Electrical Equipment - Course PI 30.2

THREE PHASE SYSTEMS

OBJECTIVES

On completion of this module the student will be able to:

1. In a few sentences explain how three phase voltages are produced in a generator.
2. Briefly explain in writing the term "phase sequence".
3. List the two most commonly used connections in a three phase system.
4. State in a sentence the connection configuration used in Ontario Hydro generators.
5. Explain in a few sentences why the neutral point of a star connected generator is grounded via a high impedance.
6. List two possible arrangements of a Y connection and give one application of each.
7. State in writing the line and phase voltage and current relationships in a:
   a) Y configuration;
   b) Δ configuration.
8. Given a three phase transformer connection indicate using standard symbols, how the information is expressed schematically.
9. List, in writing, four reasons why three phase is preferred over more than three phases or single phase generation.
10. For synchronization of a generator to the grid, list, in writing:
    a) four points to be considered;
    b) how they are checked; and
    c) how they are adjusted.

1.0 INTRODUCTION

This module introduces the student to the:

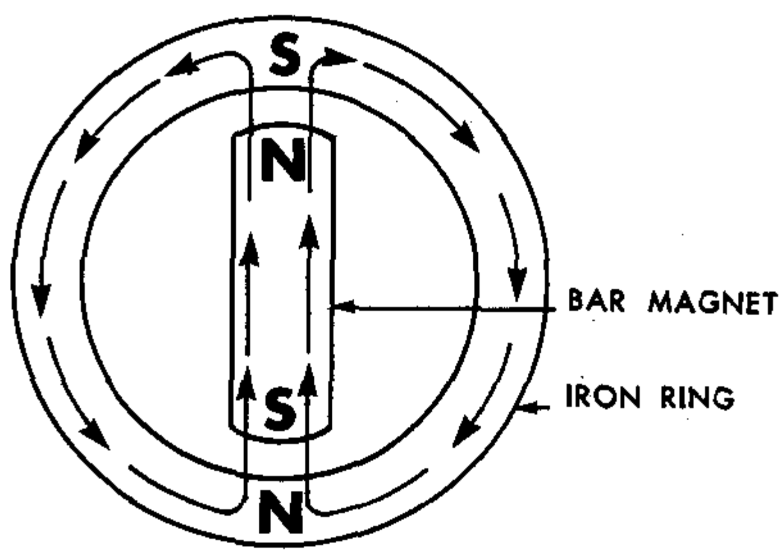
(a) concept of three phase generation and its advantages.

(b) three phase connections.

(c) synchronizing of a generator to the grid.

2.0 THREE PHASE GENERATION

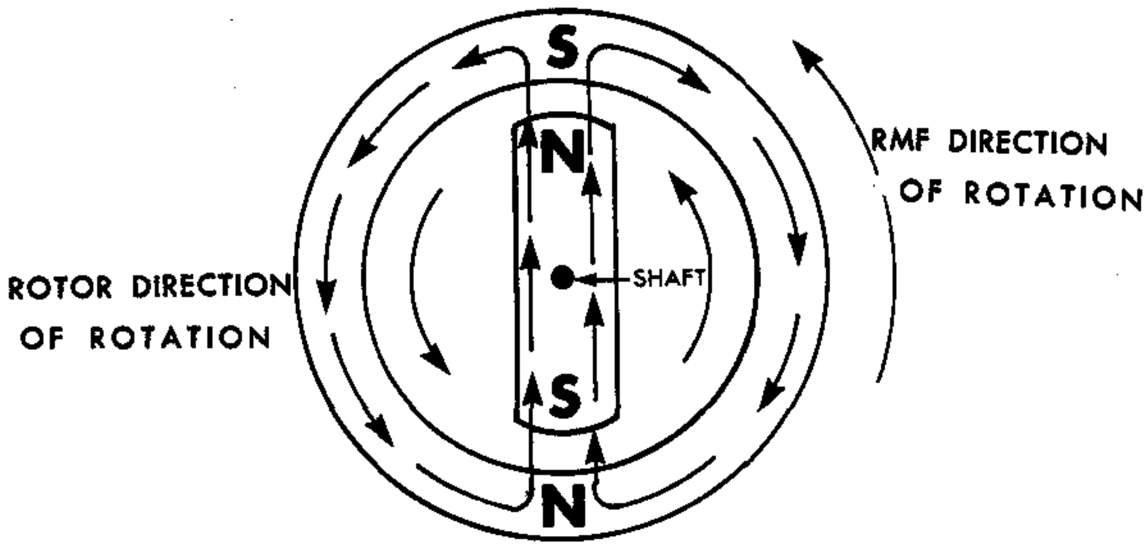
Consider a bar magnet placed in an iron ring as shown in Figure 1. The magnetic lines of force start from the north pole of the bar magnet and pass through the iron ring, since iron is a low reluctance path as compared to the air, and return to the south pole of the bar magnet thus completing the magnetic circuit.



