NUCLEAR TRAINING CENTRE

COURSE PI 30.2

NUCLEAR TRAINING COURSE

COURSE PI 30.2

ELECTRICAL EQUIPMENT

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Electrical Equipment - Course PI 30.2

IMPEDANCE

OBJECTIVES

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

1. In a few words, define
   a) Capacitive and inductive reactance
   b) Impedance

2. State, in writing, that:
   a) For a capacitor fed from an ac source the current leads the voltage by 90°
   b) For an inductor fed from an ac source the current lags the voltage by 90°

3. Explain, in writing, how a circuit can be:
   a) Inductive
   b) Capacitive

4. Given the circuit component values and the type of connection, identify the circuit behaviour as inductive or capacitive.

5. Define in one sentence the term "Power Factor Angle".

1.0 INTRODUCTION

This module introduces the student to the concept of:

(a) impedance.

(b) inductive and capacitive behaviour of an ac circuit.

(c) power factor angle.

2.0 RESISTANCE, REACTANCE AND IMPEDANCE

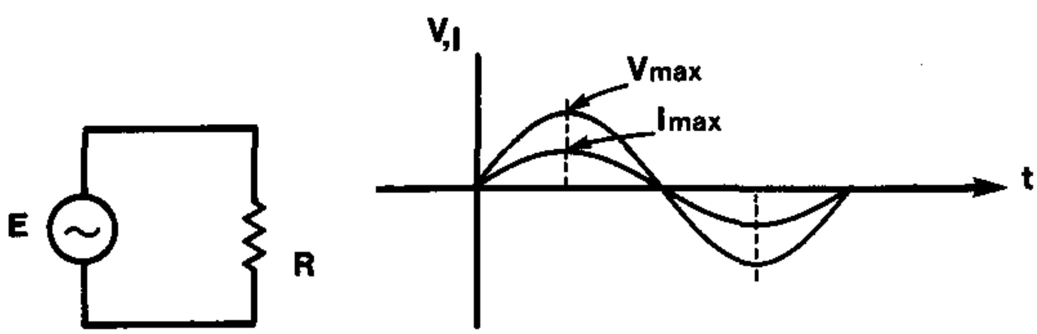
Resistance and the reactance contribute to the impedance. It is therefore necessary to have an understanding of the behaviour of these components when an ac voltage is applied to a circuit containing resistance and reactance.

2.1 Resistance

When a resistor is supplied with an ac voltage the current flowing through it will be a sine wave whose maximum value depends on the resistance R. Resistance is independent of frequency. Response of the resistance to the increase in voltage across it is the rise of current simultaneously. When the voltage decreases the current will also decrease at the same time. This phenomenon in technical terms is stated as follows:

> The Voltage drop across a resistor is in phase with the current flowing through it.

This is also shown diagramatically in Figure 1.



Voltage and Current Relationship in a Resistor

Figure 1

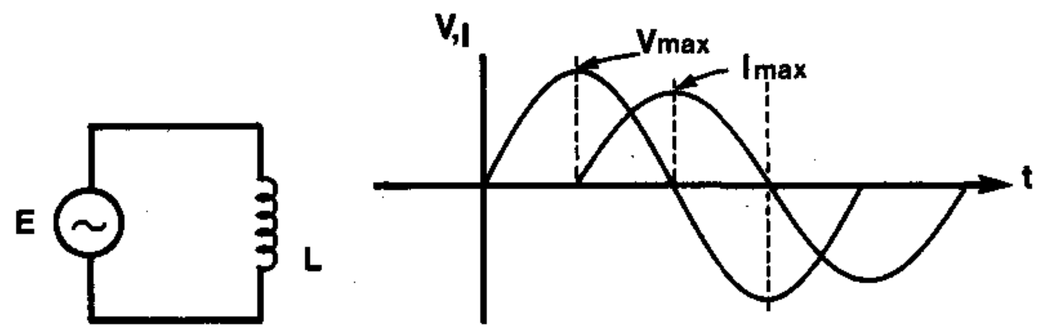
2.2 Reactance

Reactance in the circuit is contributed by the two reactive components, ie, inductance and capacitance. Inductive and capacitive reactances are calculated by the following expressions as discussed in PI 26.32-1 and 33-1.

$$X_L = 2\pi fL$$

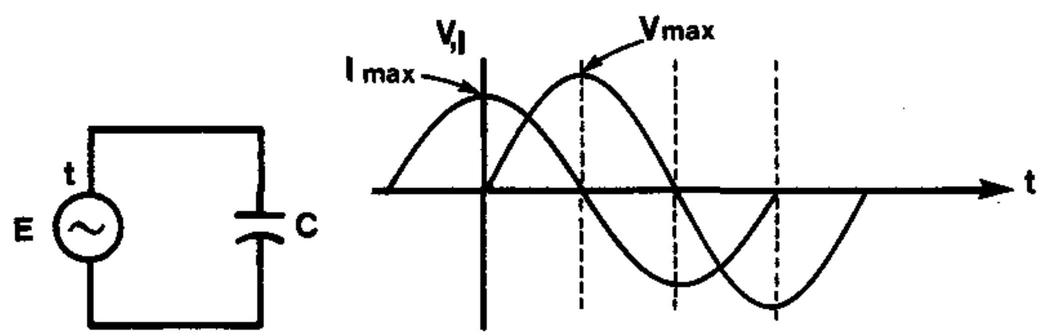
$$X_C = \frac{1}{2\pi fC}$$

The opposition offered by the inductor or a capacitor is called reactance because the inductor reacts to the change in current and the capacitor reacts to the change in voltage. Current and voltage relationships in a capacitance and an inductance are shown in Figures 2(a) and (b).



Inductor: Current Lags the Voltage by 90°.

Figure 2(a)



Capacitor: Current Leads the Voltage by 90°.

Figure 2(b)

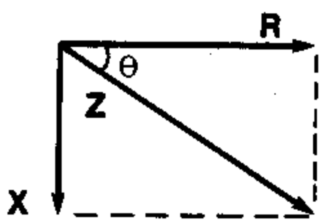
Examining the expressions for X_L and X_C, it is also apparent that the increase in frequency will increase X_L while X_C will decrease, and a decrease in frequency will cause X_L to decrease but X_C will increase. This indicates that the two reactances effectively function in opposition to each other. The opposing characteristics of X_L and X_C as well as the voltage and current relationships can be displayed by the use of vectors. (See Appendix.)

2.3 Impedance

A combined opposition effect to current flow of RL, RC or RLC is called impedance. Impedance is represented by Z and its unit is the ohm. It is calculated by using the following expression.

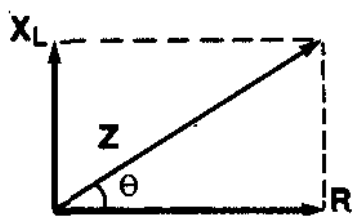
$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$\theta = \text{Arc tan} \left(\frac{X_L - X_C}{R} \right)$$



RC Circuit

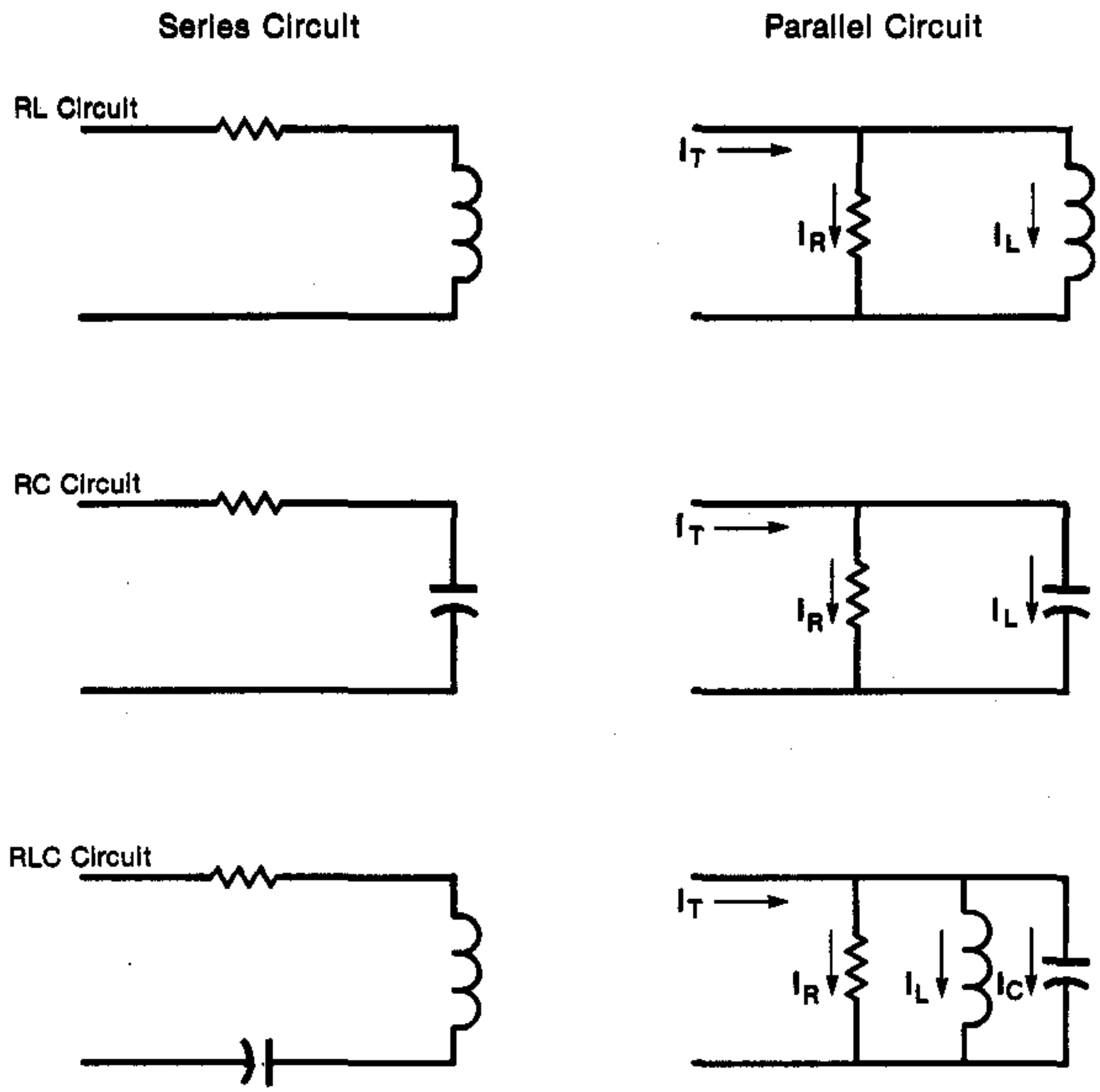
Figure 3(a)



RL Circuit

Figure 3(b)

A RL, RC or RLC circuit can be connected in series or in parallel, see Figure 4.



Series and Parallel Circuits

Figure 4

3.0 CIRCUIT BEHAVIOUR

Overall behaviour of a circuit can be inductive or capacitive depending on the following two factors.

(a) Relative magnitudes of X_L and X_C.

(b) Series or parallel connection.

3.1 Inductive Behaviour

An ac circuit under the following conditions will behave inductively, **ie, total current in the circuit will lag the applied voltage by an angle θ.**

(a) A series circuit composed of resistance and inductance.

(b) A series circuit composed of R, L and C but $X_L > X_C$.

(c) A parallel circuit composed of R, L.

(d) A parallel circuit composed of R, L and C but $X_L < X_C$.

The angle of lag between the source voltage and the total current will depend on the relative magnitudes of reactance and resistance as given below.

Do not memorize the following expressions.

$$\theta = \text{Arc tan } \frac{X_L}{R} \text{ for series RL circuit.}$$

$$\theta = \text{Arc tan } \frac{X_L - X_C}{R} \text{ for series R, L \& C circuit.}$$

$$\theta = \text{Arc tan } \frac{R}{X} \text{ for parallel RL circuit.}$$

$$\theta = \text{Arc tan } \frac{R(X_C - X_L)}{X_C \cdot X_L} \text{ for parallel R, L \& C circuit.}$$

This angle θ between the source voltage and the total current is given the name power factor angle. Its importance will be discussed in the lesson PI 26.36-2.

3.2 Capacitive Behaviour

An ac circuit under the following conditions will behave capactive, ie, **the total current will lead the applied voltage by an angle θ.**

(a) A series circuit composed of resistance and capacitance.

(b) A series circuit composed of R, L and C but $X_C > X_L$.

(c) A parallel circuit composed of R and C.

(d) A parallel circuit composed of R, L and C but $X_C < X_L$.

The angle of lead between the total current and the source voltage will depend on the relative magnitudes of reactance and resistance as given below.

Do not memorize the following expressions.

$\theta = \text{Arc tan} \dfrac{X_C}{R}$ for series RC circuit.

$\theta = \text{Arc tan} \dfrac{R}{X_C}$ for parallel RC circuit.

$\theta = \text{Arc tan} \dfrac{X_C - X_L}{R}$ for series R, L and C circuit.

$\theta = \text{Arc tan} \dfrac{R(X_C - X_L)}{X_C \cdot X_L}$ for parallel R, L and C circuit.

Again the angle θ is referred to as power factor angle and will be discussed in the lesson PI 26.36-2.

ASSIGNMENT

1. Define the term "impedance". Indicate how it is represented in the formula and what is its unit. (Section 2.3)

2. What is meant by the inductive behaviour or the capacitive behaviour of a circuit in terms of voltage and current relationships. (Section 3.1, 3.2)

3. Identify an inductive or capacitive circuit in the following cases. (Section 3.1, 3.2) See answers, Page 12.

   (a) A series circuit $R = 10\ \Omega$, $X_L = 20\ \Omega$, $X_C = 10\ \Omega$.

   (b) A parallel circuit $R = 10\ \Omega$, $X_L = 20\ \Omega$, $X_C = 10\ \Omega$.

   (c) A series circuit $R = 5\ \Omega$, $X_L = 1\ \Omega$.

(d) A series circuit $R = 20\ \Omega$, $X_C = 20\ \Omega$.

(e) A parallel circuit $R = 7\ \Omega$, $X_L = 12\ \Omega$, $X_C = 24\ \Omega$.

(f) A parallel circuit $R = 100\ \Omega$, $X_C = 50\ \Omega$.

(g) A parallel circuit $R = 75\ \Omega$, $X_L = 100\ \Omega$.

4. What is power factor angle?

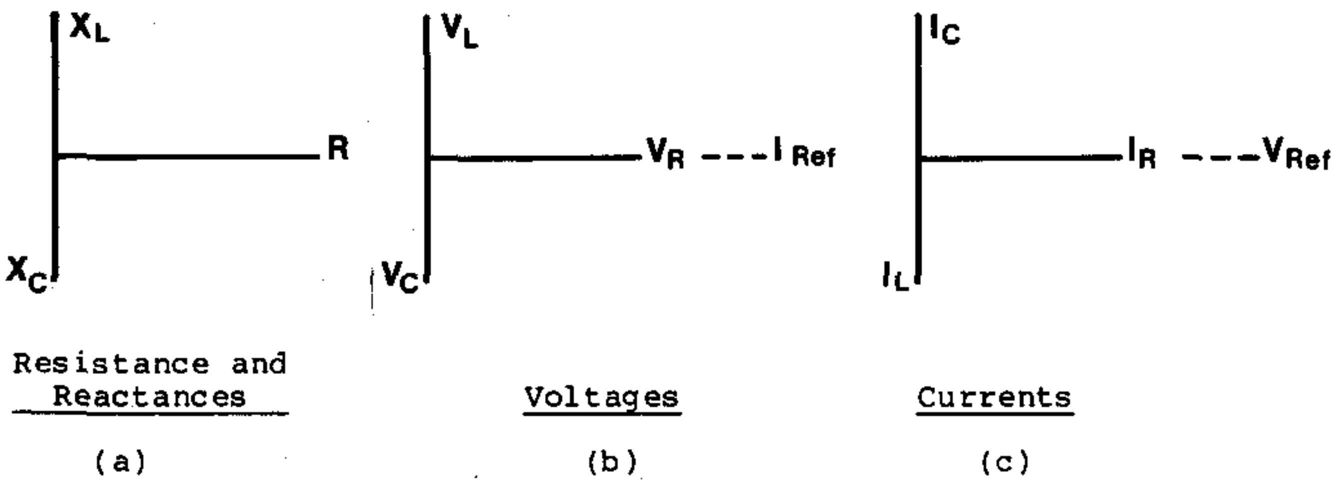
NOTE: Additional assignments are available on computer. If you wish further practice, ask the Course Manager for the mini disk package "Single-Phase Circuit Simulation" (3 disks).

S. Rizvi

APPENDIX

VECTORIAL NOTATION

The reactive phenomenon of L and C, their opposing characteristics and the voltage and current relationships can be represented conveniently by the use of vector diagrams shown in Figure 1. In all cases resistance or the voltage across it or the current through it is taken as the reference. Counter-clock rotation of vector is considered as positive direction.



Vectorial Representation

Figure 1

Examine Figure 1(a). Horizontal axis is assigned to the resistance and used as the reference.

Positive vertical axis is assigned to X_L } opposing characteristics
Negative vertical axis is assigned to X_C }

Examine Figure 1(b) used in series circuits. Current being same in the series circuit it is used as reference. Horizontal axis is assigned to the voltage across the resistance.

Positive vertical axis is assigned to the voltage across the inductance because the voltage across the inductance leads by 90° as compared to the current.

Negative vertical axis is assigned to the V_C because the voltage across a capacitor lags by 90° as compared to the current. This representation is useful in series circuits since the current in a series circuit is the same through each component.

Examine Figure 1(c) used in parallel circuits. Voltage being the same in parallel circuit, it is used as reference.

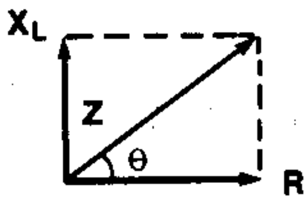
Horizontal axis is assigned to the current through the resistance.

Positive vertical axis is assigned to the current through the capacitance. This indicates that the current in a capacitor leads the voltage across it by 90°.

Negative vertical axis is assigned to the current through the inductor. This indicates the fact that the current in an inductor lags the voltage across it by 90°.

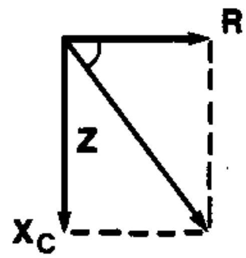
Impedance

Impedance can be determined vectorically by adding the resistance and the reactance vectors as shown in Figure 2.



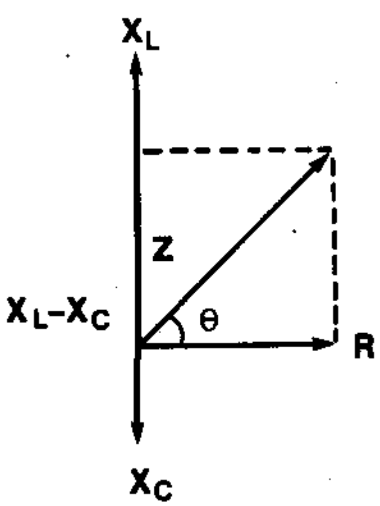
R, L Circuit

(a)



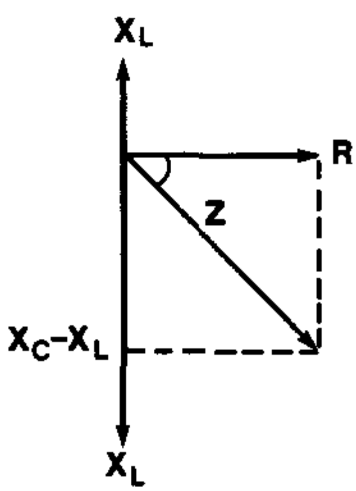
R, C Circuit

(b)



R, L, C Circuit $X_L > X_C$

(c)



R, L, C Circuit $X_C > X_L$

(d)

Answers For Assignment Question 3

(a) $X_L > X_C$ in a series circuit: circuit is inductive.

(b) $X_C < X_L$ in a parallel circuit: circuit is capacitive.

(c) Series R, L circuit: circuit is inductive.

(d) Series R, C circuit: circuit is capacitive.

(e) $X_L < X_C$ in a parallel circuit: circuit is inductive.

(f) R, C parallel circuit: circuit is capacitive.

(g) R, L parallel circuit: circuit is inductive.

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:

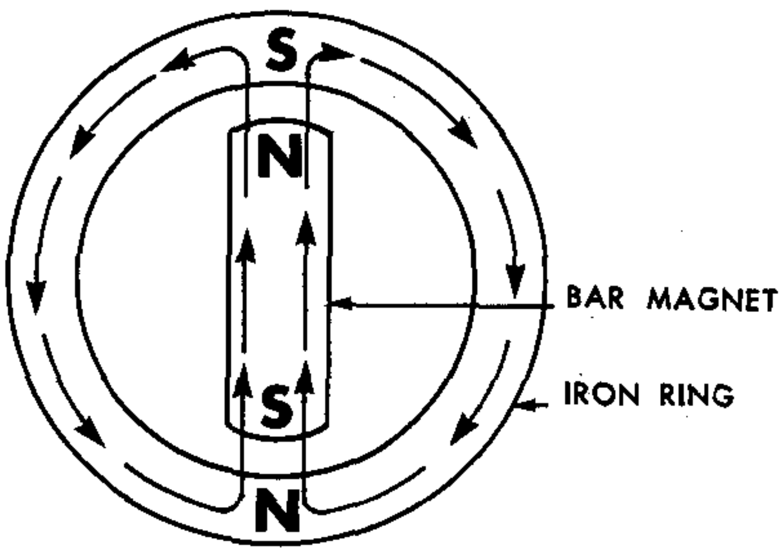
(a) concept of three phase generation and its advantages.

(b) three phase connections.

(c) synchronizing of a generator to the grid.

