1. No Physterisis or Peddy current losses
2. No I2R losses (copper losses)
3. No leakage flux
4. Linear B/H curve and no saturation

B

H

* 1. Impedance Transformation

a: ideal transformation ratio

The apparent load impedance on the primary circuit or its effect on the primary circuit.

Example:

A single phase 220/110 V transformer

50 Hz

S=5 kVA

It delivers a secondary current of 20 ampere at 0.8 PF lagging at rated voltage

Assume ideal transformer

110V

220V

1. Find
2. Find referred to the primary side
   1. Open circuit and Short circuit tests
      1. Open -circuit test

A

VP rated LV side of transformer

V

Watt meter

In this test gives, Pcore = Ph +Peddy

Ph: hysteresis losses

Peddy: eddy current losses

Values measured:

* + 1. Short -circuit test

V

A

Variac start from zero

Watt meter

S/C

H.V. side is usually used to get a noticeable voltage i.e. 4% of 220V which is about 9V, while 4% of 11 kV is 440V. (MV/LV power transformers)

We start from zero and increase carefully the voltage of the variac (potentiometer) until the ammeter reads IFL.

We measure VS/C , IS/C , and PS/C=the full load copper losses.

We fix the total series impedance referred to the primary side.

Resultant:

Xeq

Irated

Req

VS/C

* 1. Efficiency

S is the rated apparent Full load power in kVA

X is the fraction of full load of the transformer

Pcore: core losses (no load losses)

PCu: copper losses

A 200kVA single phase transformer has an η of 98% at FL of the max. η occurs at ¾ of FL, calculate the:

1. The core losses
2. The FL copper losses
3. The efficiency at full and half load

Ignore magnetizing current and assume a PF of 0.8 lagging at all loads.

Let the value of the secondary current IS at FL to be I

The η at FL = 98%

As ηmax occurs at ¾ FL; therefore,

1. At half load:
   1. Equivalent circuits and Phasor diagram

From O/C and S/C tests, we have found the O/C test so we have established Z0, , Ioc and from them we get :

From the S/C test we found the series impedance ZSE which is expresses as:

Example:

If test on transformer

A 20 kVA, 8000/240V, 60Hz

Transformer parameters to be determined from:

O/C test:

S/C test:

i.e. secondary S/C

Solution:

From S/C:

Equivalent circuit:

IS’

IP

Xeq

Req

VS’

VP

Rcore

XM

O/C T-shaped equivalent circuit:

RP

XP

XM

Rcore

VS’

XS’

RS’

VP

For T-shaped

Phasor Diagram:

IPRP

IPXP

VP

IS’

I0

EP

ϕ

IS’

V’S

I’SR’S

E’S

Example:

A 20kVA single phase 8kV/277V 50Hz has

RP= 32Ω, XP= 45Ω

RS= 0.05Ω, XS= 0.06Ω

ROC= 250kΩ, XM= 30kΩ

Transformer supplying FL at rated voltage and PF=0.8 lagging

Find

1. VP referred to the secondary
2. Voltage regulation at that load
   1. The Per Unit System

15 kV

220 kV

220 kV

11 kV

66 kV

Transmission line

66/15 kV

* 1. The Auto Transformer

Normal Transformers have usually two windings: one primary and another secondary. However, the Auto transformer has one winding which is tapped. We either have to lower or increase the voltage.

Current in the coils are related at the terminals by the equations

From equations (1) and (4) we obtain:

And from equations (6) and (3) we obtain:

Step up Transformer

Step down Transformer

When the voltage ratio is 2:1 the Sout is at 50% but a transformer with ratio of 2:3 due to core cost mainly is large but losses are less in auto transformer.