A Magnetic Field Established in the Iron Ring

Figure 1

Due to the fact that the magnetic lines of force from the bar magnet are passing through the iron ring we can say that a magnetic field is established in the iron ring. Now consider that the bar magnet is mounted on a shaft passing through its centre and the shaft at each end is mounted on bearings. (See Figure 2.)



A Cross-Section of the Shaft, The Magnet and the Iron Ring

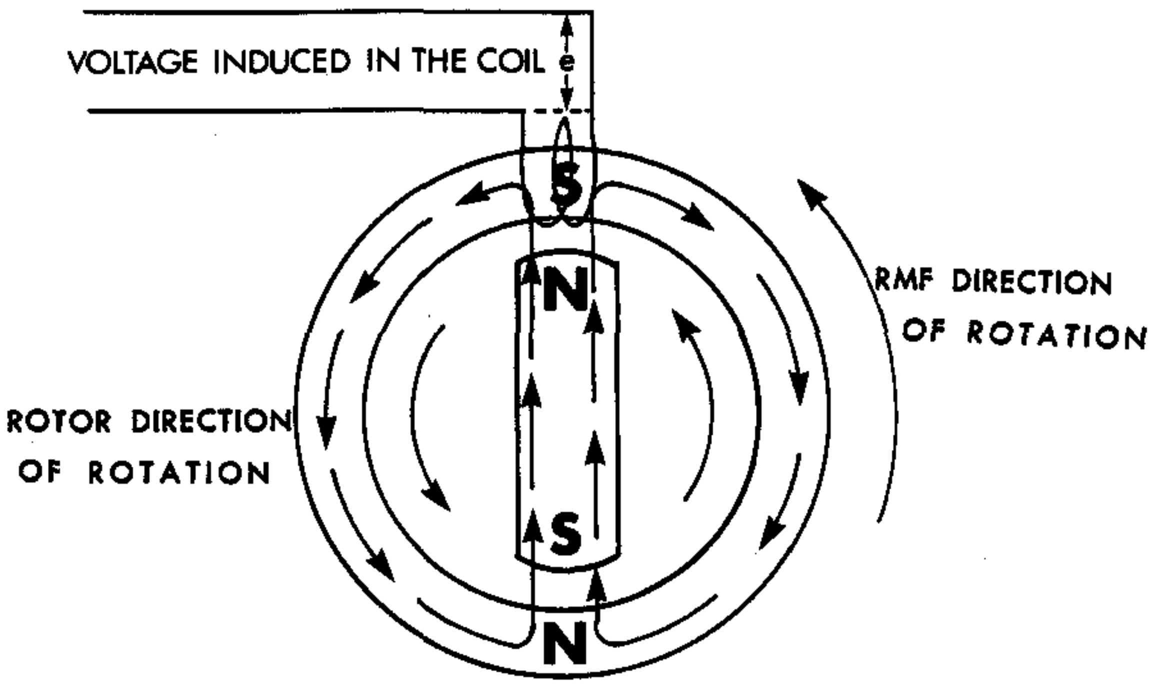
Figure 2

If the shaft is rotated by some means the bar magnet mounted on the shaft will rotate with it hence the magnetic field associated with the bar magnet will also rotate with it. This sets up a rotating magnetic field (RMF) in the iron ring.

A coil is now placed on the iron ring as shown in Figure 3. As a result there is:

- magnetic field
- a conductor
- relative motion between the conductor and the magnetic field.

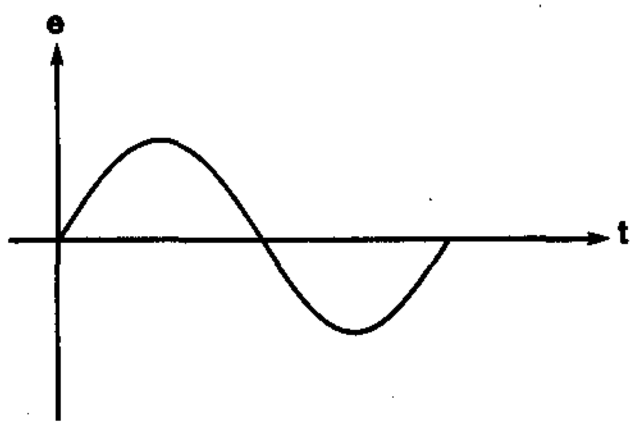
All the requirements for electromagnetic induction are met and a voltage will be induced in the coil.



A Coil Placed in the Rotating Magnetic Field

Figure 3

Induced voltage in the coil will be maximum when the magnet is facing the coil as shown in Figure 3. Waveform of induced voltage is shown in Figure 4.