2.0 THREE PHASE GENERATION

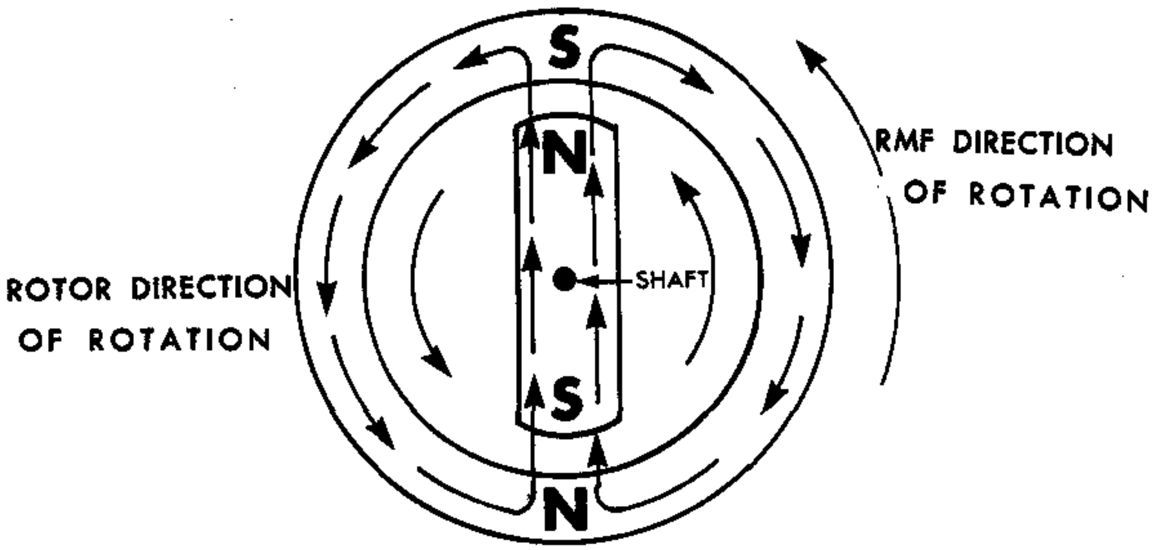
Consider a bar magnet placed in an iron ring as shown in Figure 1. The magnetic lines of force start from the north pole of the bar magnet and pass through the iron ring, since iron is a low reluctance path as compared to the air, and return to the south pole of the bar magnet thus completing the magnetic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

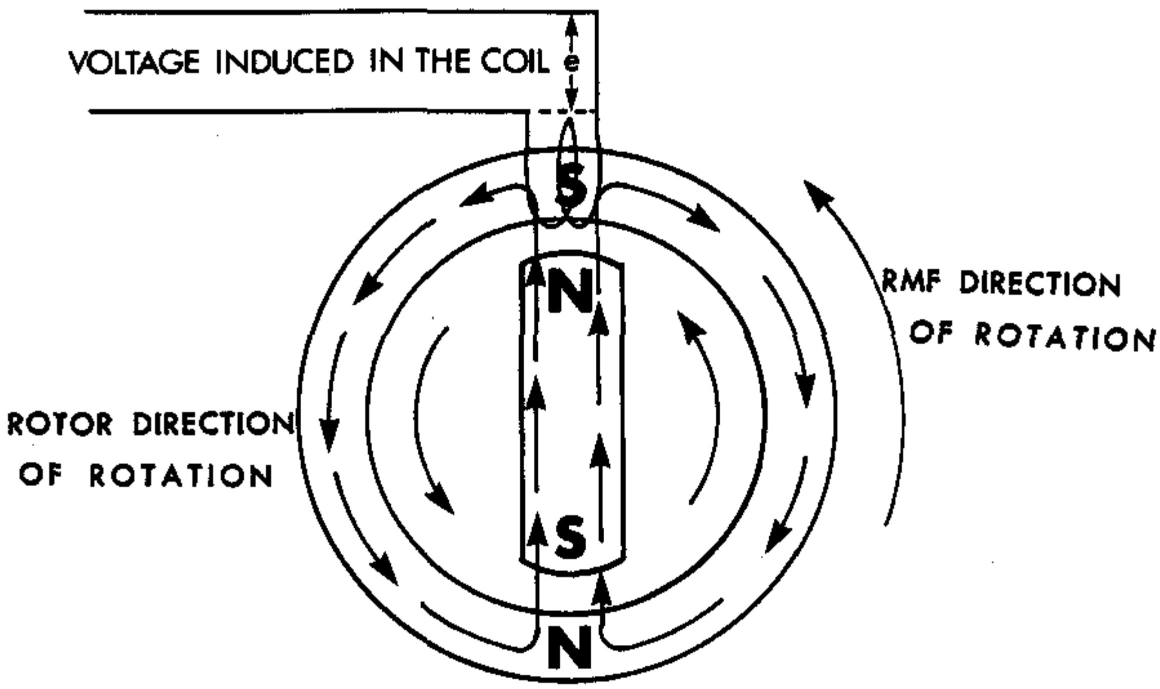
Figure 2

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.

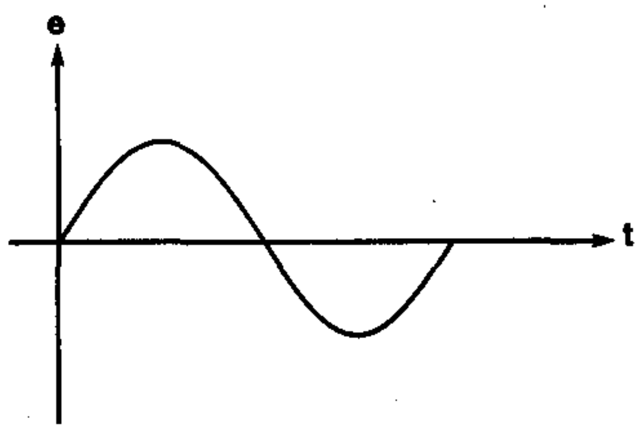
All the requirements for electromagnetic induction are met and a voltage will be induced in the coil.



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

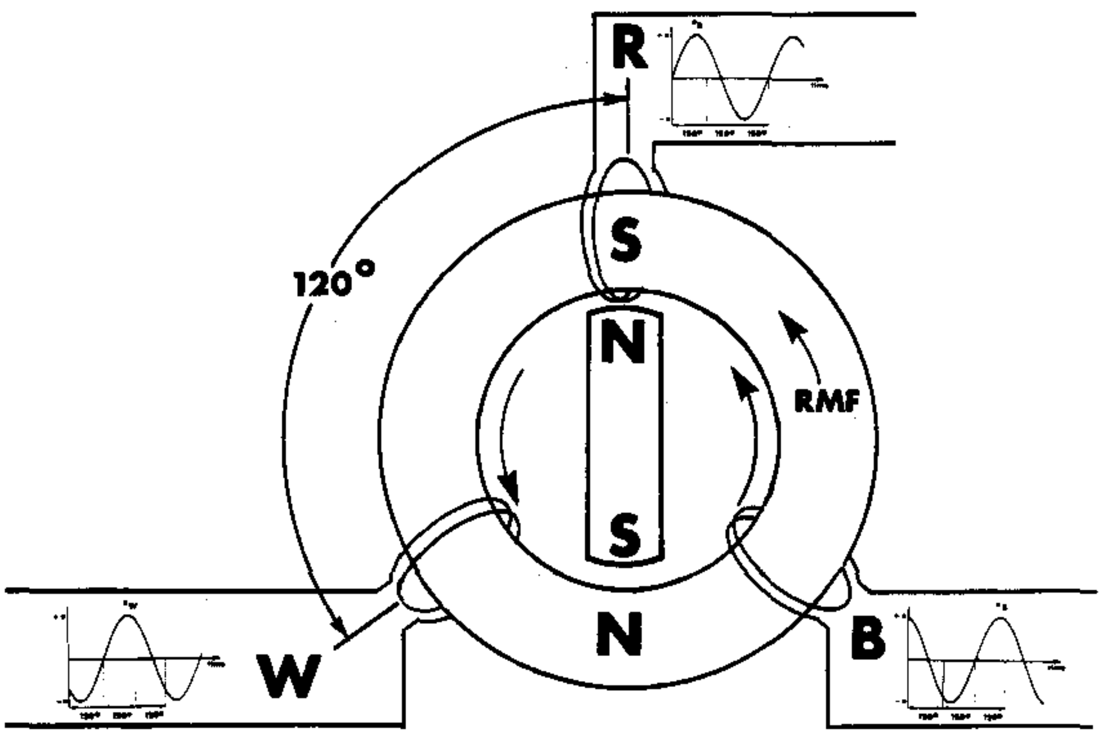
Figure 4

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.

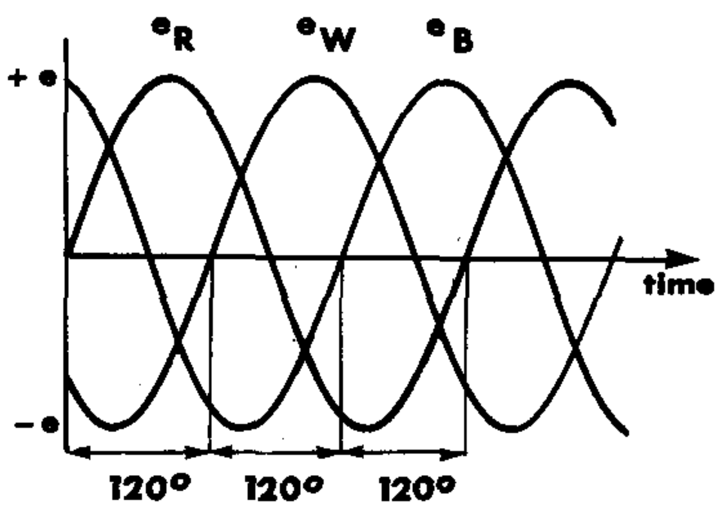
Coils are placed in slots in the stationary part (stator) of the generator as conductors. An iron core takes the place of the iron ring and provides a magnetic path.

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

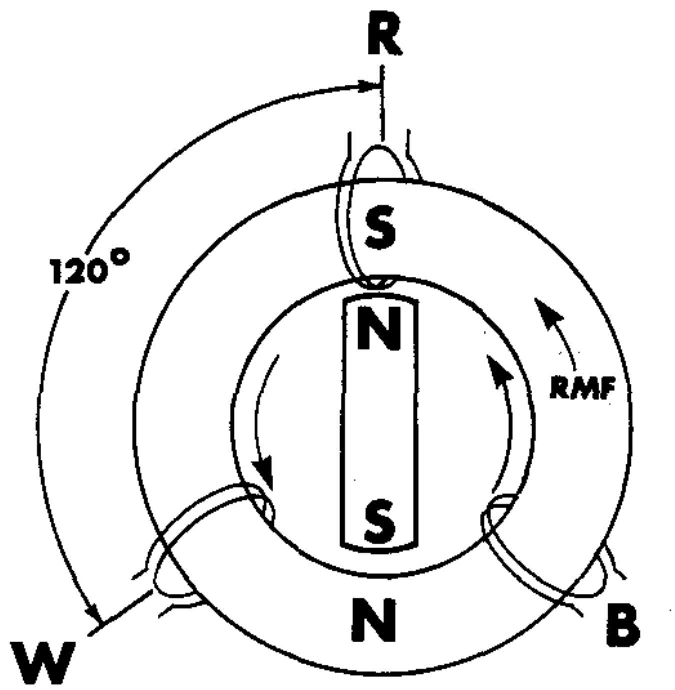
Figure 6

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.



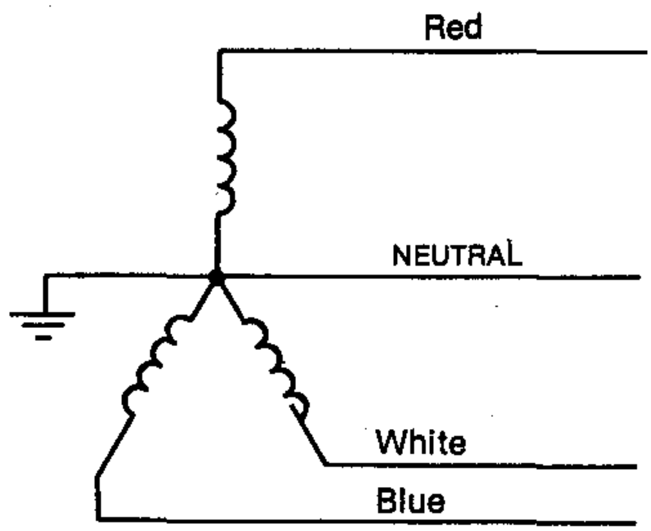
Three Coils Not Interconnected in Any Configuration

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

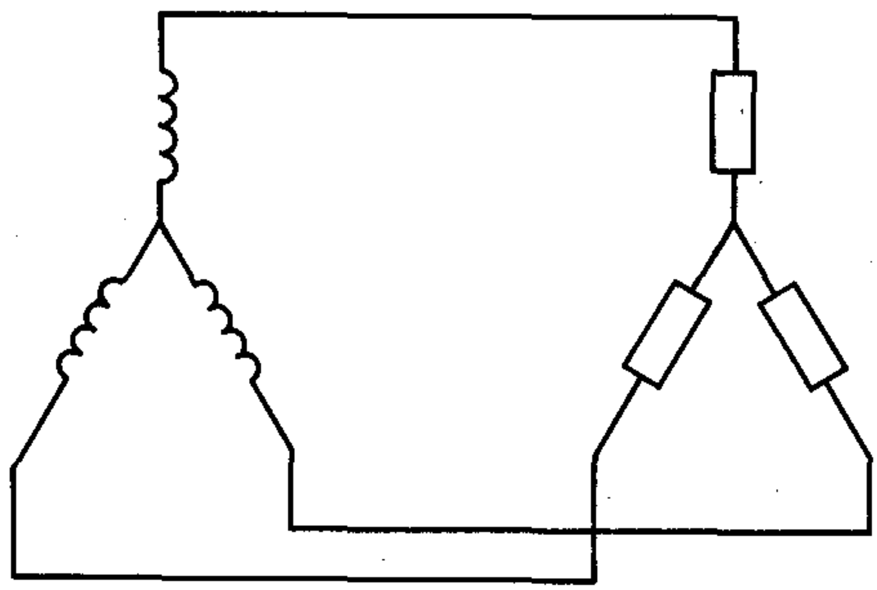
Figure 8

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.

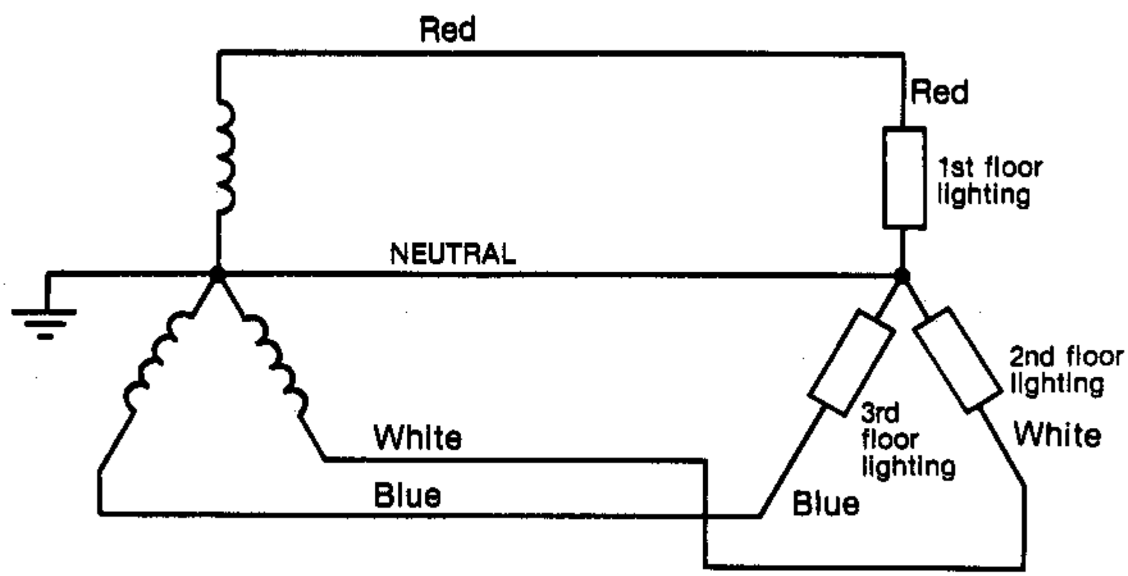
Three Phase, 3-Wire Star, Balanced Load.

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.

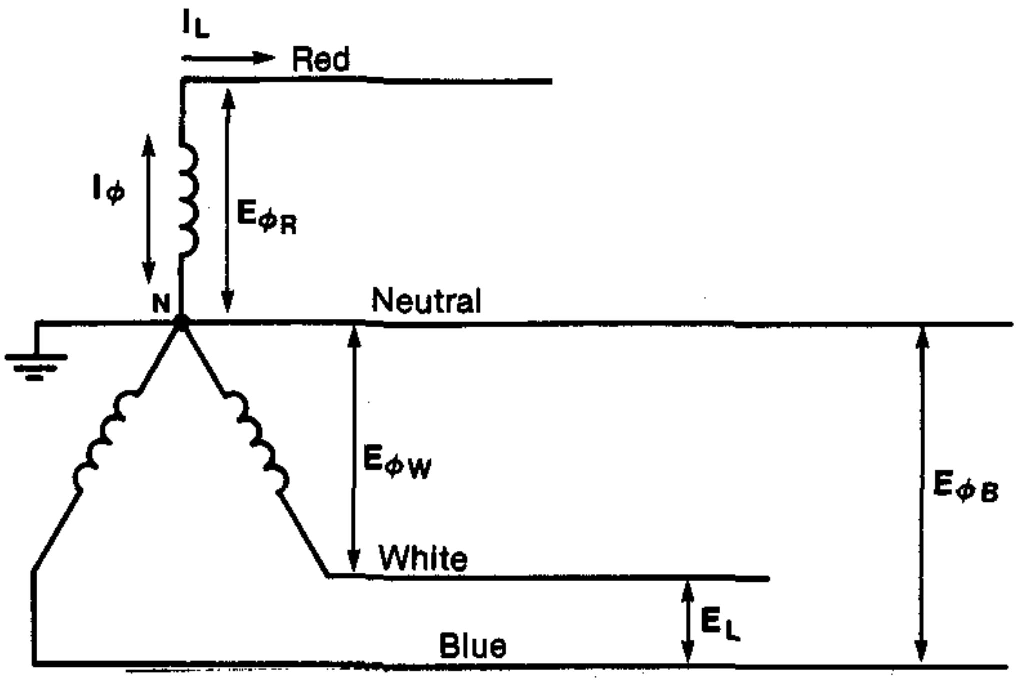
Unbalanced Three Phase Y Connected Load.

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.

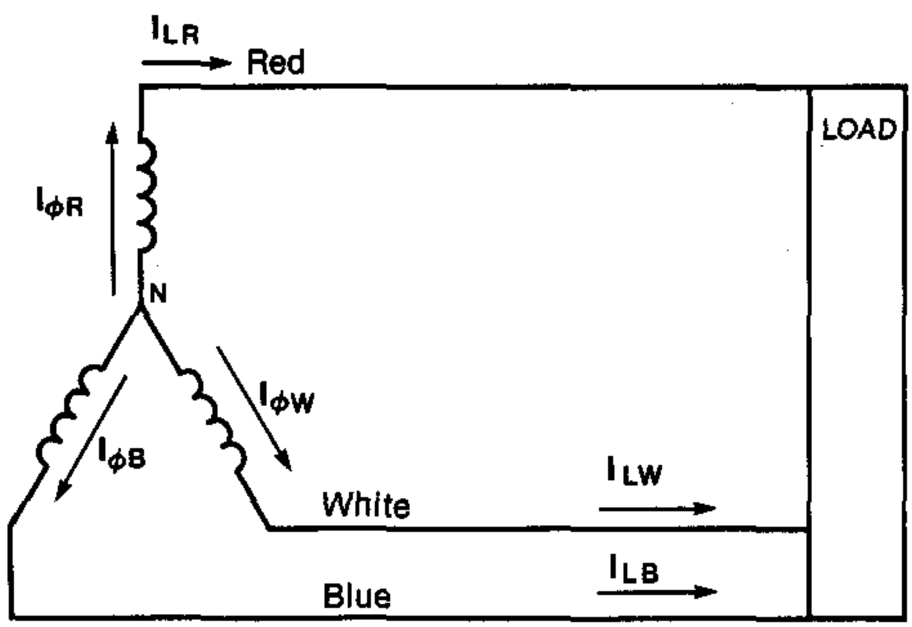
In Y configuration a relationship between the line voltage and the phase voltage exists as given in the expression below.

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

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:

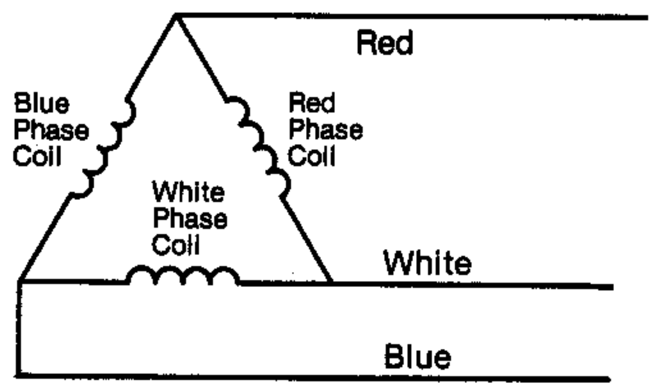
Phase Current = Line Current

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.

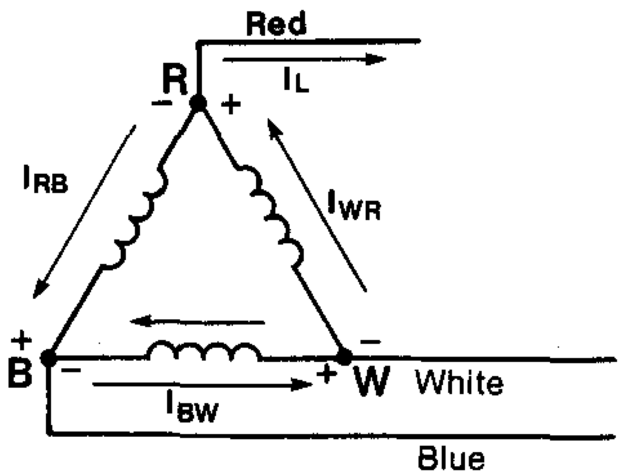
4.1 Phase and Line Voltages in Δ Configuration

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.)

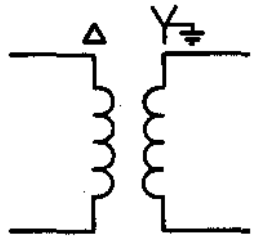
$$I_L = \sqrt{3}\, I_\phi$$

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.

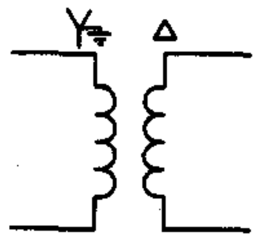
(a)



Primary Δ and Secondary Y Grounded

Figure 15(a)

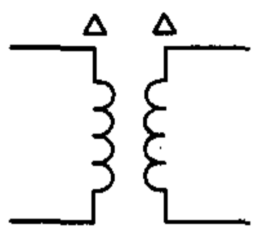
(b)



Primary Y Grounded, Secondary Δ

Figure 15(b)

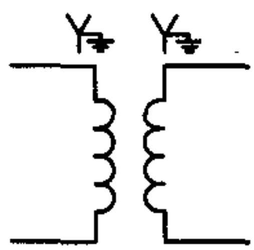
(c)



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.

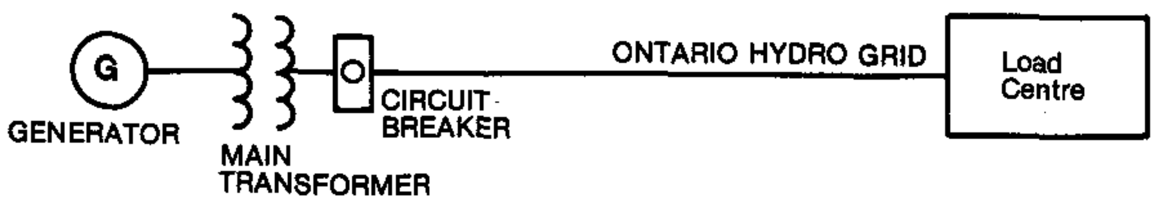
(d) Three phase motors are self-starting while single phase motors require an auxiliary start winding.