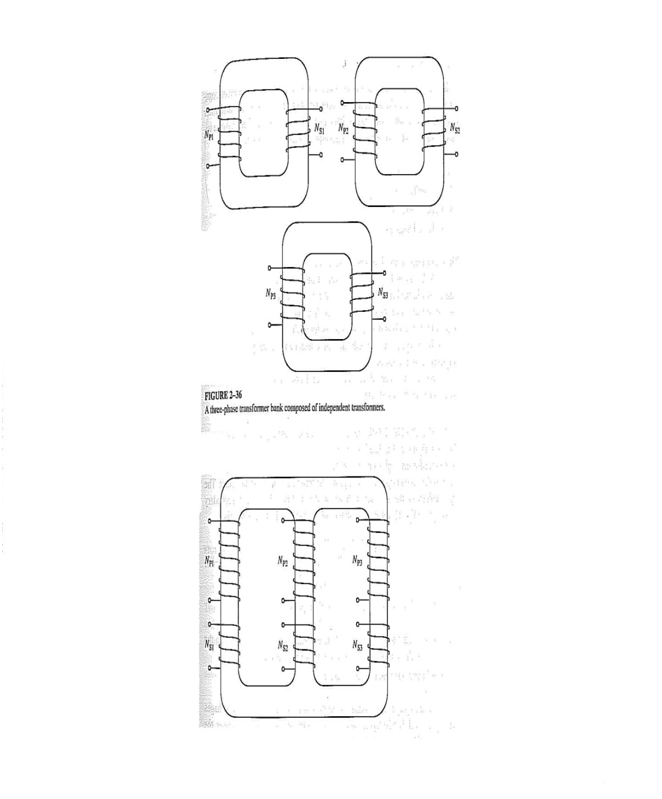
Example:

A 10kVA, 120/480V transformer used as an auto transformer connecting a 480V load to a 600V supply.

1. Determine its kVA rating as an auto transformer
2. Determine its efficiency at FL at PF=0.9 lagging

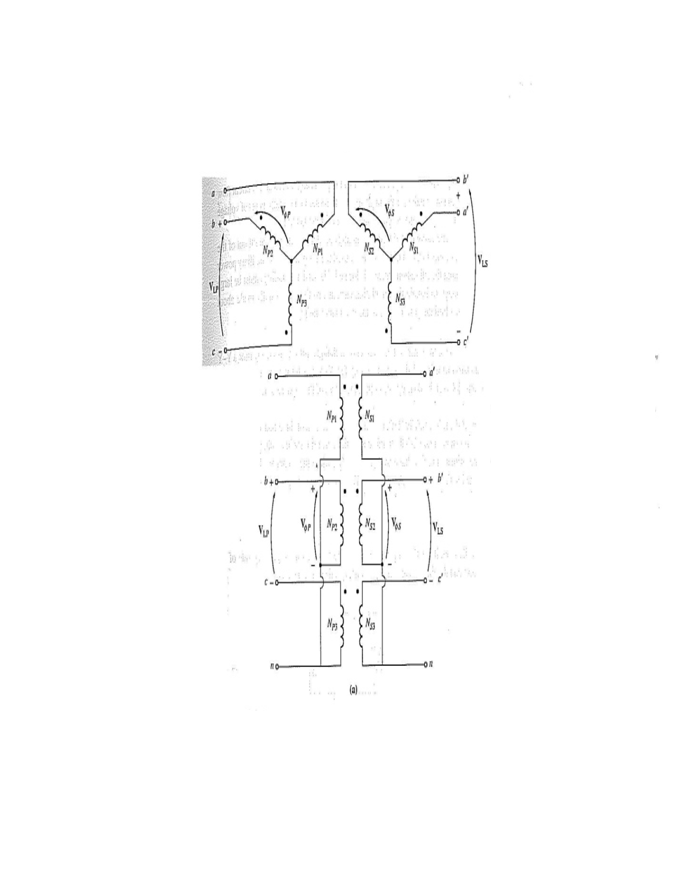
* 1. 3-Phase Transformers

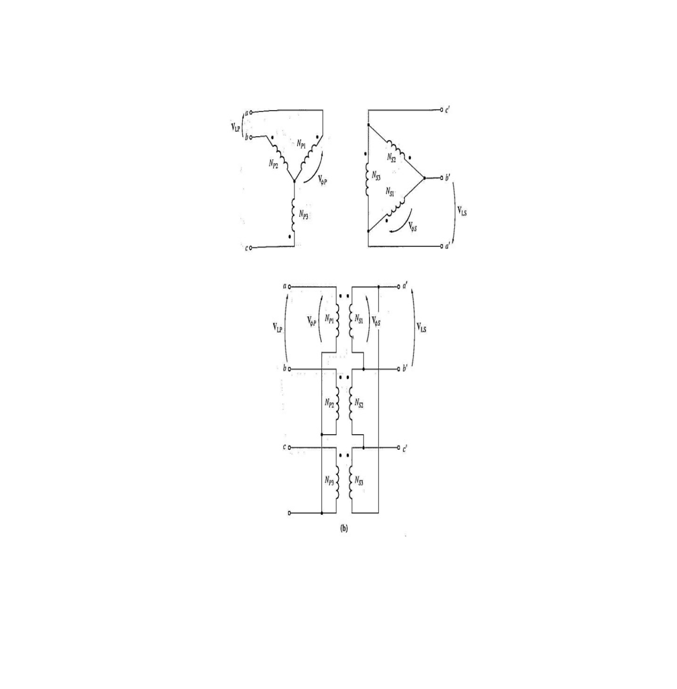
The 3-phase transformers are lighter, smaller, cheaper, and slightly more efficient. They are concentric with less flux leakage. The high voltage should be insulated by the core. It also has better leveling between the high voltage and low voltage. The side is connected to the tank by bushings.