Induced Voltage in the Coil

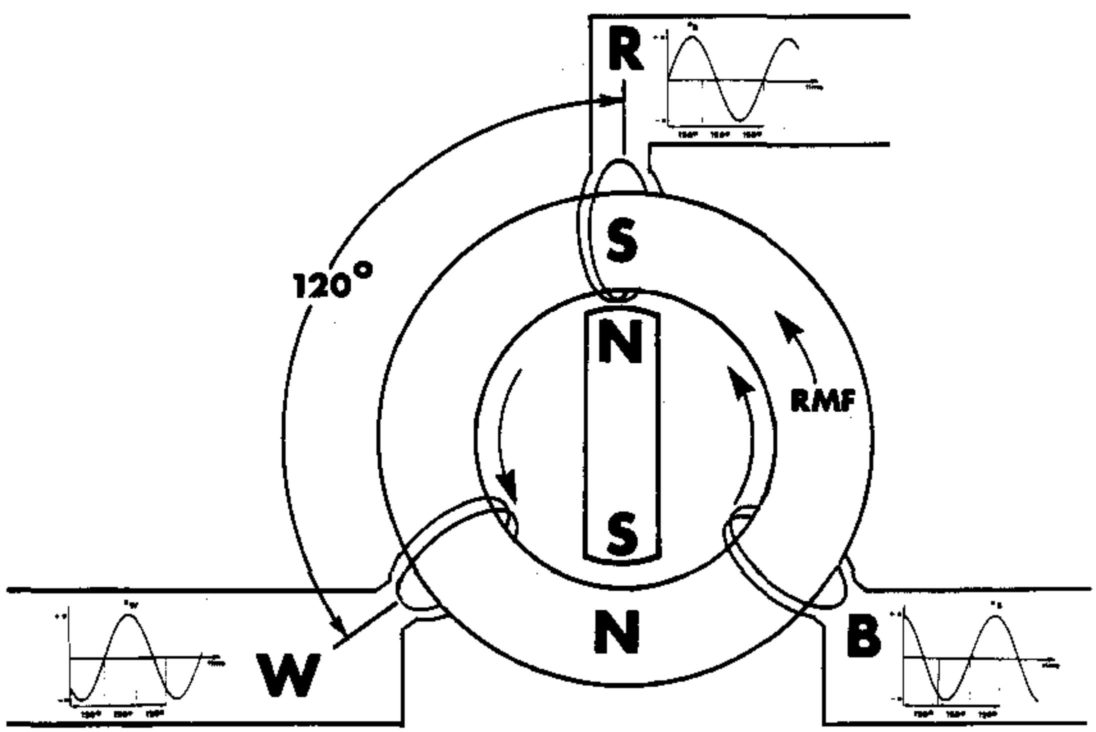
Figure 4

This is a single phase generator since there is only one coil in the magnetic field and only one sine wave output as shown in Figure 4. If three coils, 120° apart are placed on the iron ring as shown in Figure 5, then a sine wave of voltage will be induced in each of the coils. Now there are essentially three single phase generators built into one. It is referred to as a three phase generator. Ontario Hydro gives each coil a name thus:

Red Phase represented by R.
White Phase represented by W.
Blue Phase represented by B.

The voltage induced in the Red phase will be maximum when the magnet is facing the Red coil as shown in Figure 5. Similarly the voltage induced in the White coil will be maximum when the magnet has rotated and is facing the White coil, and the voltage induced in the Blue coil will be maximum when the magnet has rotated again and is facing the Blue coil.

Since Red, White and Blue coils are 120° apart their maximum induced voltages will also be 120° apart as shown in Figure 6.



Three Phase Generator

Figure 5

In power plants the generators use the same principle. The magnetic field is provided by an electromagnet mounted on a shaft. The magnitude of current flowing through the electromagnet determines the strength of the magnetic field.

The shaft on which the electromagnet is mounted is coupled to the turbine. Rotation of the turbine therefore rotates the magnetic field of the electromagnet thus providing the relative motion.

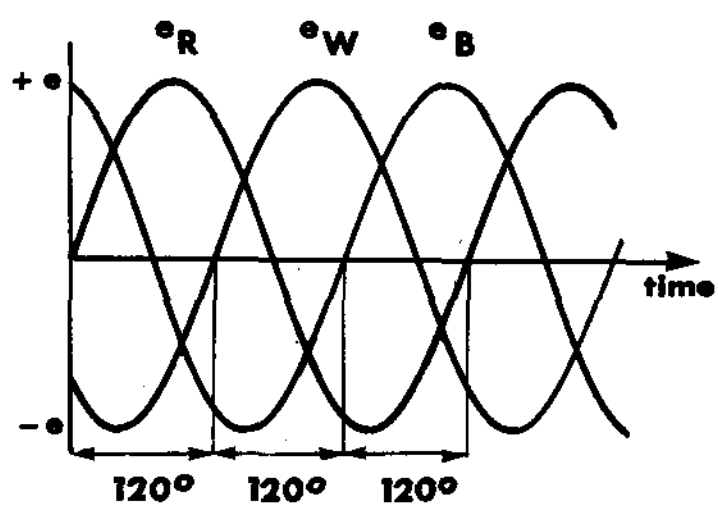
Coils are placed in slots in the stationary part (stator) of the generator as conductors. An iron core takes the place of the iron ring and provides a magnetic path.