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

Electrical Equipment - Course PI 30.2

POWER AND POWER FACTOR

OBJECTIVES

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

1. In a few sentences explain the following terms:
   a) active power;
   b) reactive power;
   c) apparent power.

2. Draw a power triangle to represent a specific single phase load.

3. Briefly in writing define "power factor", and show the relationship between the apparent power and active power at:
   pf=1
   pf=0.

4. Given the information as related to the active, reactive, apparent power and power factor, calculate the indicated quantity.

5. State in writing two common methods of improving the power factor.

1.0 INTRODUCTION

This lesson introduces the student to the concept of:

(a) active, reactive and apparent power.

(b) power factor.

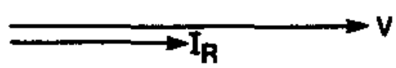
(c) methods of power factor correction.

2.0 POWER

Power is the rate at which energy is consumed in a circuit, resulting in useful work being done by lights, heaters, motors, etc.

2.1 Power in a Resistor

When an alternating current flows through a resistor, energy is dissipated as heat. The rate of energy consumption is termed the active power, P, and is calculated as $P = V \times I_R$ where V is the rms voltage across the resistor and I_R is the rms current through it.



V-I In a Resistor

Figure 1

V and I_R are in-phase with each other, see Figure 1 and the resultant active power, P, has units of watts (or kW or MW).

2.2 Power in an Inductor or Capacitor

Inductors store energy in their magnetic field and capacitors store energy in their electric field. Thus when these elements are fed from an ac source they do not consume energy but simply store it and return it to the system during successive half-cycles. The current flowing from the supply to perform this function is termed reactive current and so we say that inductors and capacitors take reactive power, Q, calculated as:

$$Q = V \times I_L$$

$$\text{or,} \quad Q = V \times I_C$$

where I_L and I_C are the currents in the inductor and capacitor respectively.

(a) Inductor (b) Capacitor

V-I Relationships

Figure 2

Since Q is due to reactive current and is a product of Volts x Amps, the units used are Reactive Volt Amperes. (VAR or kVAR or MVAR).

N.B.: No Active Power is consumed in a pure inductor or capacitor.

3.0 ACTIVE POWER, APPARENT POWER, REACTIVE POWER

3.1 Mechanical Analogy

Consider a horse pulling the loaded mine cart on the tracks in Figure 3. In pulling the cart from point A to point B on the tracks, as shown, the horse must provide power to overcome:

(a) the gravitational force on the loaded cart.

(b) the friction between the cart wheels and the tracks, and bearing friction.

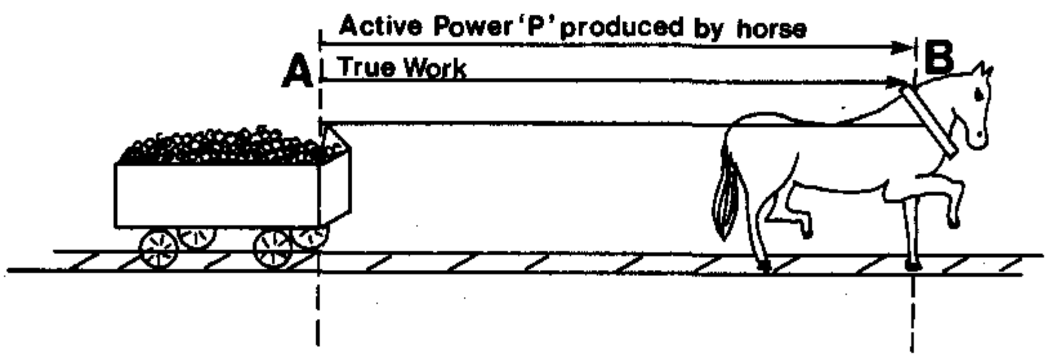
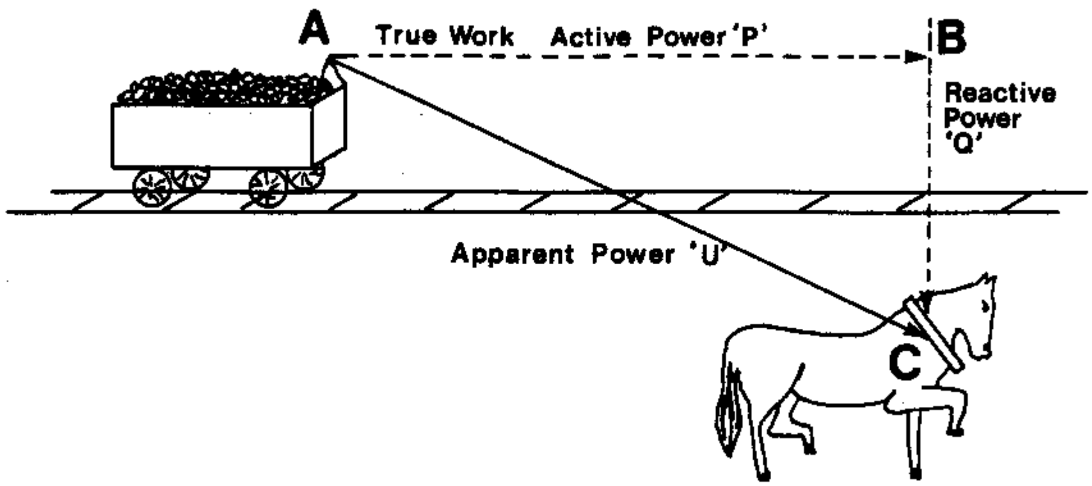


Figure 3

Mechanical Analogy of Active Power P

All the power supplied by the horse results in true work, ie, moving the cart from point A to point B.

Now consider a new untrained horse is brought in which, instead of pulling the cart along the tracks, pulls it at an angle θ as shown in Figure 4. It is the same cart on the same tracks, loaded to the same level, pulled at the same speed and to the same distance.



Horse Pulling the Cart at an Angle

Figure 4

The horse has done a true work equal to the length of the line AB. But it appears that he has done the work equal to the line AC. Line AC is referred to as "apparent work". Apparent work in this case appears to be more than true work.

Where does this difference between the true work and apparent comes from? What is it that the horse is doing differently? To answer this, examine Figure 4 again.

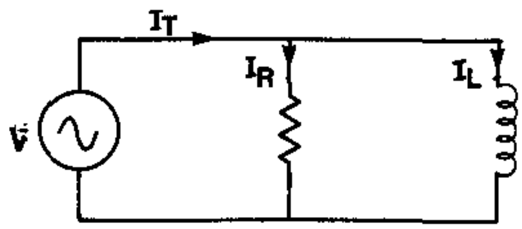
Horse is pulling the cart at an angle θ. The length of the line BC is directly proportional to the angle θ. The amount of work which seem to have been done by the line BC does no good to increase or decrease the true work of moving the cart from A to B. This work is called reactive work because it is in reaction to the angle θ. Reactive work combined vectorially with the true work gives the apparent work.

3.2 Power Triangle

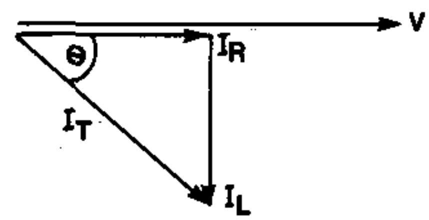
In a circuit containing both R and L or R and C the total current, I_T, will be at some angle θ relative to the voltage, but this can obviously be split into two components, one of which is in-phase with the voltage and one displaced from the voltage by 90°. Comparing this with the case of the horse pulling the mine car, we can see that the component of current which is in-phase with the voltage will produce active power, whilst the reactivecomponent of current, at 90° to the voltage, produces reactive power.

If we take a circuit consisting of R and L in parallel, Figure 5 (a), the vector diagram of currents will be as shown in Figure 5 (b). I_R is in phase with the voltage and I_L lags the voltage by 90°.

$$\bar{I}_T = \bar{I}_R + \bar{I}_L \qquad \text{(Vector Addition)}$$



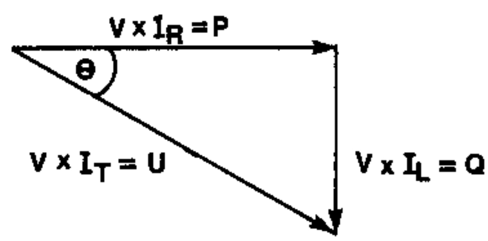
(a) Parallel RL Circuit.



(b) Vectorial Representation.

Figure 5

If we multiply each component of the current triangle by V (a constant), a new triangle is formed, Figure 6.



Power Triangle

Figure 6

This is called the power triangle and the hypotenuse, $U = V \times I_T$, is called the apparent power of the circuit. The units are voltamperes (VA or kVA or MVA).

4.0 POWER FACTOR

4.1 Power Factor (pf) is Defined as Follows:

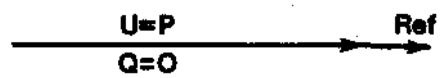
$$pf = \frac{\text{Active Power}}{\text{Apparent Power}}$$

and has a minimum value of zero and a maximum of 1.

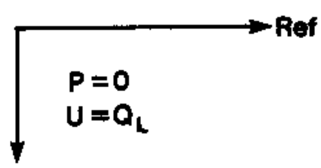
From Figure 6, $pf = \frac{P}{U} = \cos\theta$

Hence the power factor is also equal to the cosine of the phase angle between voltage and current in the circuit. This angle is called the power factor angle. (See Lesson PI 26.34-1; 3.1 and 3.2.)

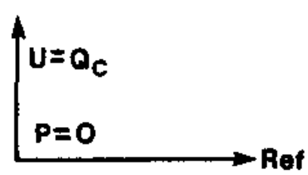
It should now be clear that for a resistor, pf = 1, (θ=0) whereas for an inductor or capacitor, pf = 0 (θ = 90°), see Figure 7.



(a) Resistor-Unity pf. θ = 0°.



(b) Inductor-Zero pf. θ = 90°.



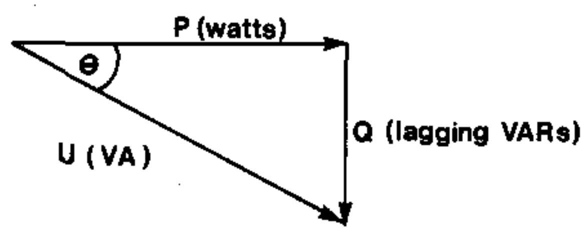
(c) Capacitor-Zero pf. θ = 90°.

Figure 7

4.2 Leading and Lagging Power Factors

Ideally, supply utilities would prefer to supply power to consumers at unity power factor since this would result in active power and apparent power being the same, and the current would be minimum.

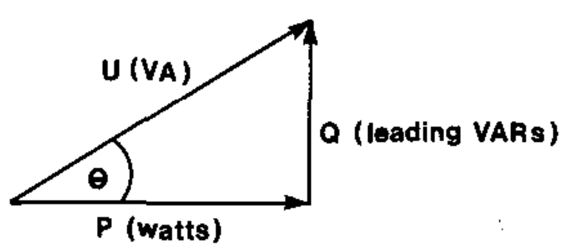
The corresponding I^2R losses in the transmission lines would thus be minimized. However, most industrial loads take inductive reactive VAR's to provide magnetic fields in motors, and since inductive circuits take a lagging current from the supply, the reactive power is designated as lagging VAR's. The power factor under these circumstances is thus said to be a lagging power factor. (See Figure 8.)



Lagging pf Load

Figure 8

The converse is true for a capacitive load where the capacitive reactive VAR's set up electric fields. These are called leading VAR's since capacitors take a leading current from the supply. See Figure 9.

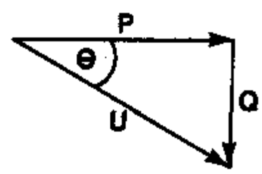


Leading pf Load

Figure 9

4.3 Calculations

Applying the trigonometry to the power triangle, the following relationships can be established.



Power Triangle

Figure 10

$$U^2 = P^2 + Q^2$$

$$U = \sqrt{P^2 + Q^2}$$

$$P = U \cos \theta$$

$$Q = U \sin \theta$$

Example

A transformer is supplying a 10 MW load at 0.85 power factor lagging.

(a) What is the apparent power (VA) supplied by the transformer?

$$P = U \cos \theta$$

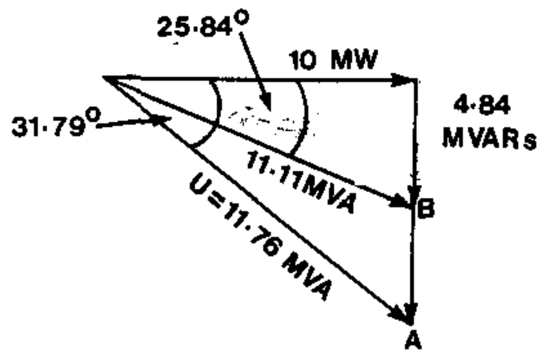
$$\text{Cos } \theta = 0.85$$

$$U = \frac{P}{\cos \theta} = \frac{10 \text{ MW}}{0.85} = 11.76 \text{ MVA}$$

(b) What is the minimum MVA rating of the transformer?

Since the transformer must deliver 11.76 MVA this must be the minimum VA rating of the transformer for it to do the job without overheating. The manufacturer, however, does not make an off-the-shelf transformer of 11.76 MVA. Hence the next higher standard available MVA rating must be used (ie, 15 MVA).

(c)



Power Triangles For Example Part (c)

Figure 11

Existing load conditions are shown at point A in Figure 11.

Original power factor angle = Arc Cos (0.85) = 31.8°.

Original MVAR required = 11.76 sin 31.8° = 6.2 MVAR.

If the existing load power factor is now improved to 0.9.

∴ New power factor angle = Arc cos 0.9 = 25.8°.

New MVAR supplied = 10 tan 25.8° = 4.84 MVAR. New load conditions are shown at point B of Figure 11.

New MVA required = $\frac{10 \text{ MW}}{0.9}$ = 11.11 MVA

(d) Comparison of new and original MVA required indicates that we can now place additional load on the transformer, and still stay within the original rating of 11.76 MVA.

Load conditions with the additional load on the transformer are shown at point C in Figure 12, assuming the additional load P, is at unity power factor.

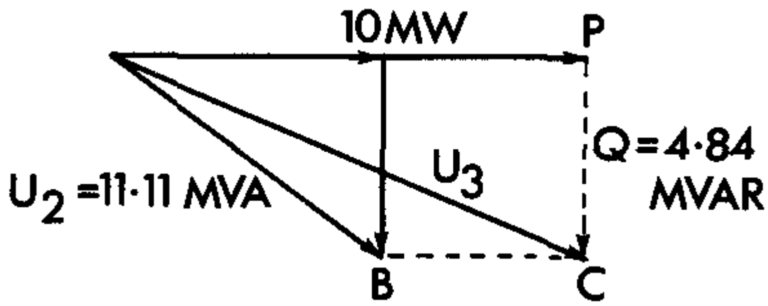


Figure 12

The total active power is now (10 + P)MW and the total reactive power remains constant at 4.84 MVAr.

The apparent power, u_3 = 11.76 MVA, the original rating of the transformer.

$$U_3^2 = (10 + P)^2 + Q^2$$

$$\therefore \quad (10 + P) = \sqrt{U_3^2 - Q^2}$$

$$= \sqrt{(11.76)^2 - (4.84)^2} = 10.718 \text{ MW}$$

$\therefore$ Additional load, P = 0.718 MW = 718 kW

4.4 Power in Three-Phase Systems

In a balanced 3-phase load, the power in each phase will be identical, so the total power dissipated will be three times the power dissipated per phase.

Consider a star-connected system, with phase voltage V_ϕ, phase current I_ϕ, operating at a power factor given by cos θ.

The apparent power per phase = $V_\phi I_\phi$

For the three phases, total apparent power, U, is thus $3\ V_\phi I_\phi$.

It should be remembered that, in a 3-phase, star-connected system, $I_L = I_\phi$ and $V_L = \sqrt{3}\ V_\phi$ hence

$$U = 3\ \frac{V_L}{\sqrt{3}}\ I_L = \sqrt{3}\ V_L I_L$$

Similarly $P = \sqrt{3}\ V_L . I_L \cos\theta = u \cos\theta$

and $Q = \sqrt{3}\ V_L\ I_L \sin\theta = u \sin\theta$

Identical relationships exist if the load is delta connected.

4.5 Power Factor Correction

On Ontario Hydro power system, the consumer load is inductive in nature due to the many motors and other equipment used by the customer. As a result a large value of reactive power must be supplied by the generator or other equipment. It can be done by one or both of those given below.

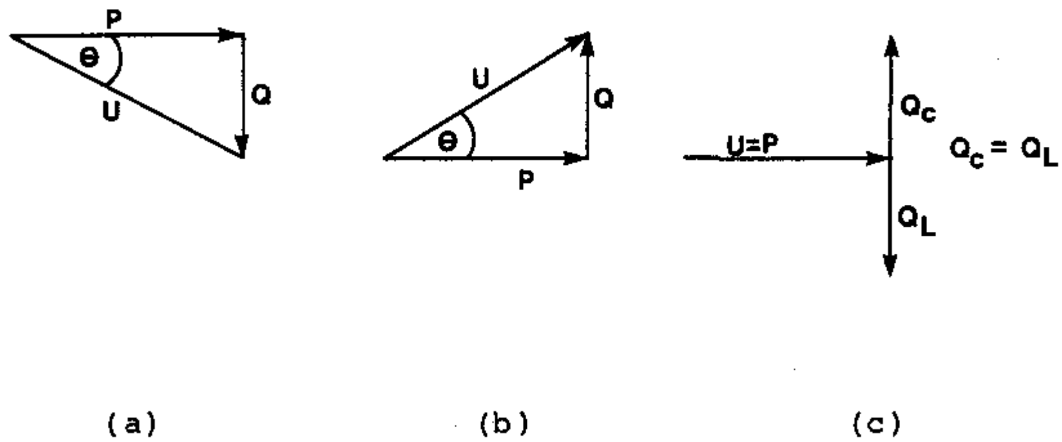
(a) use static capacitors.

(b) use synchronous motors.

In motors and transformers, the use of static capacitors is common.

The principle used in power factor correction is that the inductive load consumes lagging VAR's as shown in Figure 13(a).

Capacitor provides leading VAR's as shown in Figure 13(b). If a capacitor is combined with the inductive load then the lagging VAR's of inductor and the leading VAR's of capacitor will cancel each other as shown in Figure 13(c) and the apparent power will become equal to active power.



Inductive and Capacitive VAR

Figure 13

ASSIGNMENT

1. What is:

   (a) Active Power? (Section 2.1)

   (b) Reactive Power? (Section 2.2)

   (c) Apparent Power? (Section 3.2)

   (d) Draw a power triangle to show P, Q, U and properly label each side. (Section 3.2)

2. Define Power Factor. At pf = 1 and pf = 0 indicate the relationship between apparent power and active power. (Section 4.1)

3. Heat transport pump motor at Bruce NGS-A is 11 000 HP and operates at 0.85 pf and 90% efficiency. What is the minimum VA rating of the transformer feeding the motor? Answer: 10.73 MVA (1 HP = 746 W)

4. In Question 3, what will be the transformer size required to feed this motor if a capacitor is connected in the circuit to improve the power factor to 0.9 lag? Answer: 10.13 MVA.

5. List two common methods used in the Ontario Hydro system for power factor correction. (Section 4.5)

S. Rizvi
F. McKenzie

Electrical Equipment - Course PI 30.2

THE CANDU GENERATING STATION

OBJECTIVES

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

1. Define, in a few sentences, the four classes of power used in a CANDU generation station and list at least two typical loads served from each class of power.
2. Describe, in a few sentences, the normal and the emergency supply for each class of power.

1. Introduction:

This lesson takes a simplified look at a CANDU nuclear generating station and introduces the student to the following.

(a) Main components and their purpose in a CANDU system.

(b) Classes of power in a CANDU nuclear generation station.

2. Main Components and their Purpose:

The pull-out diagram, at the end of this module shows a simplified CANDU generation station.

2.1.1 Reactor: Provides heat from nuclear reaction.

2.1.2 Fuelling Machine: Removes expended fuel bundles from the reactor and replaces them with fresh fuel bundles.

2.1.3 Heat Transport Pump: Circulates heavy water (D_2O) between the reactor and the steam generator. The circulation of D_2O transfers the heat produced in the reactor to the steam generator.

2.1.4 Steam Generator: Takes the heat from the coolant D_2O and converts the light water into steam. This steam is then supplied to the turbine.

2.1.5 Turbine: Converts the energy in the steam into mechanical energy.

2.1.6 Generator: Converts the mechanical energy provided by the turbine into electrical energy.

2.1.7 Main Transformer: Applies the generator output to the Ontario Hydro grid. It steps up the voltage from 24kV at Pickering, for example (18.5kV at Bruce) to 230kV and reduces the current.

2.1.8 Ontario Hydro Grid: The grid can be considered as a pool of electricity. All The generators in the system feed their power into the grid. It is a massive system of transmission lines which operate at 230kV and carry electrical power all over Ontario. Customers, via an appropriate transformation line, can draw power from the grid.