There are 4 main connections of 3-phase transformers:

1- Wye -Wye (Y-Y)

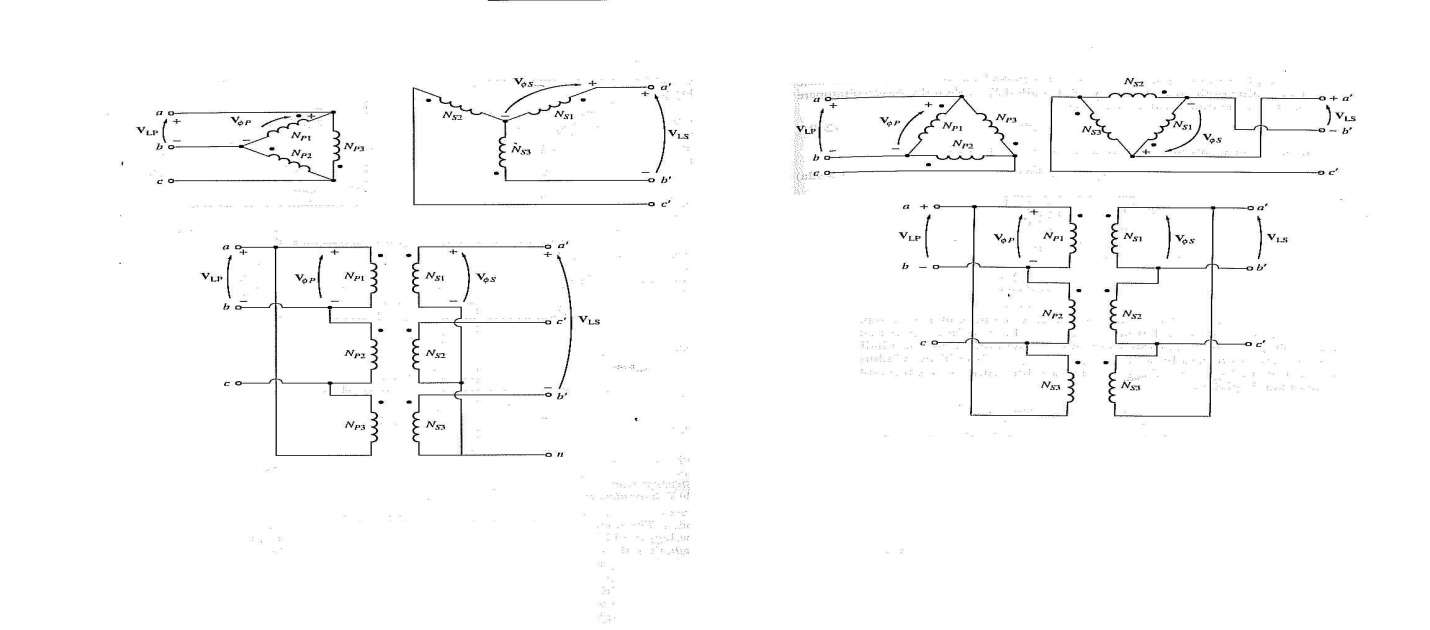




2- Wye-Delta (Y- Δ)

4-Delta-Delta (Δ- Δ)

3-Delta-Wye (Δ-Y)



Remark: For each transformer:

Example

A 3-Φ bank of transformers in a power system is used to step up the voltage of 13.8 kV 3-Φ generator to 138 kV transmission line. The generator rating is 41.5 MVA.

Specify the voltage, current, the MVA rating of each transformer and establish the table of operating condition for Y-Y, Y-Δ, Δ-Y, Δ-Δ.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  | | | |  | | | |
|  |  |  |  | |  |  |  |
|  | 7.97 | 1736 | 13.83 | | 79.67 | 173.6 | 13.83 |
|  | 7.97 | 1736 | 13.83 | | 138 | 100.2 | 13.83 |
|  | 13.8 | 1002 | 13.83 | | 79.67 | 173.6 | 13.83 |
|  | 13.8 | 1002 | 13.83 | | 138 | 100.2 | 13.83 |