The result is a three phase induced voltage in the three sets of coils.

2.1 Phase Sequence

Phase sequence is the order in which the voltage peaks occur in a three phase generator.

In Ontario Hydro, Red-White-Blue is the standard phase sequence. In Figure 6, the Red peak is occurring first then the White then the Blue. Phase sequence therefore is Red-White-Blue.



RWB Phase Sequence

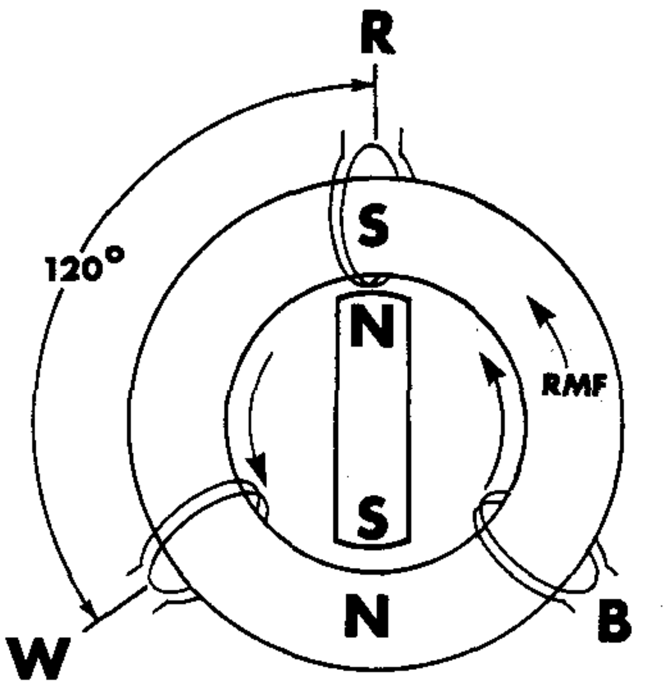
Figure 6

3.0 THREE PHASE CONNECTIONS

Looking at Figure 7 it is evident that if the induced voltage from each coil is to be transmitted to the load, it will require two lines per phase and a total of 6 lines. This becomes inconvenient and expensive.

To overcome this problem three phase supplies and loads are connected in one of two possible configurations as follows:

(i) Star Connection.
(ii) Delta Connection.



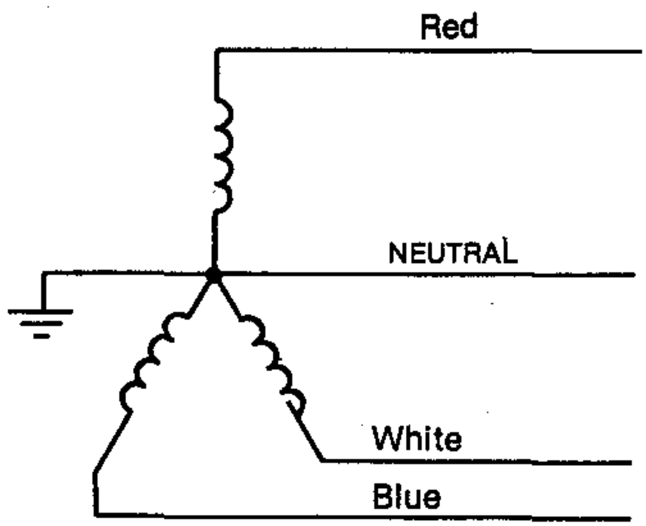
Three Coils Not Interconnected in Any Configuration

Figure 7

3.1 Star or Wye Connection

One terminal of each coil, all of which will have instantaneously the same polarity, is connected together as shown in Figure 8. The junction point is called the "Neutral". Three wires, one from each of the Red, White and Blue phases, are brought out as supply terminals. The neutral point may be connected to ground (earth) via a high impedance. Current in the neutral is the vectorial sum of the three phase currents. Under normal balanced conditions it is zero.