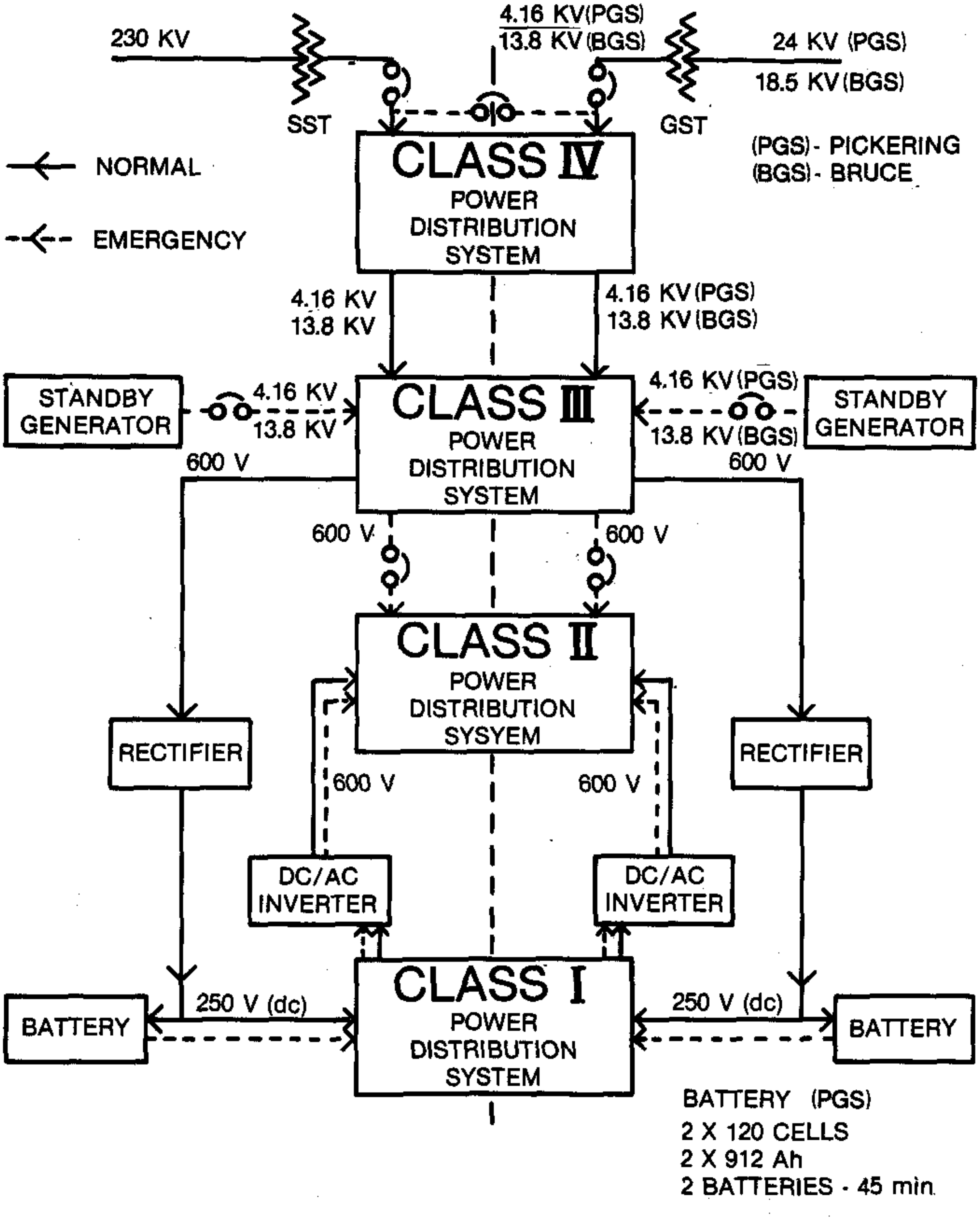
2.1.9 Unit Services Transformer (UST):

A unit is one complete system containing a reactor, turbine, generator and auxiliaries. Power required to operate this system is drawn, from the generator of that unit, by a unit services transformer, called UST. The UST is a step down type of transformer, whose ratings vary from station to station.

2.1.10 System Services Transformer (SST):

If the generator is not operating, some systems must still keep running. The power to run these systems comes from the grid, by means of a system services transformer, SST. This is a step-down type of transformer, whose ratings vary from station to station.

3. Classes of Power and Typical Loads:



3. Classes of Power and Typical Loads:

Personnel and plant safety are of the utmost importance in a CANDU design. To ensure a safe and proper operation of the system, station power supplies are divided into four classes, as discussed below.

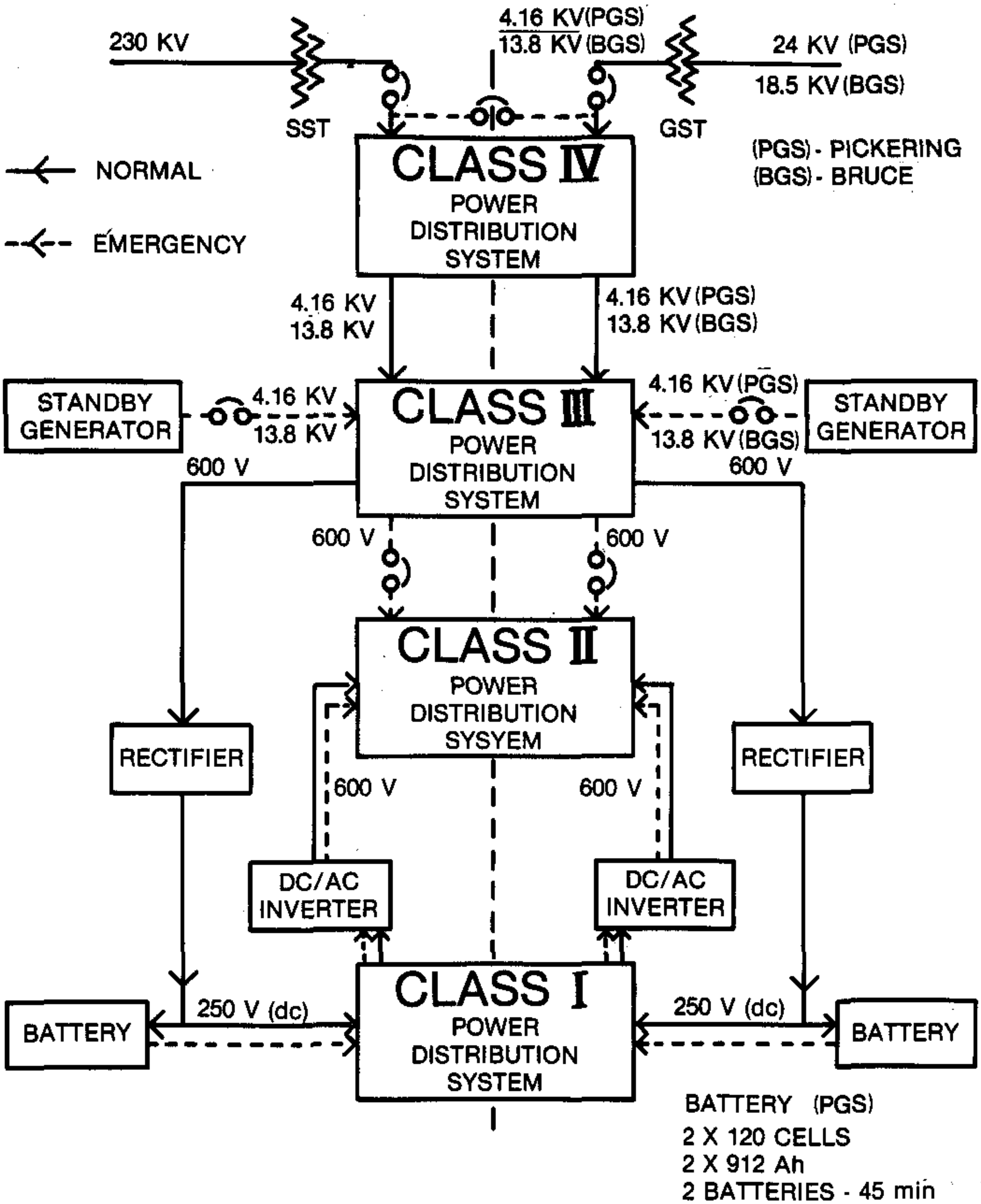
(a) Class IV power: Class IV power/loads can be interrupted **indefinitely** without affecting personnel or plant safety. Typical loads on a class IV system are: normal lighting, and primary heat transport pump motor.

(b) Class III power: Class III power/loads can be interrupted for **one to three minutes** without affecting the safety of personnel or of the plant. Typical loads on a class III system are: moderator main circulation pump motor, the motor driving the pressurizing feed pump in the feed and bleed system.

(c) Class II power: Class II power/loads can be interrupted for **0.25 seconds** without affecting the safety of personnel or the station. Typical loads on a class II system are: digital control computors, reactor safety systems.

(d) Class I power: Class I power/loads can **never** be interrupted without affecting the safety of the personnel or the plant. Typical loads on a class I system are: protective relaying, circuit breaker control, turbine lube oil emergency pump motors, emergency seal oil pump motors, emergency stator conductor water cooling system pump motor.

3.1 Normal and Emergency Sources:



3.1 Normal and Emergency Sources:

What load will be powered by what class of power is determined by its importance. Each power class has a normal power source and an emergency power source which takes over once the normal source is not available. Refer to the figure shown on the left.

(a) Class IV power: Half of the load is carried by the unit services transformer (UST) and the other half of the load is carried by the system services transformer (SST). However if the UST fails, the SST will supply 100% power from the grid. In this manner, the Ontario Hydro grid also serves as an emergency power supply for the class IV system. Other modes of supplying power to class IV systems are used depending on which Nuclear Station is being considered.

(b) Class III Power: Normally, class III power is supplied from the two class IV sources. Should the UST and the SST both fail, then the standby diesel generators or gas turbines automatically turn on and begin picking up the load, sequentially. This whole process would take less than three minutes.

(c) Class II power: Class II power is normally fed from class I, via an inverter, which changes dc to ac. The "inverter" at Pickering NGS is a dc motor which drives an ac generator. The inverter at Bruce NGS is a static (electronic) device. At either station, if the normal class I supply fails, class II power is supplied from the battery banks until the standby generators in class III are operating.

(d) Class I power: Class I is normally obtained from class III, via a battery charger (rectifier). Should the battery charger or the class III supply fail, then the class I is obtained from a battery bank, which is always maintained in its fully charged state by a battery charger. Class I power is generally 250V dc.

3.2 Load Distribution

For reliability reasons each class of power is split into two separate circuits. Each circuit draws the power from an independent source. This is shown in the diagram on the left by a dotted line dividing the diagram into two halves. Total load can be transferred from one to the other circuit.

ASSIGNMENT

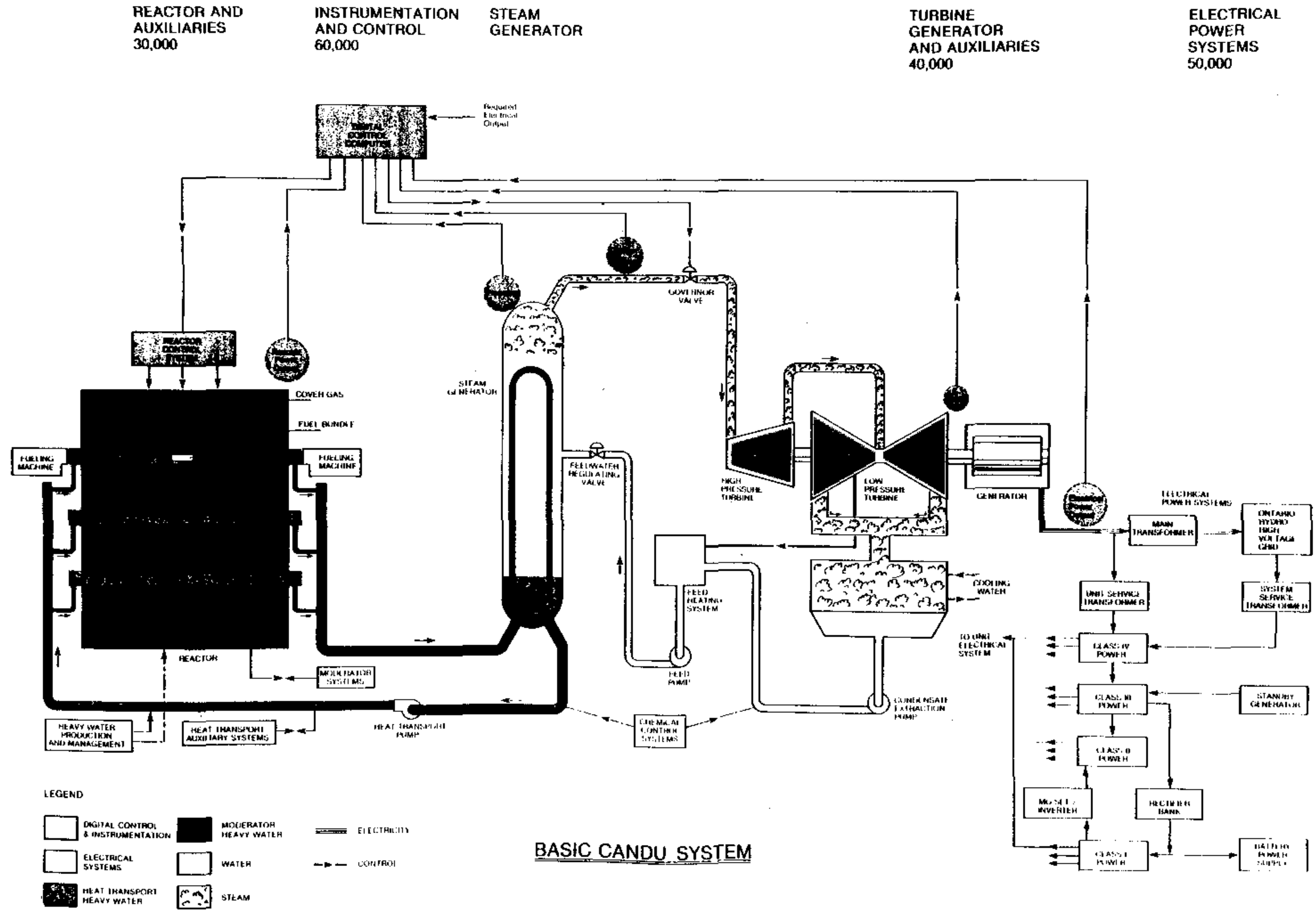
1. In the basic CANDU diagram shown on the pull-out sketch, label and briefly explain the purpose of each component. (Section 2).

2. Define the four classes of power as used in the CANDU system and give two examples of a typical load on each class of power. (Section 3).

3. What is the normal and emergency supply, for each class of power. (Section 3).

S. Rizvi

NOTES



BASIC CANDU SYSTEM

Electrical Equipment - Course PI 30.2

CONDUCTORS

OBJECTIVES

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

1. In one or two sentences:
   a) Define the term "ACSR";
   b) Explain the purpose of the steel core in ACSR cable.

2. Briefly, in writing or using a table or chart, list the considerations made in the selection of a conductor material for:
   a) Generators and Transformers;
   b) Transmission lines;
   c) Grounding Conductor;
   d) IPB;
   e) Bus Bars.

3. Define, in one or two sentences, the following units used for conductor size:
   a) Square Mil;
   b) Circular Mil;
   c) AWG.

4. Briefly, in writing, state the three methods which can be used to reduce conductor resistance.

5. In one or two sentences, state two electrical considerations that affect the conductor size.

6. Briefly, in writing, state and explain each of the general considerations given for the joining of aluminum cable.

7. Briefly explain what an Isolated Phase Bus is, what metal it is made from and how and why additional cooling is provided.

8. a) Briefly explain what a Bus bar is and which metals are used for its construction;
   b) List two types of indoor bus bars and two types of outdoor bus bars.

9. List, in writing, six factors which can damage a cable.

CONDUCTORS

1. Introduction

This lesson examines the;

(a) Basic properties of the material used as conductors.

(b) Units, types, and the applications of conductors.

(c) Care of cables in the power plant.

2. Electrical Conductors

Electrical conductors are used to convey power from an electrical source (eg, a generator) to an electrical load (eg, a light bulb, heater, heat transport pump motor).

Conductors are made from metals which easily conduct electric current; that is, they have low resistance to electrical current flow. Low resistance of conductors is attributed to the fact that their atoms give up free electrons more readily. Copper and aluminum are frequently used as conductors. A comparison of these two conductors is shown in the table below.

	Copper	Aluminum	
Tensile strength for same conductivity (MPa)	150	80	Cu is stronger
Density kg/m^3	8930	2700	Cu is heavier
Cross-section relation for same conductivity and length (mm^2)	1	1.56	Cu is smaller
Specific Resistance (Ω·meter x 10^{-8})	1.7	2.65	Cu offers less resistance
Corrosion Resistance	Good	Poor	Al oxidizes instantly
Temperature Expansion Coefficient	17 x 10^{-6} m/°cm	24 x 10^{-6}m/°cm	Al expands more
Melting Point °C	1083°C	660°C	Cu can withstand higher temperatures
Cost	High	Lower	Cu is more expensive

Table 1

2.1 ACSR Cable

Aluminum Conductor with Steel Reinforcement (ACSR) is made of aluminum strands with a steel core in the centre. This steel core is used to compensate for the poor mechanical properties of aluminum. Figure 1, below, shows the construction of ACSR cables.

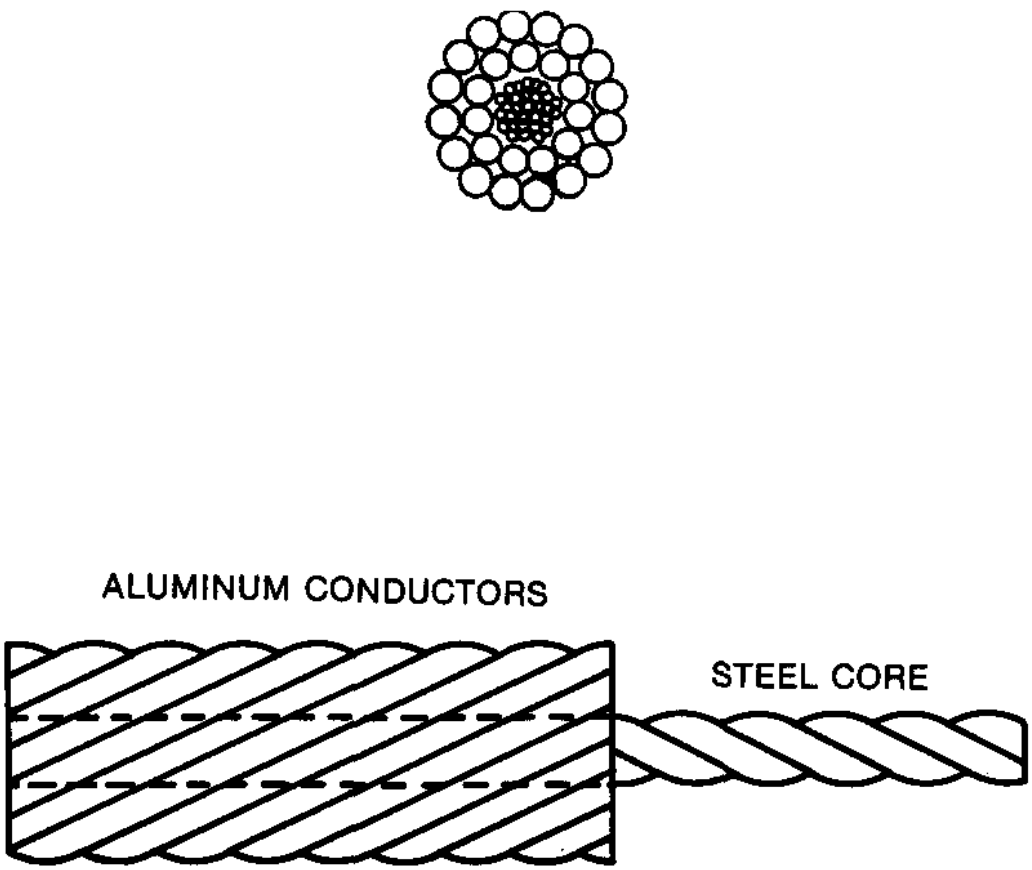


Figure 1: Aluminum Conductor with Steel Reinforcement (ACSR)

3. Selection of Conductor Material

The selection of a conductor material is made on the basis of the properties most desired for a given application. In large electrical generators and large transformers, factors of concern for conductors are:

(a) Physical size.
(b) Low winding resistance.
(c) Ease of making connection.
(d) Good mechanical strength.
(e) Good corrosion resistance.
(f) High melting point.
(g) Cost.

Copper possesses all of the above properties except (g). Properties desired outweigh the cost. Hence, copper is used in large generators and transformers. Cost of these units in Ontario Hydro plants can be over a million dollars each.

In transmission lines, it is desired to have:

(a) Low cost.
(b) Good mechanical strength.
(c) Light weight.
(d) Low resistance.

Aluminum comes closest to providing most of these requirements. Low cost and the distances involved in transmission lines justify the use of aluminum. In practice, aluminum conductors with steel reinforcement are used for improved strength.

Grounding

Only copper is permitted, due to its low electrical resistance and good corrosion resistance properties.

Isolated Phase Bus (IPB)

Aluminum is used, due to cost considerations. IPB will be discussed in Section 9.1.

Bus Bars

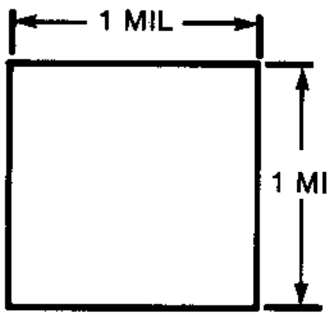
Copper, aluminum, or ACSR conductors can be used depending on the cost and the mechanical strength required.

4. Units of Area of Cross-Section

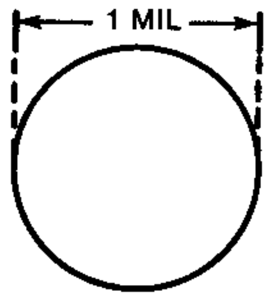
4.1 SQUARE MIL

ONE MIL = 0.001 inch or 1×10^{-3} inch.

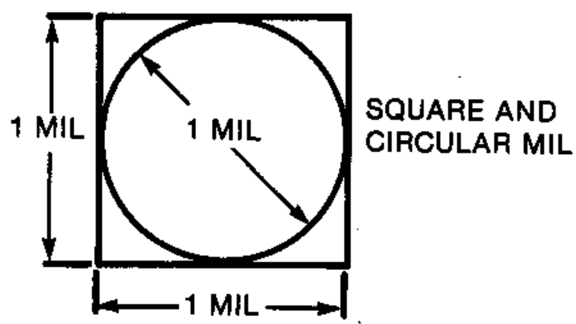
SQUARE MIL is the unit of cross-sectional area used for square conductors. A square mil is the area of a square; the sides of which are 1 mil in length. This is shown in Figure 2A, below.



(A) Square MIL



(B) Circular MIL



(C) Comparison of CIRCULAR MIL to SQUARE MIL

Figure 2: Square MIL and Circular MIL

4.2 Circular Mil

The CIRCULAR MIL is the standard unit for wire cross-sectional area which is used in American wire tables. A circular mil is the area of a circle having a diameter of 1 mil. The area of cross-section (in circular mil units) for a circular conductor is obtained by squaring the diameter of the conductor, which is expressed in mils. See Figure 2(B).

By definition:

$$\text{AREA(in circular MILS)} = (\text{diameter in MILS})^2$$

A comparison of Circular MILS to Square MILS is shown in Figure 2(C)

In large sizes, wires are stranded to increase the flexibility of the cable. The strands are single wires twisted together, in sufficient number to give the required cross-sectional area of the cable. The total area in circular mils is obtained by multiplying the circular mils of one strand bythe number of strands in the cable.

4.3 American Wire Gauge (AWG)

AWG is the method of wire sizing used in North America. AWG is also known as Brown Sharpe Gage (B & SG). Wires are manufactured under this sizing system in North America. As apparent from Table 2, the wire diameter becomes smaller as the gage number becomes larger.

A wire gauge, as shown in Figure 3, is used to measure the wire sizes from 0 to 36 AWG. The wire must fit the slot not the circular hole past the slot, to obtain a proper size, when using this gauge.