$I_N = I_R \angle 0° + I_W \angle -120° + I_B \angle 120°$ (DO NOT MEMORIZE)



Ground Star or Wye Connection

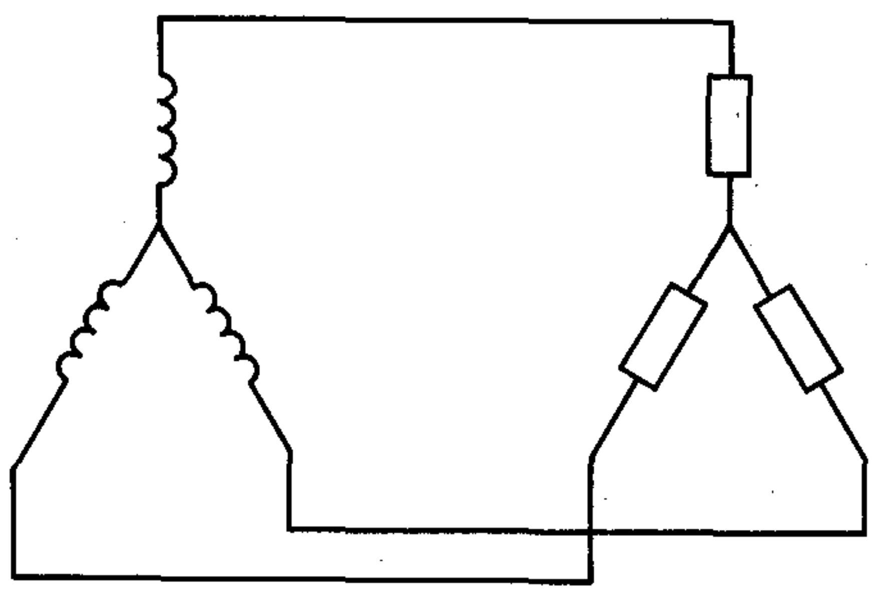
Figure 8

If there is a fault on one of the phases then the current magnitude through that phase will be much higher than the other two phases. Neutral current in this condition will not be zero but a finite value which could be very large. This is why the neutral of the generator is connected to ground via a high impedance and reduces the fault current to a reasonable value ($\leq$5A). Current through the neutral is also used to operate the relays for protection of the generator or transformer.

Three phase transformers can also be connected in star configuration but their neutral point may or may not be connected to ground via an impedance.

3.2 Three Wire Star Configuration

If only three wires from the three phases are brought out with no neutral wire then the system is referred to as three phase three wire star connection. This arrangement is used when it is certain that the load on each phase will be equal in magnitude. This makes the neutral current zero and eliminates the need for an added neutral conductor. (See Figure 9.) An example of such a load is a three phase ac motor.



Three Phase, 3-Wire Star, with Ungrounded Neutral.

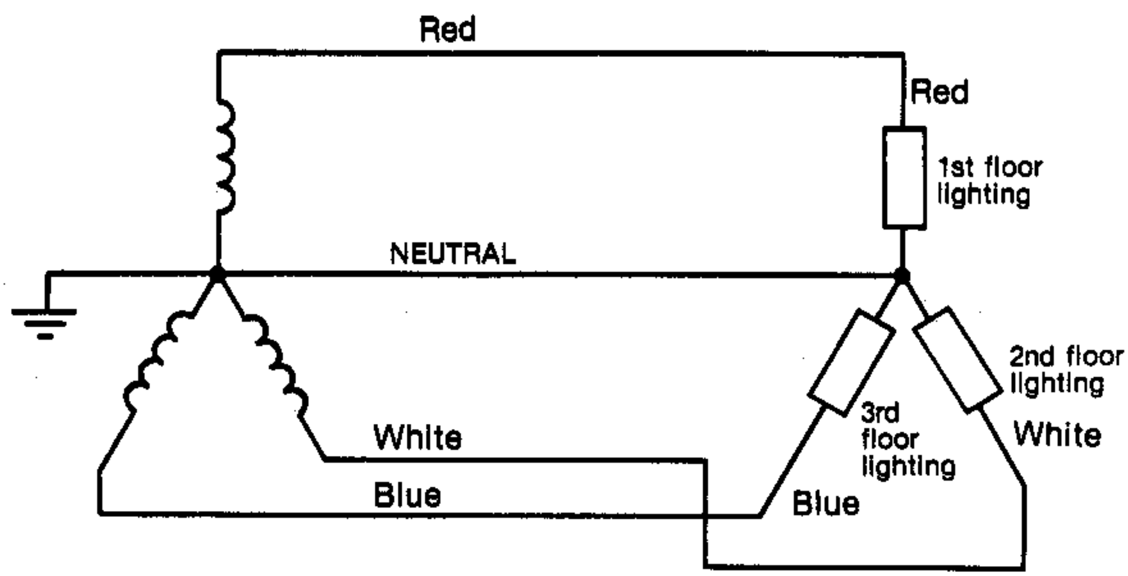
Three Phase, 3-Wire Star, Balanced Load.

Three Phase, Three Wire, Y Connected System

Figure 9

3.3 Four Wire Star Configuration

It is not always possible to guarantee a balanced load on each phase, eg, lighting or heating loads. It is possible that more lights or heaters connected to the Red phase are on compared to the Blue or White phase. This creates an unbalance of phase currents and the neutral current will no longer be zero requiring an additional conductor from the neutral of the supply to the neutral of the loads, as shown in Figure 10.