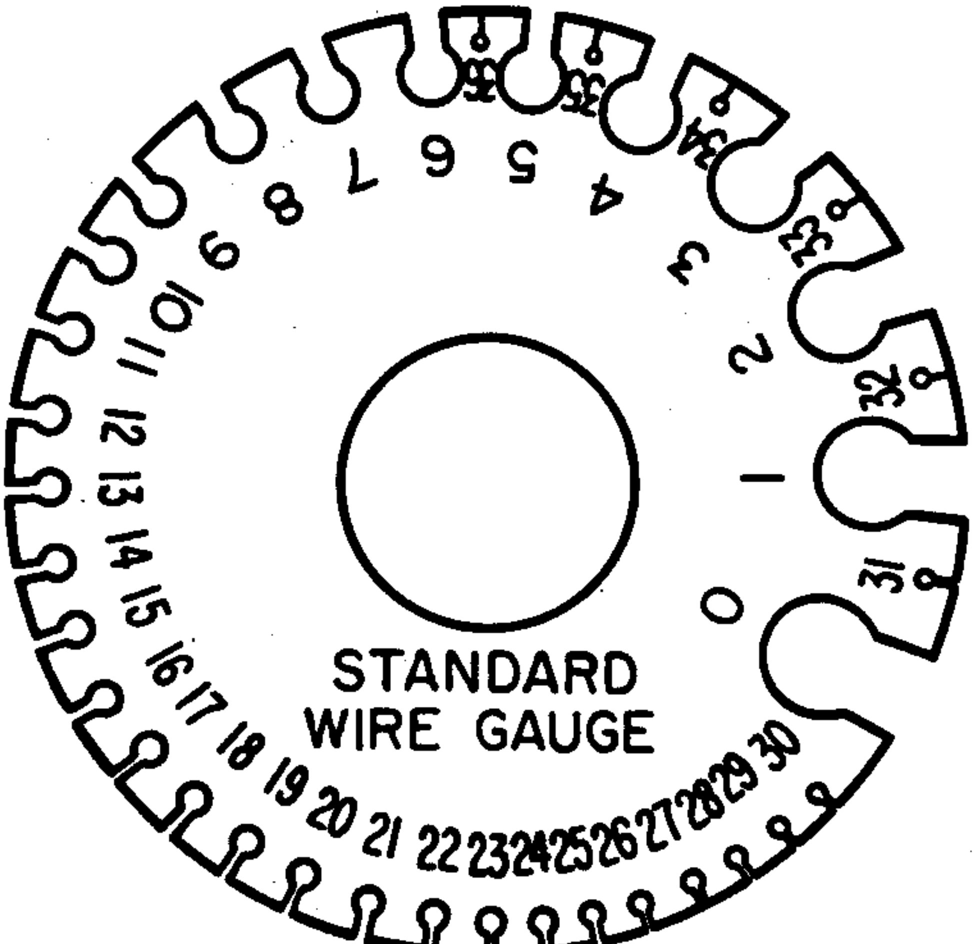


Figure 3 - AWG

TABLE 2 - Standard Annealed Solid Copper Wire
American wire gauge -- B & S

Gauge Number	Diameter (mils)	Cross Section: Circular mils	Cross Section: Square inches	Ohms per 1000 ft: 25°C (=77°F)	Ohms per 1000 ft: 65°C (=149°F)	Ohms per mile 25°C (=77°F)	Pounds per 1000 ft
0000	460.0	212,000.0	0.166	0.0500	0.0577	0.264	641.0
000	410.0	168,000.0	0.132	0.0630	0.0727	0.333	508.0
00	365.0	133,000.0	0.105	0.0795	0.0917	0.420	403.0
0	325.0	106,000.0	0.0829	0.100	0.116	0.528	319.0
1	289.0	83,700.0	0.0657	0.126	0.146	0.665	253.0
2	258.0	66,400.0	0.0521	0.159	0.184	0.839	201.0
3	229.0	52,600.0	0.0413	0.201	0.232	1.061	159.0
4	104.0	41,700.0	0.0328	0.253	0.292	1.335	126.0
5	182.0	33,100.0	0.0260	0.319	0.369	1.685	100.0
6	162.0	26,300.0	0.0206	0.403	0.465	2.13	79.5
7	144.0	20,800.0	0.0164	0.508	0.586	2.68	63.0
8	128.0	16,500.0	0.0130	0.641	0.739	3.38	50.0
9	114.0	13,100.0	0.0103	0.808	0.932	4.27	39.6
10	102.0	10,400.0	0.00815	1.02	1.18	5.38	31.4
11	91.0	8,230.0	0.00647	1.28	1.48	6.75	24.9
12	81.0	6,530.0	0.00513	1.62	1.87	8.55	19.8
13	72.0	5,180.0	0.00407	2.04	2.36	10.77	15.7
14	64.0	4,110.0	0.00323	2.58	2.97	13.62	12.4
15	57.0	3,260.0	0.00256	3.25	3.75	17.16	9.86
16	51.0	2,580.0	0.00203	4.09	4.73	21.6	7.82
17	45.0	2,050.0	0.00161	5.16	5.96	27.2	6.20
18	40.0	1,620.0	0.00128	6.51	7.51	34.4	4.92
19	36.0	1,290.0	0.00101	8.21	9.48	43.3	3.90
20	32.0	1,020.0	0.000802	10.4	11.9	54.9	3.09
21	28.5	810.0	0.000636	13.1	15.1	69.1	2.45
22	25.3	642.0	0.000505	16.5	19.0	87.1	1.94
23	22.6	509.0	0.000400	20.8	24.0	109.8	1.54
24	20.1	404.0	0.000317	26.2	30.2	138.3	1.22
25	17.9	320.0	0.000252	33.0	38.1	174.1	0.970
26	15.9	254.0	0.000200	41.6	48.0	220.0	0.769
27	14.2	202.0	0.000158	52.5	60.6	277.0	0.610
28	12.6	160.0	0.000126	66.2	76.4	350.0	0.484
29	11.3	127.0	0.0000995	83.4	96.3	440.0	0.384
30	10.0	101.0	0.0000789	105.0	121.0	554.0	0.304
31	8.9	79.7	0.0000626	133.0	153.0	702.0	0.241
32	8.0	63.2	0.0000496	167.0	193.0	882.0	0.191
33	7.1	50.1	0.0000394	211.0	243.0	1,114.0	0.152
34	6.3	39.8	0.0000312	266.0	307.0	1,404.0	0.120
35	5.6	31.5	0.0000248	335.0	387.0	1,769.0	0.0954
36	5.0	25.0	0.0000196	423.0	488.0	2,230.0	0.0757
37	4.5	19.8	0.0000156	533.0	616.0	2,810.0	0.0600
38	4.0	15.7	0.0000123	673.0	776.0	3,550.0	0.0476
39	3.5	12.5	0.0000098	848.0	979.0	4,480.0	0.0377
40	3.1	9.9	0.0000078	1,070.0	1,230.0	5,650.0	0.0299

5. Specific Resistance or Resistivity

Specific Resistance or Resistivity, is the resistance, in ohms, offered by one unit volume, of a substance, to the flow of electrical current. Resistivity is the reciprocal of conductivity, and vice versa. It is represented by the Greek letter ρ. The temperature at which the resistivity is measured must be specified.

6. Types of Conductors

A CONDUCTOR is a wire or combination of wires (not insulated from one another), suitable for carrying an electric current.

A STRANDED CONDUCTOR is a conductor composed of a group of bare wires twisted together.

A CABLE is either a stranded conductor, single-conductor, or a combination of conductors insulated from one another (multiple-conductor cable). The term cable is a general one; In practice, it is usually applied only to the larger sizes of conductors. A small cable is more often called a stranded wire or cord. Cables may be bare or insulated. The insulated cables may be sheathed (covered) with lead, or protective armour.

Another common conductor is the BUS BAR. A high voltage bus bar is frequently just a hollow aluminum or copper tube, as is found on the main generator output. A low voltage bus may consist of flat straps or rectangular bars. Bus bars are commonly used, bare, but they can be covered with an insulating material, if the specific application requires insulation.

Figures 3 and 4 illustrate various configurations of wire, cable, and bus bar. Shown also, are typical sizes and applications.

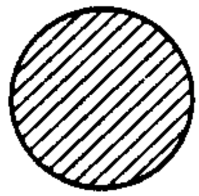
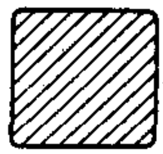
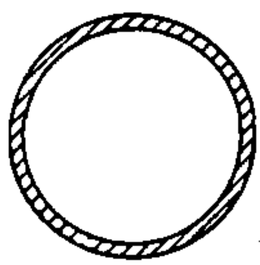
Type	Illustration	Application
Solid round		Bare or insulated wire for power work; insulated for magnet wire
Solid grooved		Trolley contact wire
Solid, square		Magnet wire and windings for electrical equipment
Solid, retangular		Magnet wire and windings for electrical equipment, bus bars
Tubular		Bus bars, IPB

Figure 3: Configurations of Electrical Conductors

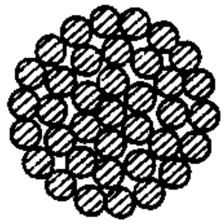
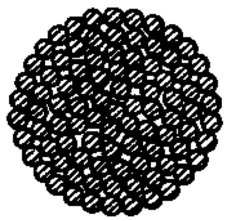
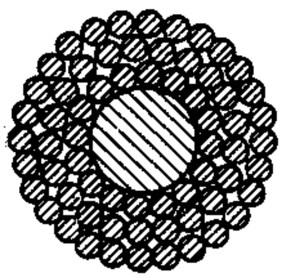
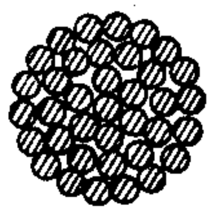
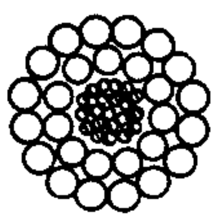
Type	Illustration	Application
Standard, concentric-stranded		Bare or insulated cables
Bunch Stranded		Flexible cords and fixture wire
Annular concentric-stranded with rope core		Varnished-cambriac -insulated and solid type paper-insulated single-conductor cables.
Stranded (All Aluminum)		Bus bars
Annular aluminum, stranded with steel core (ASCR)		Bus bars

Figure 4: Configurations of Electrical Conductors

7. Selection of Conductor Size

Selection of conductor size refers mainly to the area of cross-section of the conductor. The following considerations are made in this process.

(a) Current carrying capacity of the conductor (normally referred to as the ampacity of the conductor). Each size conductor is rated to carry a certain maximum current, safely. If this current rating is exceeded, then the conductor will overheat. To overcome this problem, a sufficiently large conductor size is used, with a rating higher, than the current expected in the circuit.

(b) Voltage drop allowable in the conductor. All conductors have an inherent resistance R. When a current of I amperes flows through it, a voltage drop of V volts occurs across the conductor. This has two effects:

(i) Voltage at the load is reduced by the amount of internal voltage drop in the cable.

(ii) As the load current varies, internal voltage drop will also vary. This results in poor voltage regulation at the load end.

To reduce the internal voltage drop in the cable, it is necessary to reduce the resistance of the conductor.

7. Selection of Conductor Size (continued)

Recall that $R = \rho \frac{\ell}{A}$ where R is resistance
where ρ is resistivity
where ℓ is length
where A is area

Hence, in order to reduce the internal voltage drop in the cable, it is necessary to reduce the resistance of the conductor. This can be done in any of four ways, as summarized below:

(a) Select low resistivity material, ie, copper or aluminum.

(b) Reduce the conductor length. However, in a given installation this length is fixed.

(c) Increase the area of cross-section of the conductor. This will result in larger, heavier and a more costly conductor, which will require larger and stronger supports and other installation accessories. If the voltage drop in the cable is not tolerable, this compromise would have to be made. It is sometimes beneficial to raise the supply voltage to reduce the current, hence internal voltage drop and I^2R loss in the conductor, eg, transmission lines.

(d) Raise the supply voltage to reduce the current. Hence, the internal voltage drop will be less and the resultant I^2R power loss will be less. This is commonly done with transmission lines.

8. Connecting Aluminum Conductors

Aluminum oxidizes almost instantly. The aluminim oxide layer formed on a conductor surface is hard, and it is a very poor conductor of electricity. When connecting aluminum conductors, the following special precautions must be taken:

(a) Non-oxidizing lubricant must be used.

(b) A special connector must be used. It breaks the oxide film and provides a good metal-to-metal contact.

(c) A special connector must be used for ACSR conductors. This connector is shown in Figure 5, below.

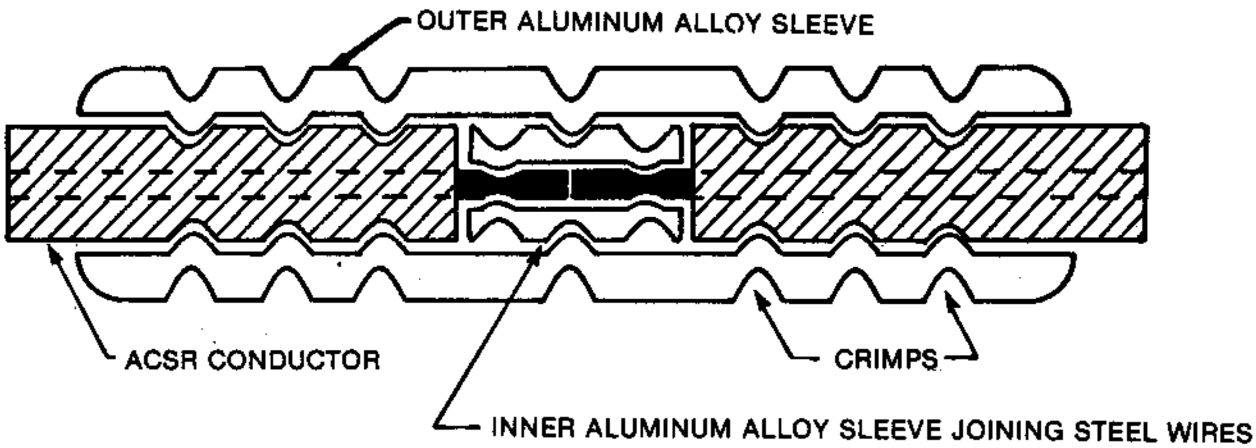


Figure 5: Special connector for joining ACSR conductors

Note, in the figure above, that aluminum sleeves are used to join the ACSR conductors together. The illustration shows only a few crimps in the sleeve. However, in actual practice many more crimps would be made to ensure that there is sufficient contact area between the ACSR conductor and the aluminum alloy sleeve.

9. Conductors and Cables in a Power Plant

In power plants, power conductors and cables are used for:

(a) Taking power from the electrical generator to the main transformer. (These conductors are known as the Isolated Phase Bus).

(b) Taking power from the main transformer to the Hydro Grid. (This is done via overhead ACSR conductors or aluminum conductors for short distances).

(c) Distributing power to the distribution panels (by means of bus bars).

(d) Taking power from the distribution panels to the various motors, lighting and other loads. (This is done via cables).

Figure 6 shows all of the above components in a power plant. A brief discussion of each will be given on the pages that follow.

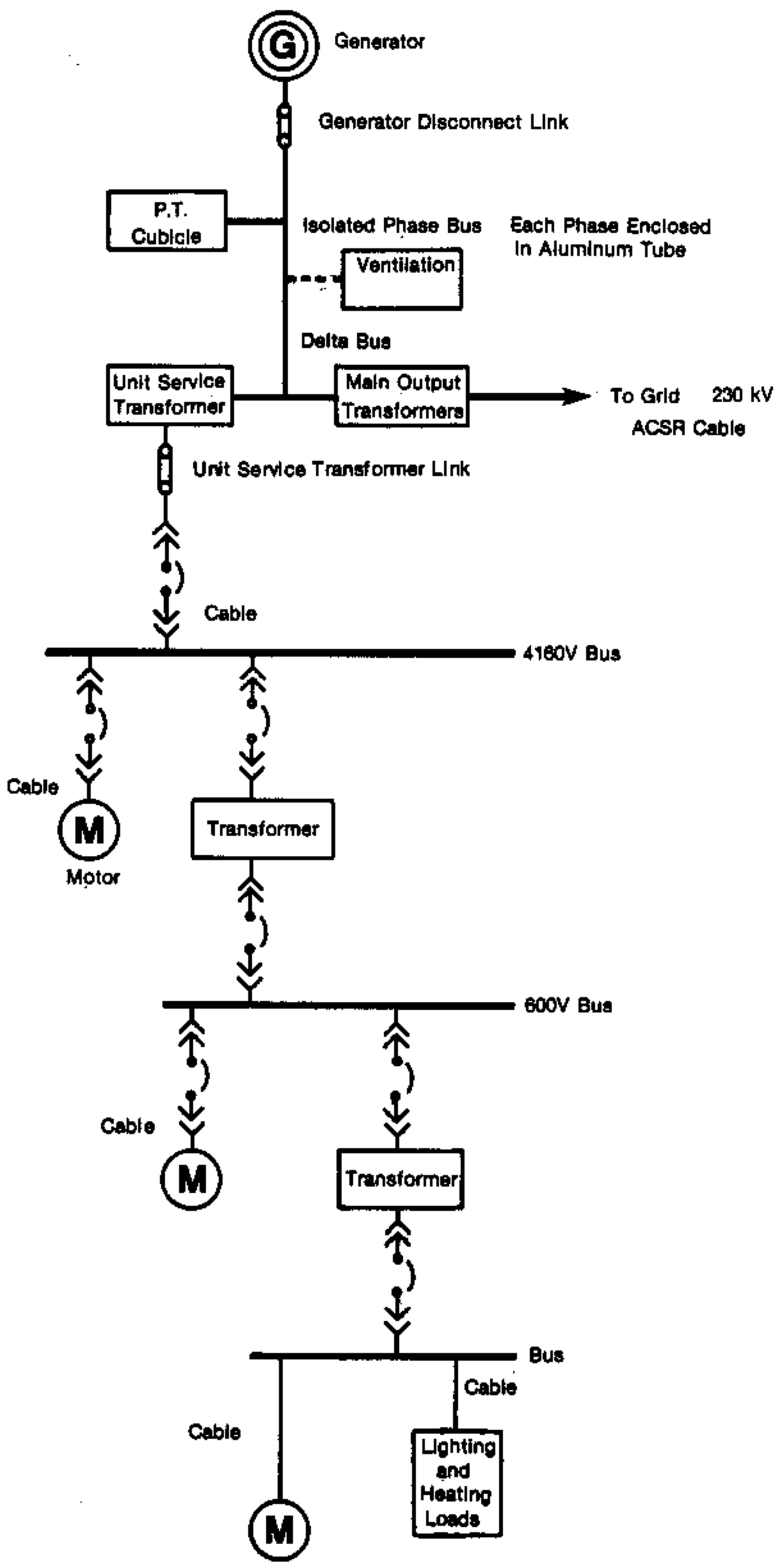
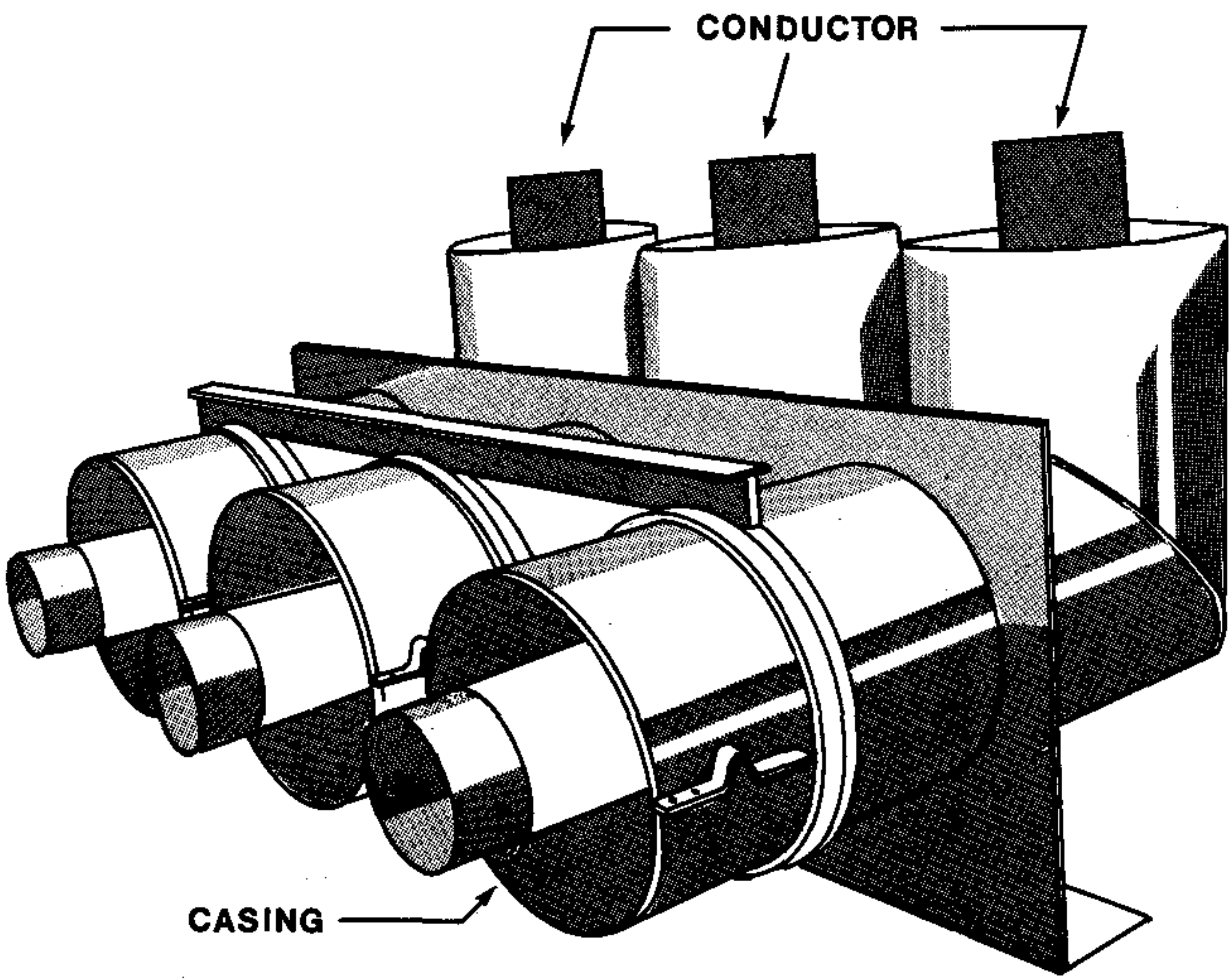


Figure 6: Buses, Conductors, and Cables in a Power Plant

9.1 Isolated Phase Bus (IPB)

The IPB takes the power from the generator to the main transformer. This conductor system carries the largest magnitude of current in the plant. At Pickering "A", the current can be as high as 16,500 amperes, and at Bruce "A", the current can be as high as 30,000 amperes. Since very large conductors are required to carry this amount of current, economics dictates the use of aluminum.

The IPB conductor is tubular and it is placed in a circular or rectangular casing to provide forced air cooling and environmental protecton. Figures 7(A) and 7(B) show sections of the IPB. Cooling is necessary to remove large I^2R heat developed and this is provided by forced air circulation.



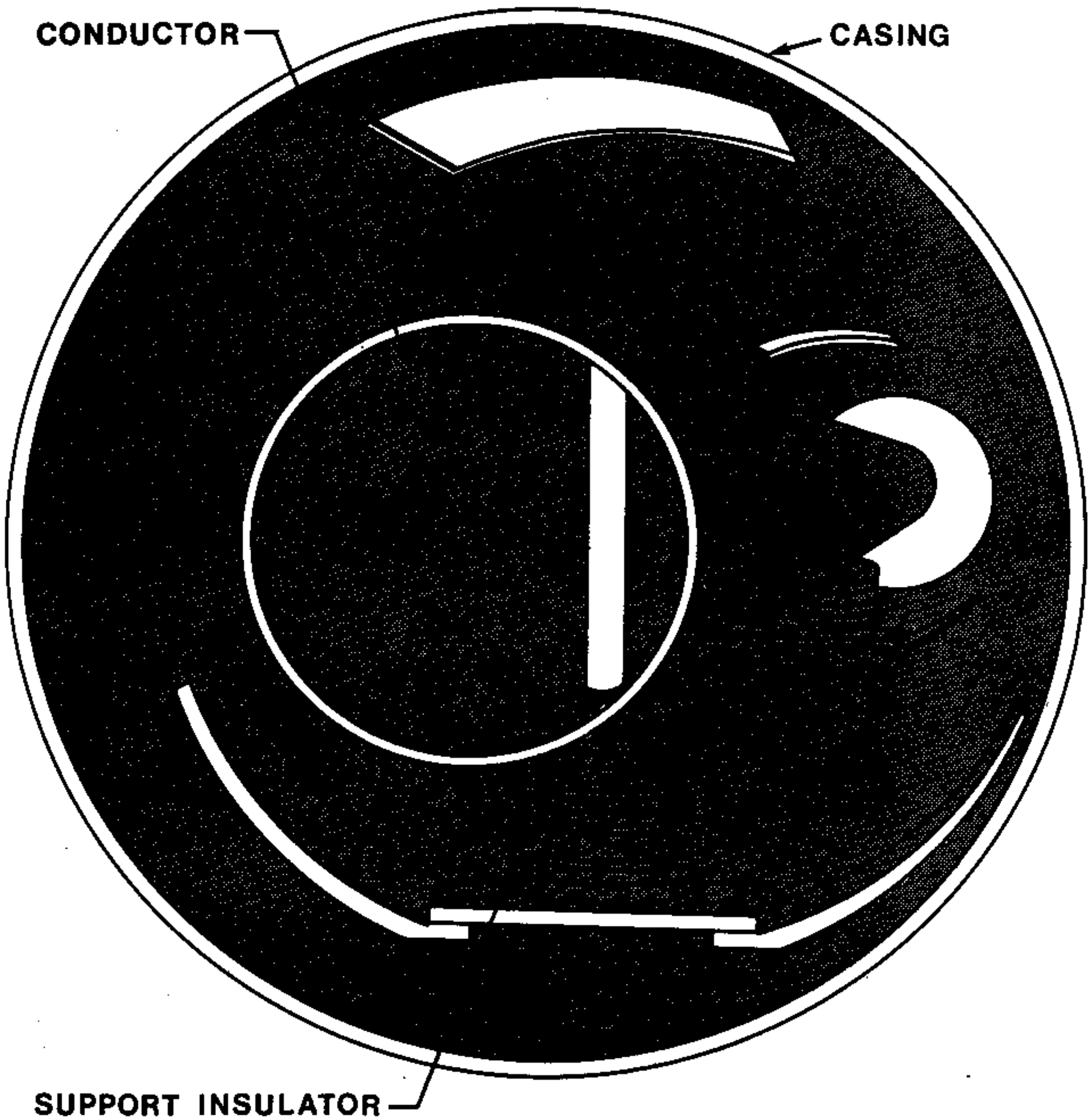


Figure 7(B): Isolated Phase Bus mounted on support insulators in the cooling duct. (Only one conductor is shown)

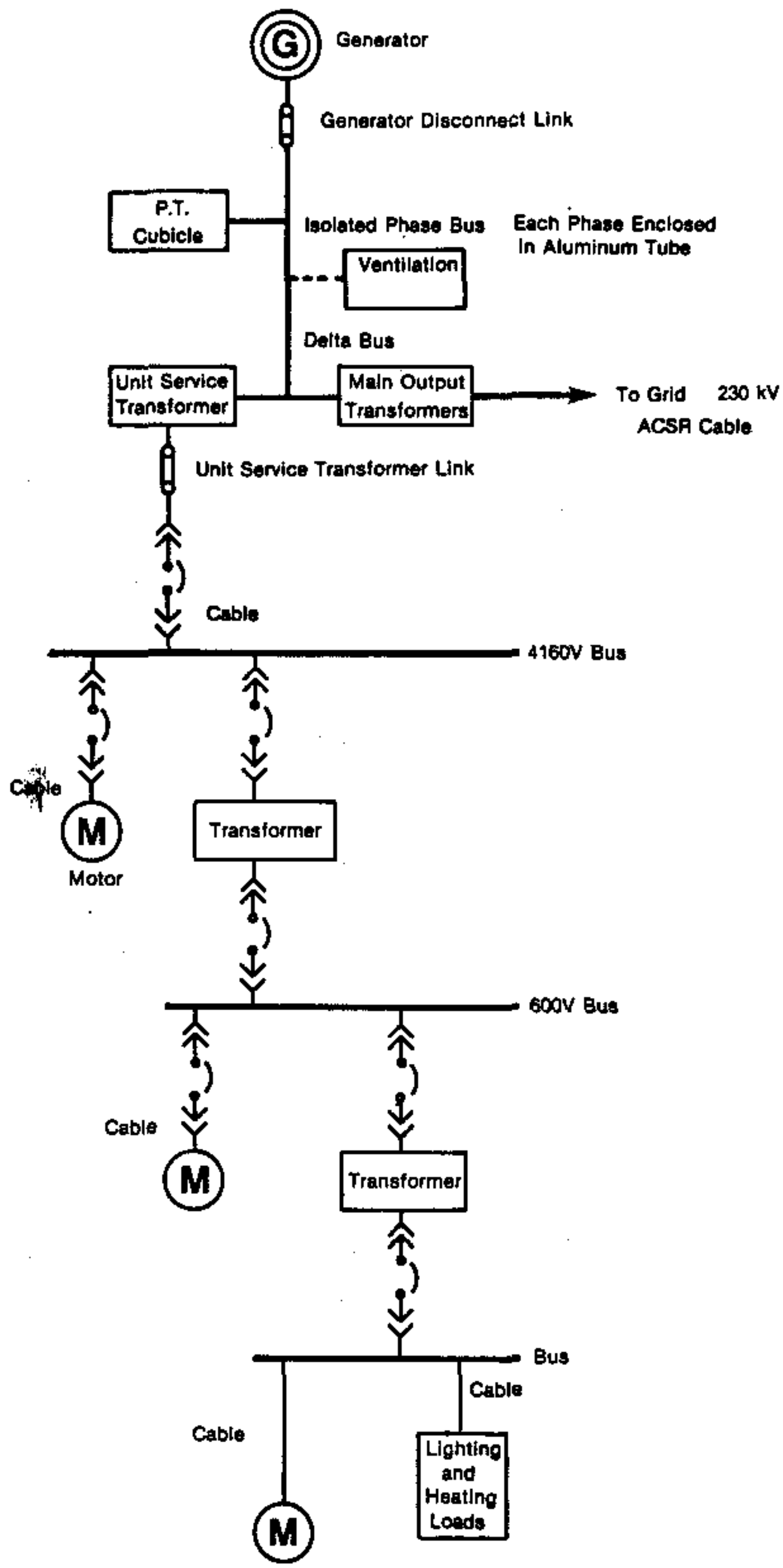


Figure 8: Conductors and Cables in a Power Plant

9.2 Generator Transformers-to-Switchyard Connection

The output of the main transformer is at 230 kV or 500 kV. As a result, current is much smaller here than in the IPB. To carry this smaller current, small size conductors are used. Conductors used are normally ACSR types. Stranded aluminum cable may also be used for short distances.

9.3 Power Distribution at the Panel

A bus is a conductor which serves as a common connection to two or more circuits. Power into the panel is brought by a cable and fed to a bus. A bus can feed many circuits connected to it, as shown in Figure 9, below.

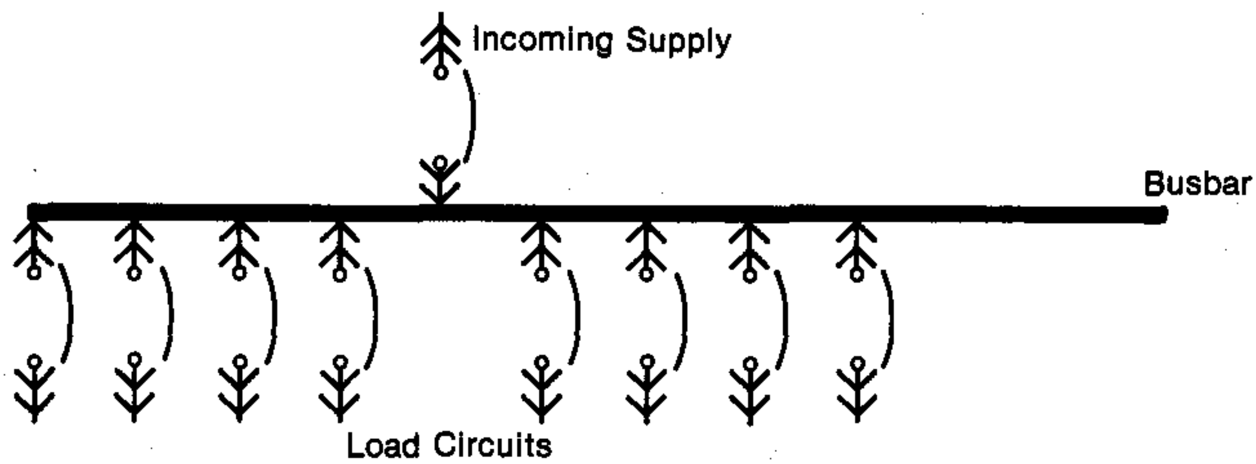


Figure 9: Single line diagram showing a bus bar with an incoming supply and load circuits.

9.3.1 Types of Bus Bars

Bus bars are divided into the following categories:

(a) Indoor Bus Bars

This type of bus bar is used at 600 V, 4160 V and 13800 V, in nuclear generating stations. They can be either:

(i) Insulated.
(ii) Non-insulated.

(b) Outdoor Bus Bars

They can be:

(i) tubular types. The tube can be either aluminum or copper.

(ii) *Flexible type; constructed from* ACSR. *This type* of bus bar is used in 115 kV, 230 kV and 500 kV applications. It connects to and from the main transformer terminals, and the disconnect switches to the transmission line.

The flexible type of outdoor bus bar is supported from overhead structures, using strain-relief type insulators and the tubular type is supported from pedestal type insulators. Flexible connectors are used between the tubular bus bars to allow for expansion and contraction of the joints.

10.0 Care of Cables

In a power plant if the cables are properly cared for, they will give trouble-free service for the life of the station. Cable failure is usually attributable to one of the following:

(a) Heat (Refer to PI 30.21-2, Section 4.1.3)

Cable insulation is designed to withstand a maximum rated temperature. Any increase above this rating will permanently damage the insulation. To prevent this condition:

(i) Adequate ventilation must be provided when the cables are carrying current.

(ii) They must not be installed on hot surfaces.

(iii) Temperature rating of the insulation used, must be selected to suit the application.

(b) Cold

Insulation is also rated for a minimum sub-zero temperature. If it is subjected to colder temperatures than what it is rated for, the insulation will become brittle and will likely develop cracks. To prevent this from happening:

(i) Cables installed in areas where sub-zero temperatures are expected, must be rated to withstand such temperatures.

(ii) Handle the cable with care.

(c) Fire

Some cable insulation materials contain fire retardants, but many types do not. To prevent fires, keep flammable products away from the cable areas.

(d) Moisture

Moisture will destroy some insulation materials, such as paper. On the other hand, moisture will reduce the insulation properties of all types of insulators, which can lead to insulation failure. The outer sheath of the cables is designed to be waterproof. If damage to the outer sheath occurs, moisture will penetrate the insulation.

(e) Physical Damage

Physical damage to cables occurs by objects hitting or striking the cables. Physical damage can occur by improper installation, such as installing cables over sharp edges.

(f) Radiation

The chemical and physical properties of insulating materials are affected by radiation. Plastic type insulating materials are affected most severely by radiation, particularly the wiring harnesses on fuelling machines.

ASSIGNMENT

1. Compare copper and aluminum for their electrical, physical and thermal properties (Table 1, in Section 2).

2. (a) What is an ACSR cable (Section 2.1)?

   (b) What is the purpose of the steel core in ACSR cable (Section 4)?

3. List the considerations made in the selection of conductors for (Section 3):

   (a) Transmission Lines

   (b) Grounding

(c) IPB

(d) Large Generators and Transformers

(e) Bus Bars

4. Define the following units (Section 4):

(a) Square MIL

(b) Circular MIL

(c) AWG

5. What two electrical considerations determine the area of cross-section of a conductor (Section 7)?

6. What means can be used to reduce the conductor resistance? Explain each (Section 7).

7. *Why must special considerations be given when joining* aluminum cable? What are these considerations (Section 8)?

8. For the IPB, answer the following (Section 9.1):

   (a) What is the IPB?

(b) What metal is used for the IPB?

(c) What is the shape of the IPB?

(d) How and why is additional cooling provided to the IPB?

9. With regards to bus bars, answer the following (Section 9.3, 9.3.1):

(a) What is a bus bar?

(b) What metals are used for bus bars?

(c) What two types of indoor bus bars are there?

(d) What two types of outdoor bus bars are there?

10. List six factors which can damage a cable and must be considered when discussing cable care (Section 10).

S. Rizvi
R. Coulas

Electrical Equipment - Course PI 30.2

INSULATION

OBJECTIVES

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

1. Explain, in writing, the term "leakage current" and indicate the normal range of its magnitude.
2. Briefly state, in writing, four factors which affect insulation resistance.
3. Briefly state, in writing, five insulation materials and one application of each.
4. Explain, briefly, in writing the term "insulation failure".
5. Briefly state, in writing, seven causes of insulation failure.
6. In two or three sentences, explain why the fault current must be interrupted quickly.
7. In a few sentences, state why the insulation is temperature rated and and how this temperature rating is established for a given application.
8. Briefly, explain, in writing, the term "puncture" as related to electrical insulation.
9. Briefly, state in writing, two results of insulation failure.
10. In writing, list six points which must be considered in the selection of an insulation.
11. In writing, list nine points which must be considered when testing an insulation.

1. Introduction

This lesson examines:

(a) What is insulation; examples of various insulations in use.
(b) Why insulation is used.
(c) Requirements, causes of failure and their effects and hazards.
(d) Testing of insulation.

2. Insulation

Insulation is used in electrical equipment and systems to electrically separate one live conductor from the other, as in multi-conductor cable; or, a live conductor from another conducting surface, such as a grounded motor, bushing and its support structure, etc.

3. Insulation Resistance and Leakage Current

A good electrical insulator must have high resistance to current flow. However, all materials will allow some current flow through them. In insulating materials, this current is in the order of microamperes (10^{-6}A) or nanoamperes (10^{-9}A). It is referred to as **leakage current.** In a good insulation material, the leakage current is so small, (microampres) that for all practical purposes, it is considered zero.

The leakage current value is very low due to very high insulation resistance; typically, in millions of ohms.

The value of insulation resistance depends on:

(a) insulation material,
(b) insulation thickness.
(c) temperature.
(d) humidity.

Some typical insulation materials used in NGD are given in Table 1, along with their applications.

Insulation Material	Application
Air	Variable capacitors, bare overhead lines
Asbestos	Heaters, heater cords
Bakelite	Switches, breakers
Cotton	Cables, transformers, motors
Epoxy	Small transformers, bus work
Fibreglass Tape	Generators, switch sticks
Glass	Pole top insulators
Magnesium Oxide	Cables
Mica	Capacitors, generators, appliances
Nylon	Control room panel wiring
Paper	Transformers
Plastic	Cables, air circuit breakers
Polyvinylchloride (PVC)	Cables
Porcelain	HV bushings
Rubber	Test leads, safety mats and gloves
Teflon	Transformers, circuit breakers, capacitors
Mineral Oil	Transformers, circuit breakers, capacitors
Askarel Oil	Transformers, capacitors (Its use is banned in the new equipment)

Table 1

Insulation Materials Types and Their Use in NGD

4. Insulation Failure

An insulation is considered "failed" if it does not prevent current flow, other than the normal leakage current between the two live conductors or a conductor and a conductive surface. Most insulators will become conductors if some conditions, as follows, are not met.

4.1 Causes of Insulation Failure

The following are major causes of insulation failure.

4.1.1 Aging

Aging of insulation occurs due to many causes. Some of the important ones are listed below.

(a) Environment
(b) Radiation
(c) Corona
(d) Drying
(e) Excessive Heat

When an insulation ages, it becomes brittle, dry and develops cracks. Its resistance drops to a point such that it can not effectively perform as an insulator.

4.1.2 Chemical Changes

Chemical changes occurring in the insulation cause permanent damage to the insulation. Electrical properties of the new chemical product formed are normally poorer than the original.

Chemical changes in an insulation are caused by the operational environment, for example: heat, radiation, contaminants.

4.1.3 Thermal Stress

Thermal stress occurs when a material is overheated. It causes carbonization and/or melting. Overheating of insulation can be caused by the following.

(a) Fire.
(b) Fault current, which can be very large. Fault current causes large I^2R heat production, which overheats the insulation. (This is why fault conditions must be quickly interrupted).

4.1.3 Thermal Stress (continued)

(c) Extended overload. Overload current is the current which is a few percent more than the normal current. This increased current applied for an extended period of time, will overheat the insulation. This is why insulation is "temperature rated". Table 2 shows the various classes of insulation and their temperature ratings. For any application the expected operating temperature must be known. To this, a safety factor is added in order to arrive at the type of insulation needed.

As a general rule, for every 10°C increase in the operating temperature of an insulation, its life is reduced by half.

Class	Max Working Temperature °C	Examples of Materials
O(Y)	90	Cotton, silk, paper - not impregnated nor immersed in a liquid dielectric shellack.
A	105	Cotton, silk, paper - impregnated or immersed in liquid dielectric (oil).
E	120	Organic materials impregnated with asphalts, polyesters.
B	130	Mica, asbestos, fibreglass with polyester varnishes, bitumen, varnish.
F	155	Mica, fibreglass, asbestos with epoxy resin varnishes.
H	180	Inorganic insulations, silicones.
C	Over 180 (Navy 200)	Inorganics like mica, ceramics, glass, porcelain, polytetraflourethylene (teflon).

Table 2

Insulation Classes and Temperature Ratings of Various Materials Used for Electrical Insulation

4.1 Causes of Insulation Failure (continued)

4.1.4 Electrical Stress

(a) When a voltage is applied across any insulation it causes an electrical field to appear within the insulation. The intensity of the electrical field is usually specified as kV per centimeter (kV/cm) and is a measure of electrical stress of the insulation. **There is a certain electrical stress at which the insulation will be punctured.** The electrical stress to puncture new insulation is higher than that for old insulation. An increase in the electrical stress also causes the leakage current in the insulation to increase, which eventually leads to insulation failure. Every insulation must be used within its rated operating voltage. The voltage rating of the insulation must be at least equal to the line r.m.s. voltage.

Electrical stress of insulation not only depends on the magnitude of the applied voltage, but also on the shape of the electrode. Shape of the electrode influences the electric field distribution. In high voltage applications, electrodes and insulation are designed not to have sharp edges. Sharp edges create, local, high electric field intensities. Such electrical stress can be high enough to cause puncture through the insulation or cause corona.

(b) In dry air, the electrical stress to puncture (also called the dielectric strength) equals 30kV/cm. When the electric field intensity reaches 30kV/cm, the air becomes ionized, and a conductive path can be established. The conductive path can be from one conductor to the other, or from one conductor to a grounded surface, such as a transformer tank. This phenomenon is known as corona effect.

In air, corona can be observed, when the conductors in a high voltage switchyard are energized. A hissing sound can be heard, and at night, a blue or purple glow can be seen.

Corona can also occur in air pockets,which may be present in insulation, due to manufacturing defects. Corona cannot be eliminated. It can only be minimized. Some commonly used methods to minimize corona are:

- increasing the distance between the conductors.
- better manufacturing techniques to eliminate air pockets.
- improved design; for example, elimination of sharp edges, use of several conductors (bundled conductor) per phase, as done with 500kV transmission lines.

When corona occurs in air, O_2 and N_2 molecules break down to form O_3 (ozone), NO and NO_2. If moisture is present, these oxides of nitrogen combine with water to form nitric acid. In turn, this nitric acid attacks the insulation or the insulation bonding agents. This process can also occur, in tiny air pockets, within a solid insulator.

Figures 1 and 2 show porcelain insulators used in high voltage applications. Their design provides for the following:

- As many as required can be connected in a string form to provide the proper operating voltage.

- Rounded edges are designed to reduce electrical stress.

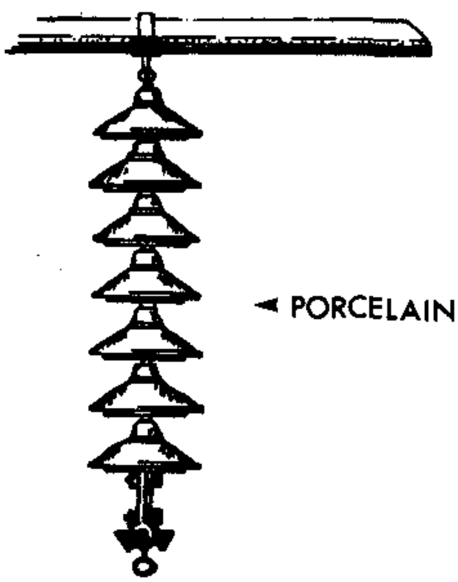


Figure 1: Typical String of Porcelain Strain Insulators

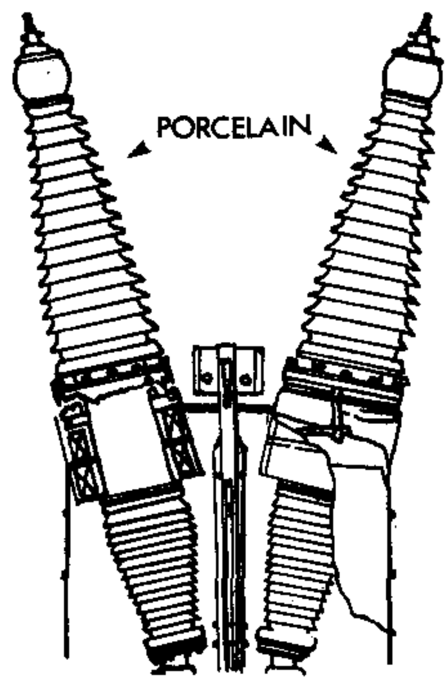


Figure 2: Two Typical Porcelain Brushing Insulators

4.1.5 External Contamination

Dirt and dust collecting on the surface of insulation can provide a layer through which current can flow. Current flowing through this layer of contamination eventually chars the insulation under it and creates a permanent carbonized path. This phenomenon is known as "tracking". Organic materials are greatly affected by tracking, while inorganics, such as porcelain are more resistive to tracking. Tracking will eventually lead to insulation failure.