Three Phase, Grounded Neutral Supply from Transformer.

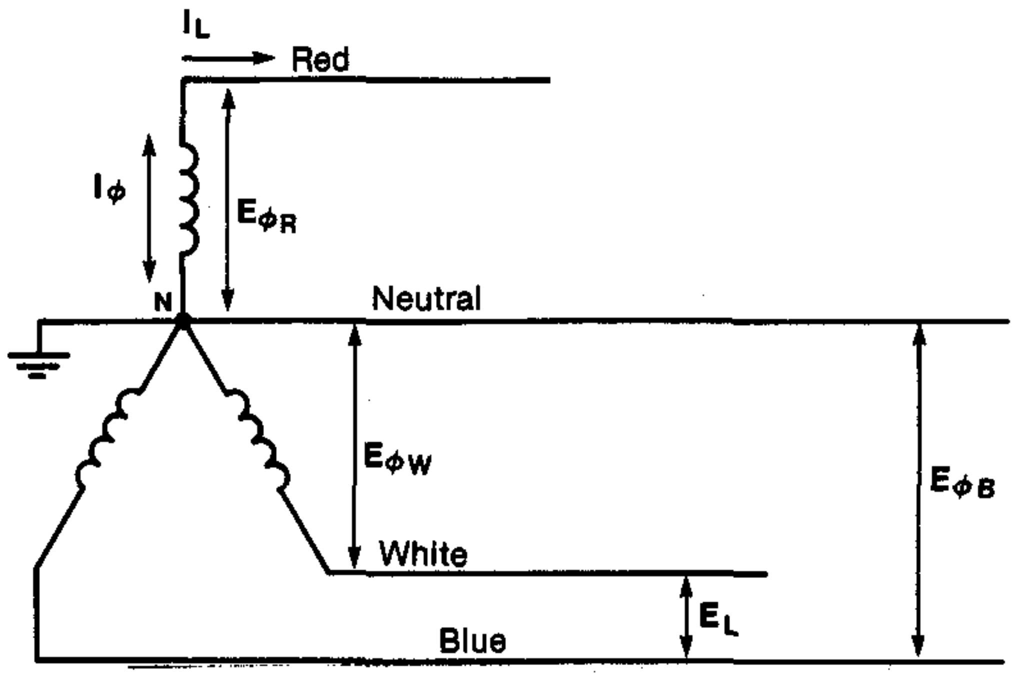
Unbalanced Three Phase Y Connected Load.

Three Phase Four Wire Y Connected System.

Figure 10

3.4 Voltages and Currents in Y Configuration

Consider a transformer connected in Y-configuration as shown in Figure 11.



Phase and Line Voltages in a Y-Configuration.

Figure 11

3.5 Phase Voltage

If a voltmeter is placed between the:

Red phase and the neutral a voltage $E_\phi R$ will be measured.

White phase and the neutral a voltage $E_\phi W$ will be measured.

Blue phase and the neutral a voltage $E_\phi B$ will be measured.

$E_\phi R$, $E_\phi W$ amd $E_\phi B$ are the voltages between one phase and the neutral and they are referred to as the phase voltages.

3.6 Line Voltage

If a voltmeter is connected between any two lines then it will measure the line voltage E_L. This is shown in Figure 11 between the White and Blue phases.

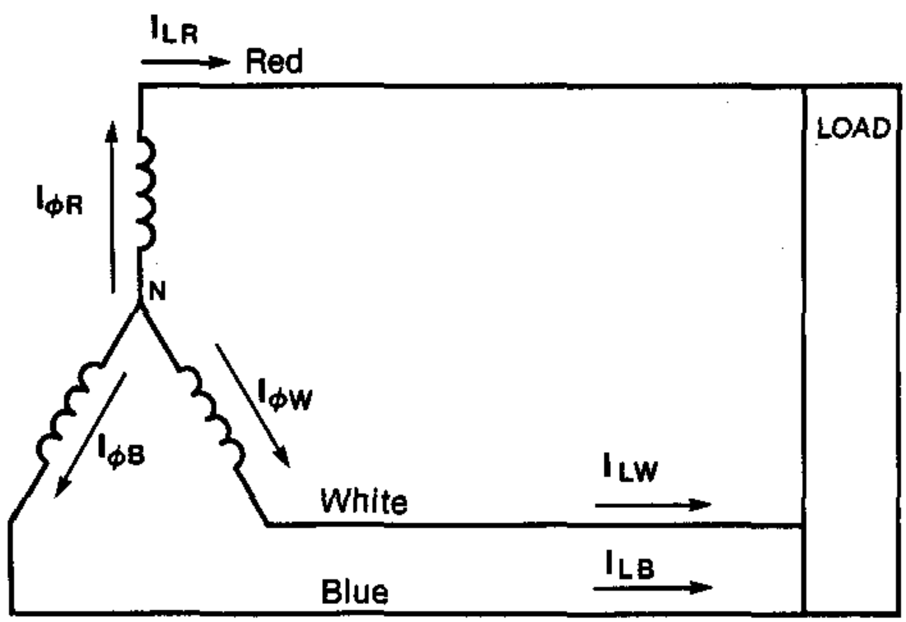
In Y configuration a relationship between the line voltage and the phase voltage exists as given in the expression below.

$$E_L = \sqrt{3}\ E_\phi$$

Proof of the above expression is beyond the scope of these notes.

3.7 Line and Phase Currents

Refer to Figure 12.



Line and Phase Current in Y Configuration.

Figure 12

$I_\phi R$ is the phase current flowing through the red phase. I_{LR} is the line current flowing through the red line going to the load.

Similar relationships can be established between the other phase and line currents.

It can be seen that the red phase current $I_{\phi R}$ comes out of the generator or transformer as the case may be and flows in to the Red line. Therefore in a Y configuration:

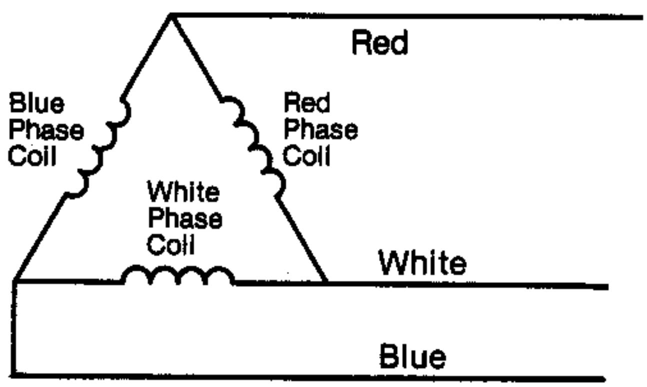
Phase Current = Line Current

or

$$I_{\phi} = I_L$$

4.0 DELTA (Δ) CONFIGURATION

A three phase system can be connected in Δ configuration as shown in Figure 13.



Δ Configuration

Figure 13

In Ontario Hydro, generators are never connected in Δ. Transformer primary is connected in Δ, eg, main transformer at the stations.

From Figure 13 it is apparent that the Δ configuration does not have a neutral hence it should not be used to supply unbalanced loads or single phase loads. This is why the secondary of such transformers is connected in Y with neutral grounded.

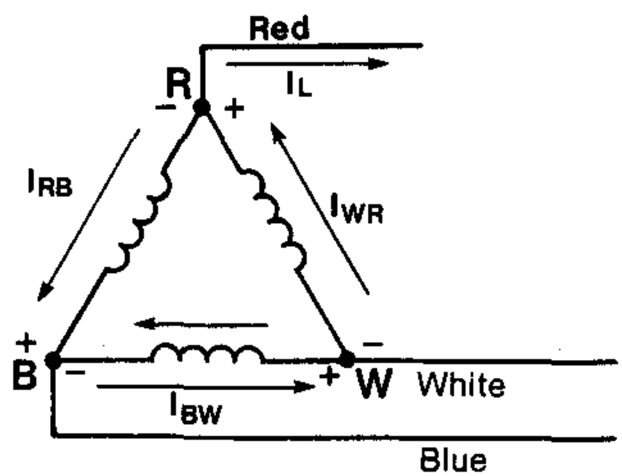
4.1 Phase and Line Voltages in Δ Configuration

If a voltmeter is connected across the Red phase coil it is essentially connected between the Red and White lines. It was seen (Section 3.6) that the voltage from one line to another line is called line voltage E_L. In Δ connection therefore:

$$E_\phi = E_L$$

4.2 Phase and Line Currents

In Figure 14 apply Kirchhoff's current law at point R.



Line and Phase Currents in Δ Configuration

Figure 14

$$\bar{I}_{WR} = \bar{I}_L + \bar{I}_{RB} \quad \text{(vectorial addition)}$$

or

$$\bar{I}_L = \bar{I}_{WR} - \bar{I}_{RB}$$

From this the following important relationship between the line and phase currents in a Δ configuration is derived. (The proof is of no concern at this point.)

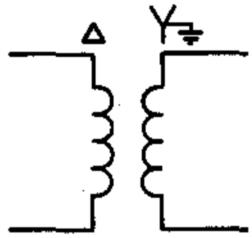
$$I_L = \sqrt{3}\, I_\phi$$

ie, in a Δ connection line current is $\sqrt{3}$ times the phase current.

5.0 METHOD OF REPRESENTATION

When a transformer is connected in a three phase system, its primary and secondary may be connected in Δ or Y. On a diagram the connection configuration used is shown as follows.