4.1.6 Internal Contamination

If moisture or dirt gets in between the conductor surface and the insulation, or if moisture is absorbed by the insulation, failure of the insulation will occur.

Some examples of insulations that can be damaged by moisture are: paper, wood, cotton, transformer oil and magnesium oxide.

4.1.7 Mechanical Stress

This is a straining force exerted on an electrical insulator. Mechanical stress deforms, cracks, or cuts an insulating material. Also, at the point of stress, electrical resistance of the insulation decreases and puncture results. Mechanical stress can be due to the following:

(a) Improper installation. Insulation installed on sharp edges can damage the insulation at the point of contact.

(b) Fault current produces high heat which reduces the mechanical strength of the insulation.

(c) Vibration. If equipment is not properly levelled or securely installed, vibration will cause the insulation to chafe through. Some insulations, such as epoxy resins, shrink due to aging. This causes loosening of the insulation and may result in vibration and eventual damage.

4.2 Results of Insulation Failure

One, of two phenomenon may occur, due to insulation failure.

(a) PUNCTURE through or tracking across the surface of an insulating material.
(b) FLASHOVER in air and gases.

In either case, high fault currents may flow.

4.3 Hazards of Insulation Failure

Insulation failure creates two concerns.

4.3.1 Hazard to personnel; it could be potentially lethal.

4.3.2 Hazard to equipment.

5. Checklist for Insulation Selection

5.1 Voltage rating: Insulation must be rated for the nominal line voltage of the circuit, in which it is used.

5.2 Temperature rating: Insulation must be able to withstand the temperature it is to be exposed to.

5.3 Waterproof: If the insulation is to be exposed to moisture, it must be waterproof.

5.4 Mechanical properties: Insulation must be able to lend itself to bending or shaping, if required, without changing its insulating characteristic.

5.5 Resistant to tracking: Insulation must have adequate surface area and have a hard, smooth,glossy finish. (For example, rubber has a low resistance to tracking; whereas, glass or porcelain has a high resistance to tracking).

5.6 Cost: Should be cost effective for the application.

6. Testing of Insulation

Insulation testing is done with an instrument called a "megger". This instrument is calibrated in ohms, KΩ, or MΩ. A megger is capable of measuring very large resistances, tens or hundreds of meg-ohms. (These are typical values for insulation resistance. Since insulations have low leakage currents, the megger must apply a high voltage across the insulating material, in order to achieve a reasonable accurate measurement.Insulation testers come in various voltage ratings. Typical values are: 100 V, 250 V, 500 V, 1000 V and 5000 V.

6.1 Points to Consider

6.1.1 The voltage output of the insulation tester must not be higher than the maximum voltage rating of the insulation, or damage to the insulation may occur.

6.1.2 Sufficient time must be allowed for the insulation test instrument reading to stabilize. This can be 3 to 5 minutes, depending on the size of the equipment, dryness, etc.

6.1.3 Insulation testing must be done in accordance with the work protection code.

6.1.4 It is useful to compare the insulation resistances of previous tests or comparable installations. Any large variations indicate a poor insulation health condition.

6.1.5 Temperature at the time of test will affect the reading.

6.1.6 Humid test conditions will result in lower insulation resistance measurements than would normally be expected.

6.1.7 New insulation will have a higher resistance reading than old insulation, of the same type. This should be considered when interpretating the test data.

6.1.8 On completion of the test, the insulation must be discharged, in order to ensure personnel safety.

6.1.9 For personnel safety, no one must come in contact with the conductor during a megger test. The conductor and the protective outer sheath could be at a high potential if the insulation is faulty.

Assignment

1. What is the purpose of insulation in electrical equipment? (Section 2).

2. Explain what is meant by "leakage current". What is the normal range of magnitude for this current in an insulation of good quality? List four factors which affect the insulation resistance. (Section 3).

3. List any five insulation materials and one application of each. (Section 3, Table 1).

4. What is meant by "insulation failure"? (Section 4).

5. List seven causes of insulation failure. (Section 4.1).

6. Why must a fault current be interrupted quickly? (Section 4.1.3).

7. Why must insulation be temperature rated? (Section 4.1.3).

8. Explain the process of "puncture" when considering an electrical insulating material? (Section 4.1.4).

9. What are the two results of insulation failure? (Section 4.2).

10. List five points which must be considered when selecting an insulation material? (Section 4).

11. List nine precautions that must be observed when testing the insulation resistance of an insulating material. (Section 5).

S. Rizvi
P. Nicholas

Notes

Electrical Equipment - Course PI 30.2

FUSES

OBJECTIVES

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

1. List, in writing, three ratings of a fuse and briefly explain each rating in a few sentences.

2. Given a fuse's characteristic curves, interpret curves and explain in writing, why these curves are referred to as inverse-time characteristic curves?

3. State, in writing, the difference between a fast-acting and a time delay fuse and give one application for each fuse type.

4. In two or three sentences, state two main advantages of HRC fuses.

5. Illustrate, with a simple sketch, the construction of an HRC fuse.

6. In three or four sentences, explain the term "co-ordination" as referred to in electrical circuit protection; using a simple sketch explain why co-ordination is necessary.

7. Select the appropriate fuse current rating, when given a motor specification and characteristic curves for a fuse.

1. Introduction

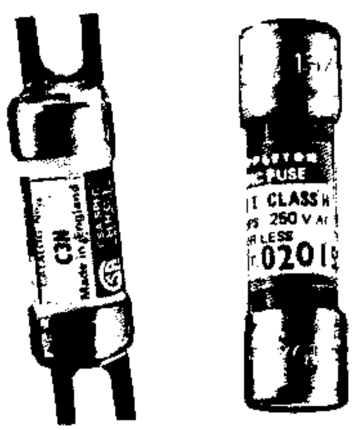
This lesson deals with:

(a) A fuse and its application.
(b) Fuse construction and specifications.
(c) Co-ordination and selection of fuse.

2. What is a Fuse

A fuse is a current sensitive device made of a conductor called an "element", surrounded by an arc quenching/heat conducting medium and is enclosed in a body fitted with endcaps. See Figure 1, below.

(a) High Rupture Capacity Fuse



(b) Cartridge Fuses

(c) Miniature, Glass Tube Fuse

(d) Plug Fuse

Figure 1: Commonly Available Fuse Types

3. Purpose of a Fuse

A fuse is a safety device. It provides safety to people and protection for equipment. A fuse is used to interrupt fault current, while allowing normal load current to pass.

The term "operation" of a fuse refers to the melting of the fuse element, or fuse blowing. When the current through the fuse reaches a point, where the heat produced by I^2R_F is sufficient to raise the element temperature to its melting point, the element melts and the fuse operates, or "blows". (R_F is the resistance of the fuse element and I is the current flowing through the fuse). At normal current, heat produced by I^2R_F is not sufficient to melt the element.

4. Fuse Ratings

Since the purpose of a fuse is to allow a normal load current to pass through and interrupt high fault currents, it has two current ratings:

(a) Continuous current rating: This means that the fuse element will not blow, age, deteriorate or overheat, if a current of up to 125% of rated capacity flows through the fuse.

(b) Interrupting current rating: This rating specifies the maximum fault current that the fuse can safely interrupt. Fuses normally "operate" from a minimum of 125% of continuous current rating, to the maximum specified interrupting current rating. This interrupting current rating can be as high as 200,000 amperes; depending on fuse type.

In addition to these two current ratings, there is also a voltage rating for the fuse.

(c) Voltage rating: After a fuse has "operated", or blown, arcing will not occur, internally or across the fuse terminals, if the fuse voltage rating is not exceeded. If the voltage rating of the fuse is lower than the voltage it is exposed to, arcing between the two ends may occur, the high fault current could continue to flow and the fuse could explode.

Fuse voltage ratings should always be equal to or greater than the circuit line voltage.

5. Fuse Construction

The basic parts of a fuse are:

(a) Fuse Element

It can be made of zinc, copper, aluminum, silver or silver alloy.

The cross sectional area of the element determines the current it is capable of handling. Element thickness, as well as, the type of material used, determine the melting point of the element.

(b) Fuse Body

It can be made of transparent glass, ceramics or fibreglass. The body should be able to withstand the mechanical forces and the heat produced during fuse "operation". As well, it must be able to provide proper electrical insulation between the two ends of the fuse, after the fuse element has blown.

(c) Endcaps and Terminals

Endcaps hold the element between the two ends of the fuse. Terminals are provided, in some high current fuses, for ease of installation.

End caps and terminals are made from copper to provide low resistance.

Screw-in type fuses are for 120V and currents of 30 amps or less. Applications of this type of fuse are normally found in the household. Screw type fuses have glass bodies with copper elements and screwends.

5. Fuse Construction (continued)

(a) Arc Quenching and Cooling

It is important to quench the arc as quickly as possible, when the fuse "operates". This is done in two ways:

(i) Create a vacuum in the fuse body. This also results in the elimination of element oxidation, thus improving fuse life.

(ii) Fill the fuse body with quartz sand which acts as a cooling agent, removes the air from the fuse, eliminates element oxidation and helps in arc quenching (by creating high resistance glass that is formed under high heat when the fuse element melts). This method is used in High Rupture Capacity (HRC) fuses.

6. Fuse Characteristics

A fuse operates when its element melts, due to the heat produced by I^2R_F. This heat produced increases as the current through the fuse increases. Hence, the fuse element melts faster for large fault currents, than for small fault currents. This time and current relationship of a fuse is referred to as the fuse characteristic. Figure 2 illustrates a typical set of characteristic curves for a fuse. These curves are very useful for:

(a) Selecting the degree of overload on a circuit.
(b) Co-ordination of other protective devices in the system.

How to interpret these curves will be discussed in the pages that follow.

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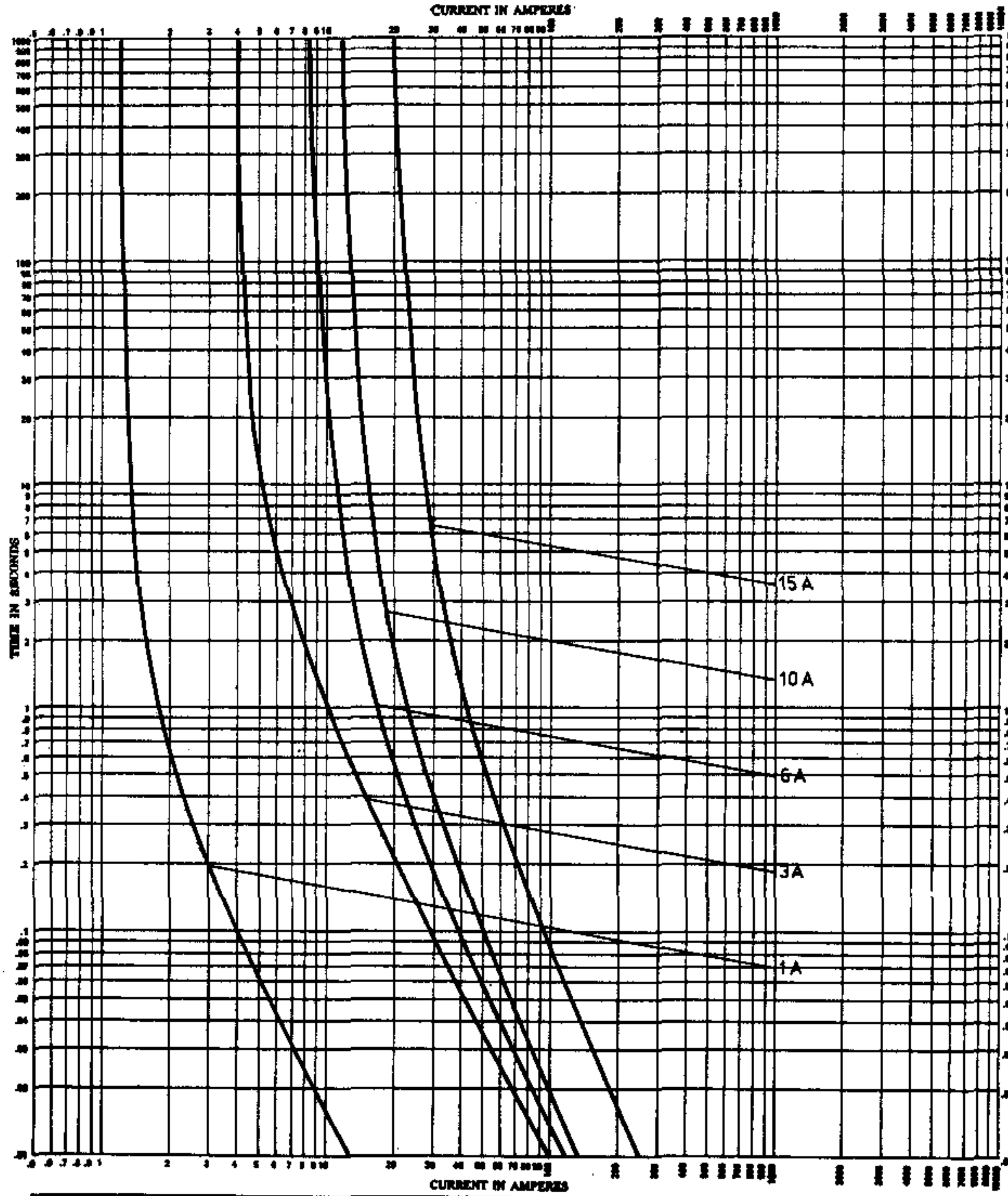

AVERAGE MELTING TIME-CURRENT CHARACTERISTIC CURVES

For TYPE HS-R 1-15A 600V Fuse Links, In OPEN

BASIS FOR DATA Standards CSA C22.2 No.106 Dated APRIL 1953

1. Tests made at .... Volts a.c at .... p.f., Starting at 25C with no initial load
2. Curves are plotted to AVERAGE Test points so variations should be ±5% IN CURRENT

No. TC-574
Date FEB. 1979

Cefco® Shawmut®
Gould Electric Fuse Division
Toronto, Canada

GOULD

Figure 2: Characteristic Curves for a Fuse

6.1 How to Interpret Fuse Characteristic Curves

Figure 3 shows the curves for 1-ampere, 3-ampere, 6-ampere, 10-ampere and 15-ampere fuses. Consider the 10-ampere fuse curve.

If 10-amperes of current is flowing through the fuse, it will never "operate", or blow.

If 30-amperes of current is flowing through this 10-ampere fuse, it will blow in approximately 0.4 seconds.

If 100 amprerea of current is flowing through this fuse, it will blow in approximately 0.02 seconds.

Hence, as the fault current increases, the time taken for the fuse to blow, decreases. This is why fuse characteristic curves are referred to, as inverse time characteristic curves.

7. Fast Acting and Time Delay Fuses

A fast acting fuse is one which operates "instantaneously", when the current rating is exceeded. This type of fuse is used on resistive loads or semiconductor circuits which can not tolerate excess current for any length of time.

However, it should be noted that "instantaneous" or fast acting fuses follow their time-current relationship shown in the characteristic curves, at the right. The term "fast acting" or "instantaneous" is misleading.

Time delay fuses are designed to carry 500% of the rated continuous current, for ten seconds, without blowing. They are used in motor circuits to allow for motor in-rush currents, which are typically about 6 times the normal full load motor running current.

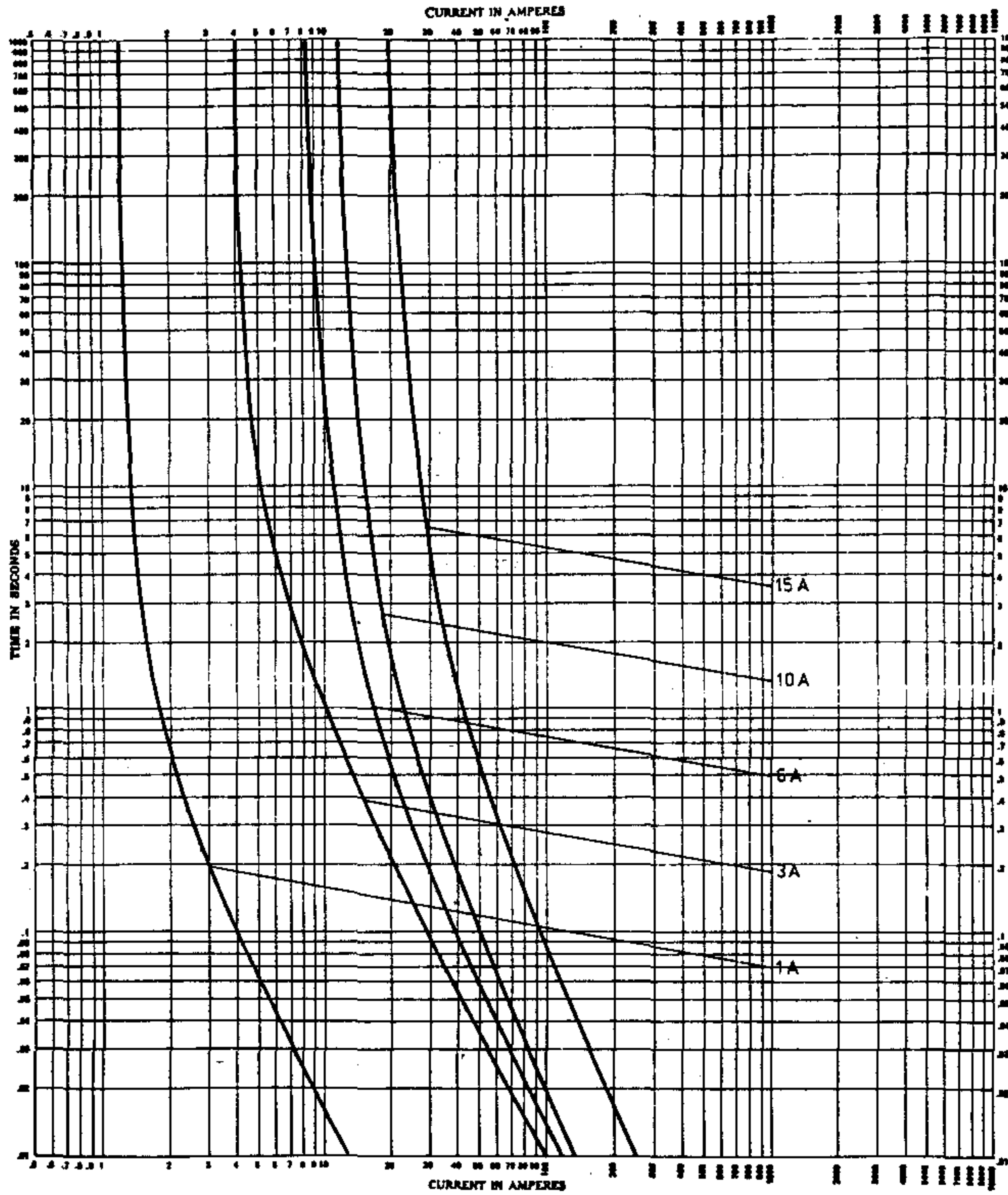

Figure 3: Characteristic Curve Example

8. High Rupture Capacity Fuses (HRC Fuses)

An HRC fuse is a type of fuse which can interrupt a high magnitude of fault current.

In power plants, HRC fuses are used extensively to protect buses, feeders and loads. The main advantages of HRC fuses are:

(a) It is a precision fuse whose operating characteristics are accurately known.

(b) It can interrupt a large magnitude of fault current.

8.1 HRC Fuse Construction

An HRC fuse is shown in Figure 4. Its construction consists of:

(a) The fuse element is made from silver or silver alloy, to improve fuse life and reduce the element resistance. Silver oxide is a good conductor of electricity. Hence, the fuse characteristics do not change appreciably over the installed life of the fuse. Also, the use of silver keeps element corrosion to a minimum.

(b) To improve reliability, the fuse element is notched. This ensures that the element will melt through at least one notch (possibly more), to quickly and cleanly, open the current path.

(c) The body of the fuse is made from ceramic or fibreglass. This provides good mechanical strength, high temperature stability and good electrical isolation between the two endcaps.

(d) The space, between the fuse element and the fuse body, is completely filled with silica sand, for the following reasons:

(i) It removes the air from inside. Hence, reduces oxidation of the element and improves the element life.

(ii) Provides cooling to the element, during the normal functioning of the fuse.

(iii) Acts as an arc quencher, by forming high resistance glass, when high heat is produced, during melting of the fuse element.

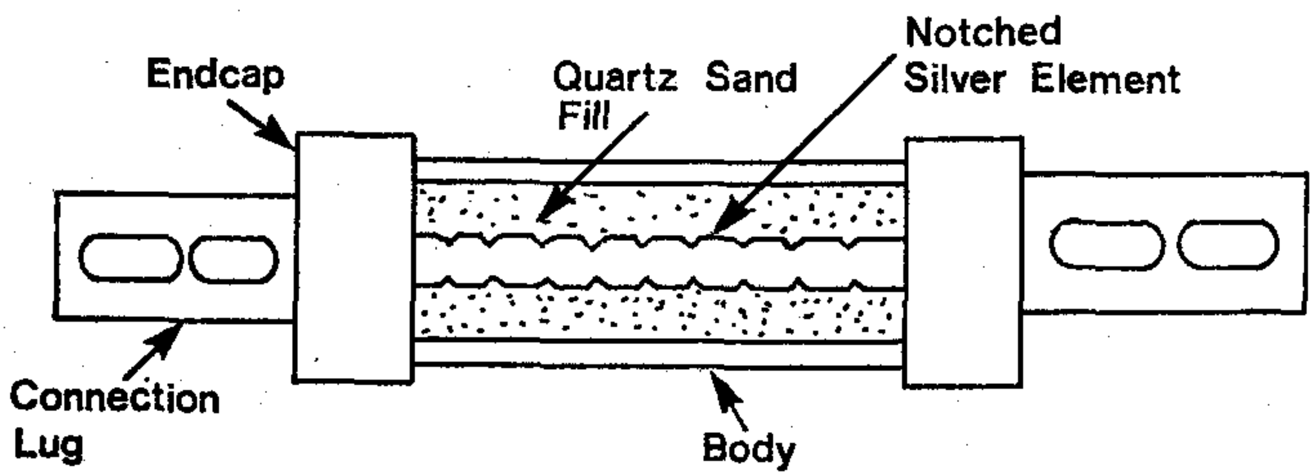

Figure 4: Internal Construction of an HRC Fuse

Note: If this fuse is only partially filled with silica sand, air could be inside the fuse. If the fuse "operates", this air will expand and may cause the fuse to explode. A partially filled fuse can be detected by shaking and listening for loose sand.

9. Co-ordination and Selection

9.1 Co-ordination

In an electrical distribution system, as shown in Figure 5, it is important that only the "load-side" fuse operates, when the fault is in the loadside. If a fault at the load causes the main supply fuse, or even a bus fuse, to operate, then it will result in unnecessary blackout and expensive down time for other loads, which are not at fault. To ensure that this does not happen, co-ordination between all the fuses, in the distribution tree, is necessary. This is done by calculating the fault current, at each step, and selecting a proper fuse accordingly.