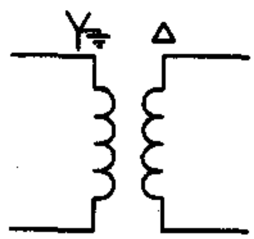
(a)



Primary Δ and Secondary Y Grounded

Figure 15(a)

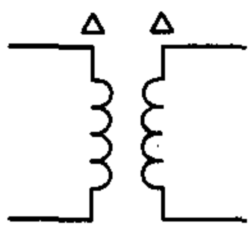
(b)



Primary Y Grounded, Secondary Δ

Figure 15(b)

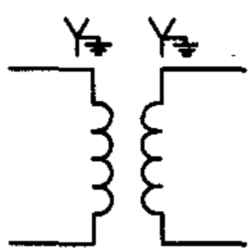
(c)



Primary Δ Secondary Δ

Figure 15(c)

(d)



Primary Y Grounded, Secondary Y Grounded

Figure 15(d)

6.0 WHY THREE PHASE SYSTEMS?

(a) The number of phases that can be generated is only limited by the number of individual sets of coils spaced appropriately in the generator. However, for example, a ten phase generator will require ten conductors for the transmission. Ontario Hydro maintains over 50 000 km of transmission lines. Ten conductors per transmission line can not be justified due to economic reasons. It is found that three phase generation, transmission and distribution is the most economical system.

(b) Three phase motors for a given horsepower are smaller in physical size compared to single phase.

(c) Smaller conductors are required to carry the same amount of power compared to single phase.

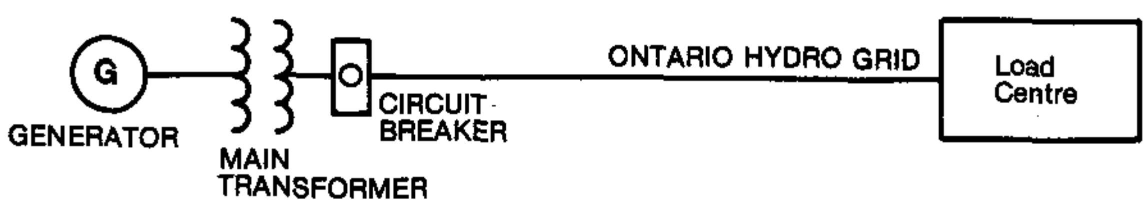
(d) Three phase motors are self-starting while single phase motors require an auxiliary start winding.

7.0 SYNCHRONIZING

Ontario Hydro customers require about 18 000 mega watts of power at the peak consumption. This power is provided by a number of generators (hydraulic, thermal and nuclear).

The number of generators operating at any time will depend on the customer demand. As a result, if the demand drops then one or more generators are removed from service. Similarly when the demand is increased one or more generators will be brought into service.

The act of bring a generator into service is referred to as synchronizing. Before a generator is synchronized to the Ontario Hydro grid the operator must check the following conditions. (See Figure 16.)



A Generator Feeding the Grid

Figure 16

(a) Generator must be generating enough voltage such that the secondary voltage of the main transformer is the same as the grid voltage. This is checked by voltmeters mounted in the control panel. Adjustments are made by the excitation control.

(b) Frequency of the generated voltage must match the grid frequency. This is done by an instrument called a synchroscope mounted in the control panel. Adjustments are made by controlling the turbine speed.

(c) Phase sequence of the generator being synchronized must be the same phase sequence as the grid. Phase sequence is checked by a phase rotation meter. Phase sequence is fixed at the commissioning stage and not changed unless the terminal connections are disturbed during maintenance.

(d) Phase angle between the grid and the main transformer must be zero. This is checked by a synchroscope.

Ask the Course Manager to give you a demonstration of the synchronizing procedure.

ASSIGNMENT

1. Briefly explain how three phase voltages are induced in a generator. (Section 2.0)

2. What is meant by the term "phase sequence"? What is the phase sequence used by Ontario Hydro? (Section 2.1)

3. What are the two possible connections of a three phase generator? (Section 3.0)

4. What is the connection configuration used for the generators in Ontario Hydro?

5. Why do the generators have their neutral point grounded via a high impedance? (Section 3.1)

6. What are the two possible arrangements of a Y connection? Give one application of each arrangement. (Sections 3.2, 3.3)

7. What is the line and phase voltage relationship in a Y configuration? (Section 3.4)

8. What is the line and phase current relationship in a Y connection? (Section 3.7)

9. What is the line and phase voltage relationship in a Δ configuration? (Section 4.1)

10. What is the line and phase current relationship in a Δ configuration?

11. Show how the following transformer arrangements will be identified on a schematic diagram. (Section 5.0)

    (a) Primary delta, secondary wye grounded.

    (b) Primary wye grounded, secondary delta.

12. List four arguments why the three phase system is the most feasible. (Section 6.0)

13. What points must be observed before a generator is synchronized to the grid? (Section 7.0)

S. Rizvi
F. McKenzie