Refer to Figure 5. From the transformer to the aluminum bus duct, there are impedances of the cables and the buses themselves. These impedances will progressively reduce the short circuit current. If a fault occurs at bus A, then it is desirable that only fuse F_1 blow. This prevents power interruption to any load connected to bus B. If a fault occurs on bus B, then only F_2 should blow, but not F_3.

In order to achieve the above co-ordination, it is required that the interruption current and "operate" time of F_2 be higher than the interruption current and time of F_1. The interruption current and time of F_3 should be higher than the interruption current and time of F_2.

Calculations involved in this process are beyond the scope of these notes. Detailed information can be found in the IEEE Buff Book, "Recommended Practice for Protection and Co-ordination of Industrial and Commerical Power Systems".

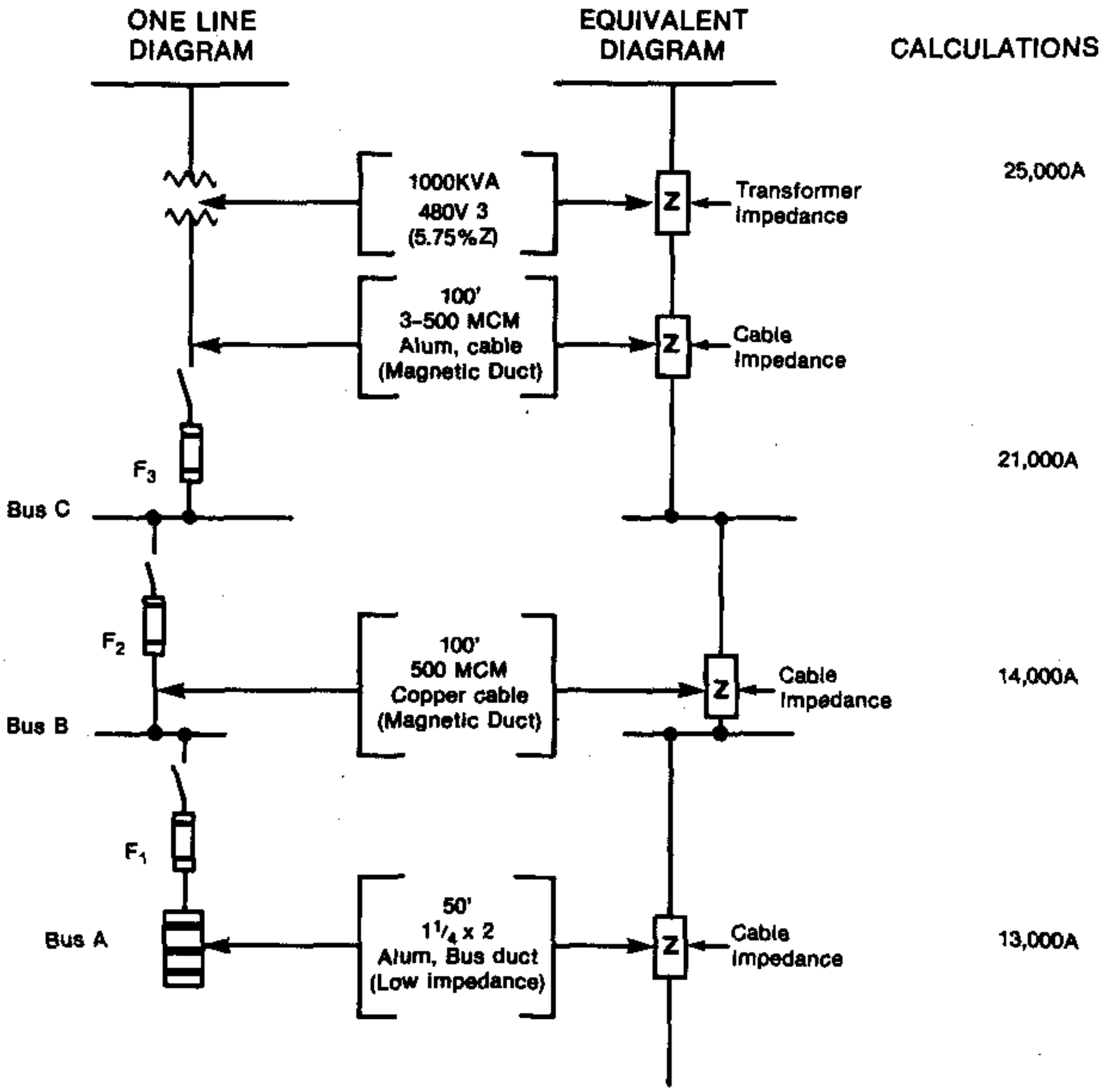

Figure 5: Distribution Tree Co-ordination

9.2 Fuse Selection For a Motor

A motor draws about six times the normal full load current, when it is started under load. The fuse, which is there to protect the motor under short circuit conditions, **must allow this high in-rush current, of the motor, to pass** .

Consider a motor whose full load current is 6 amperes and the motor takes one second to accelerate to its normal running speed.

Motor starting current = 6 x I_{FL} = 6 x 6 = 36-amperes

Motor acceleration time = 1 second.

Assume that a 6-ampere fuse is selected from Figure 6. For a 6-ampere fuse at a 36-ampere fault current, it will take 0.15 seconds to blow.

Since the motor takes one second to accelerate, the fuse will blow before the motor has fully accelerated.

However, if a 15-ampere fuse is selected, at a fault current of 36-amperes, the 15-ampere fuse would take about 2 seconds to blow. Therefore, the motor would have sufficient time to accelerate to its rated speed. Using this 15-ampere fuse, the motor can accelerate to its operational speed without blowing the fuse.

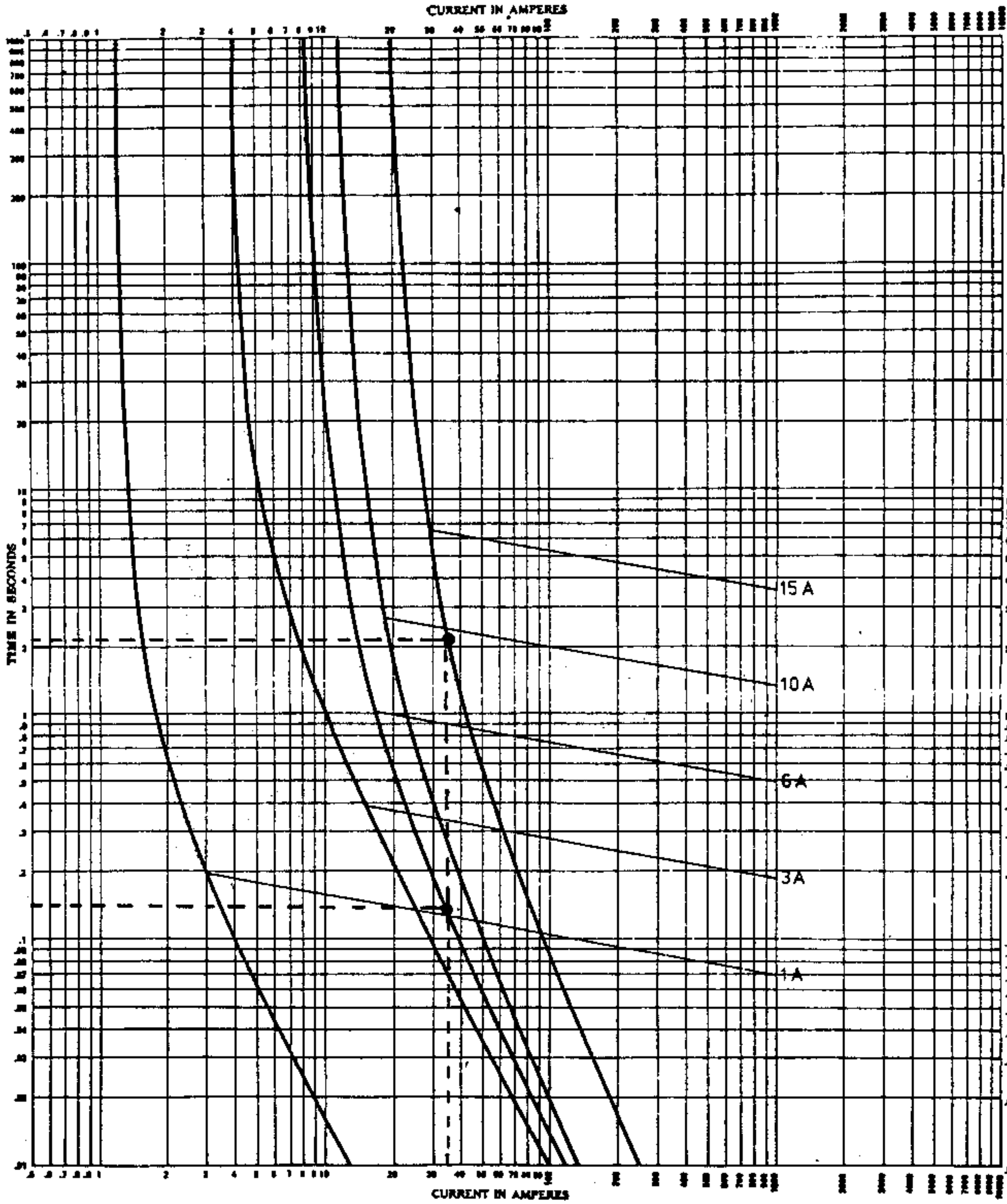

Figure 6: Fuse Selection for Motor Example

ASSIGNMENT

1. Explain what a fuse is and what purpose it serves. (Sections 2 and 3)

2. List the three ratings of a fuse and briefly explain each rating. (Section 4)

3. Explain what is meant by inverse time characteristics of a fuse. (Sections 6 and 6.1)

4. Explain what is meant by "fast acting" and "time delay" fuses. Give one application of each. (Section 7)

5. In an HRC fuse: (Section 8 and 8.1)

   (a) State two main advantages of an HRC fuse.

   (b) Give three functions for the quartz sand.

   (c) Why is the element made of silver or copper?

   (d) What is the consequence of installing an HRC fuse which has partial filling of quartz sand?

6. Why is it important to have fuse co-ordination in a distribution tree? Briefly explain how it is achieved. (Section 9.1)

7. Full load current of a motor is 50A and it takes three seconds to accelerate. For this motor, use Figure 7 and:

   (a) Locate the in-rush current on the graph.
   (b) How long it will take for the 70A fuse to blow at this in-rush current?

   (c) Can this fuse be used for the motor protection? If not, why? Recommend a proper fuse from the various fuses shown in Figure 7. (Section 9.2)

   Answers: (a) 300
   (b) .7 seconds
   (c) 100 Amp Fuse

S. Rizvi

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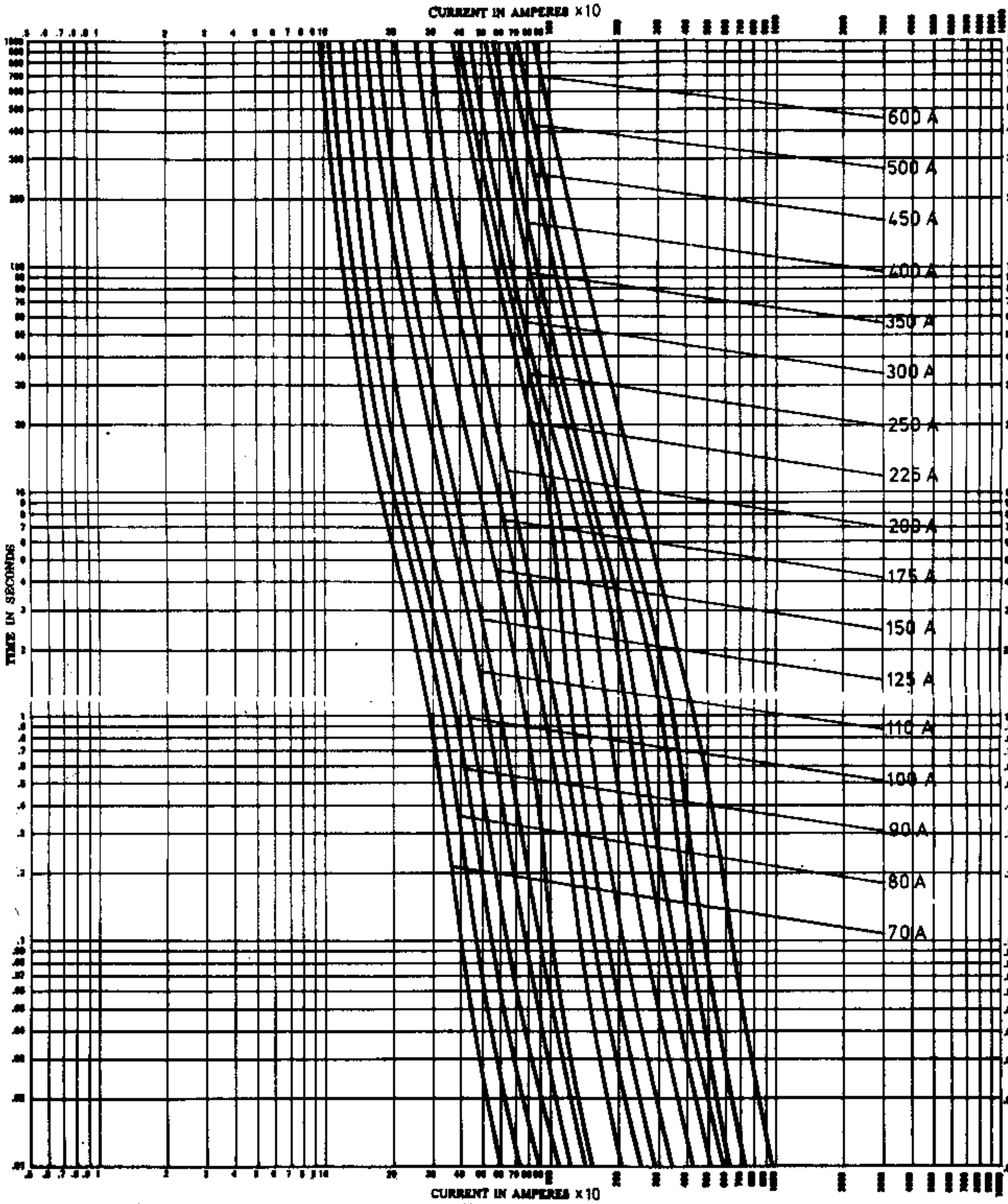


AVERAGE MELTING TIME-CURRENT CHARACTERISTIC CURVES
For TYPE CJ 70-600A 600V HRC1 Fuse Links, In OPEN
BASIS FOR DATA Standards CSA C22.2 No. 106 Dated APRIL 1953
1. Tests made at .... Volts a-c at .... p.f., Starting at 25C with no initial load.
2. Curves are plotted to AVERAGE Test points so variations should be ±5% IN CURRENT

No. TC-570
Date FEB. 1979

Figure 7: Fuse Characteristic Curves

Electrical Equipment - Course PI 30.2

DISCONNECT SWITCHES AND CIRCUIT BREAKERS

OBJECTIVES

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

1. Briefly state, in a few sentences, why a disconnect switch is only used for isolation of electrical circuits.

2. State, in writing, the common voltage range for which the following circuit breakers are used in NGD:
   a) Air
   b) Air blast
   c) Vacuum
   d) Oil
   e) Sulphur Hexaflouride (SF_6)

3. For an air circuit breaker:
   a) List, in writing, the three sets of contacts used.
   b) Discuss briefly, in three or four sentences, the purpose of each set of contacts.
   c) Discuss briefly, in three or four sentences, what metal is used to make each set of contacts and why.
   d) In point form, list the sequence of operation for opening and closing the breaker.

4. Briefly explain in writing, the terms list below, as applied to a circuit breaker.
   a) Voltage rating;
   b) Continuous current rating;
   c) Interrupting current rating;
   d) Interrupting capacity.

5. In writing, list the advantages and disadvantages of:
   a) Air circuit breaker;
   b) Air blast circuit breaker;
   c) Oil circuit breaker;
   d) Vacuum circuit breaker;
   e) SF_6 circuit breaker.

6. In three or four sentences, differentiate between the two types of air blast circuit breaker.

7. Briefly, in writing,identify the type of air blast circuit breaker used at Bruce N.G.S. A & B and state how additional isolation is provided and why.

8. Briefly, explain, in writing, the purpose of the interrupting and isolating contacts on a non-pressurized type circuit breaker.

9. If given a simplified diagram, list, in writing, the opening sequence for a fully pressurized type of air blast circuit breaker.

10. Briefly, explain in writing, and using simple diagrams how the arc is quenched in an:
    a) Air blast circuit breaker;
    b) Oil circuit breaker.

1. Introduction

This lesson will introduce the reader to:

(a) Standard electrical symbols.
(b) HV disconnect switch and its purpose in NGD.
(c) Circuit breakers; their ratings and their purpose.
(d) Types of circuit breakers used in NGD.
(e) Advantages and disadvantages of each type of circuit breaker.

2. Disconnect Switch

2.1 Electrical Symbols

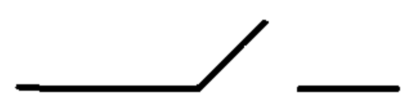


Figure 1(a): Disconnect Switch Manually Operated

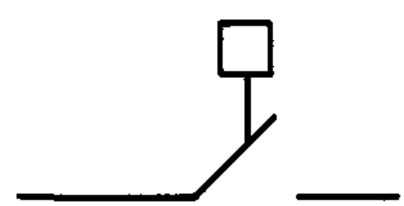


Figure 1(b): Disconnect Switch Motor Operated

2. Disconnect Switch (continued)

2.2 Construction and Operation

The current carrying parts of the disconnect switch are mounted on insulators. The switch operation is based on lever action. Figure 2 shows a HV disconnect switch.

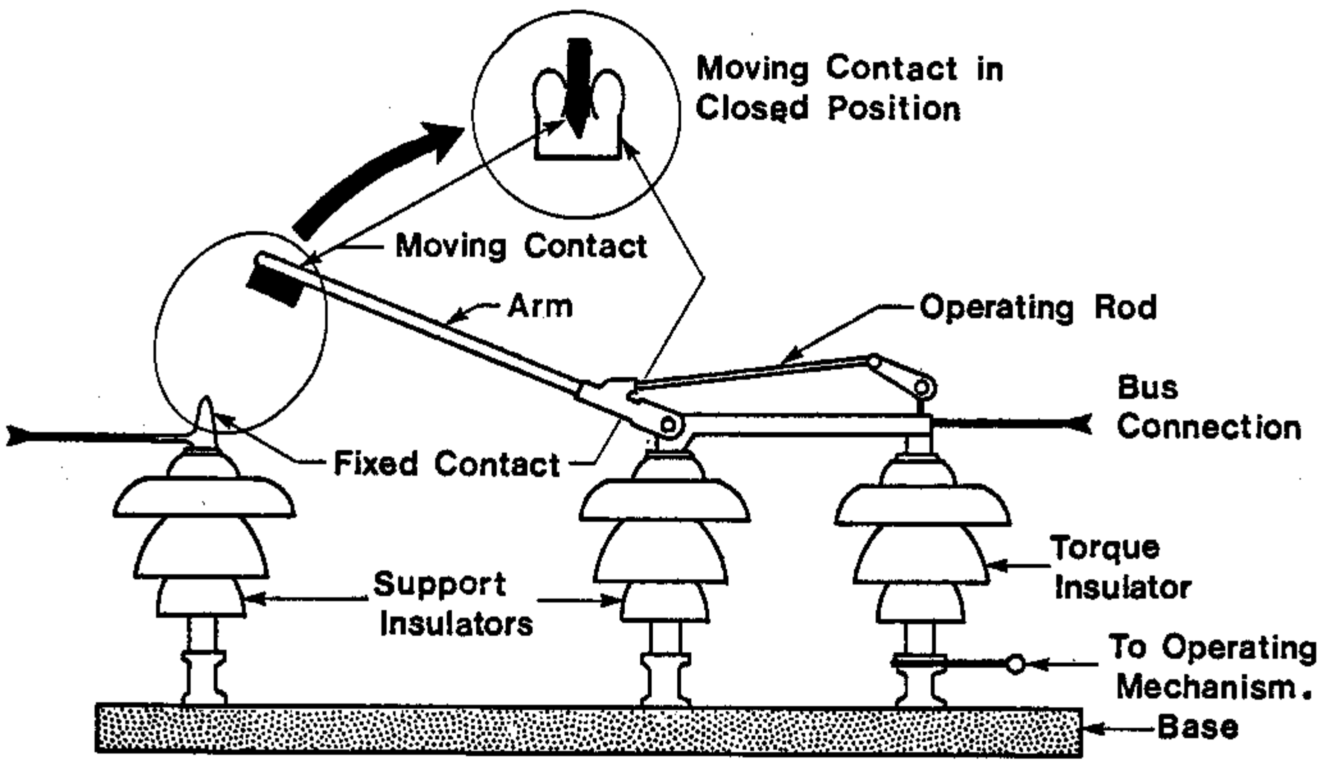


Figure 2: HV Disconnect Switch

To open (or close) the switch, the operating mechanism is operated by a hand wheel or a motor (not shown). This turns the torque insulator and causes the operating rod to pull (or push) the moving contact arm, for the opening (or the closing) of the disconnect switch. HV disconnect switches:

(a) are not capable of making or breaking the load or fault currents because they have no arc quenching mechanism.

(b) are used for isolation purposes only and are quoted as such on work permits in NGD.

3. Circuit Breakers

3.1 Electrical Symbols

Circuit Breaker
(Manual)

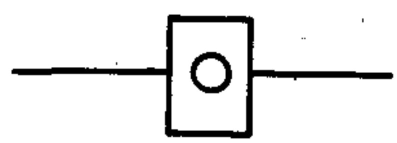
Figure 3(a)

Circuit Breaker
(Rack Out Type)

Figure 3(b)

Circuit Breaker
(Electrically Operated)

Figure 3(c)



Power Circuit Breaker
(Above 15kv)

Figure 3(d)

Figure 3

3.2 Circuit Breaker Types

Circuit breaker types are classified, depending on the medium of arc quenching used. Table 1 lists the various types of circuit breakers used in NGD. Listed, also, are some typical operating parameters for each breaker type.

Circuit Breaker Types

Table 1

Type of Breaker	Arc Extinguished by	Medium of Arc Quenching	Remarks
Air	Arc contacts and arcing horns operating in air.	Air	Used in NGD for voltages up to and including 13.8kV.
Air Blast	A blast of compressed air	Air	Used in NGD for high voltages, 115kV 230kV and 500kV.
Oil	Oil	Oil	Uses in NGD at 115kV, 230kV
Vacuum	Vacuum	Vacuum	Used at BHWP at 2.4kV.
Sulphur Hexa-fluoride (SF_6)	SF_6	SF_6	Gaining acceptance by OH. Available in range of voltages up to 500kV.

Notes

3.2.1 Air Circuit Breakers

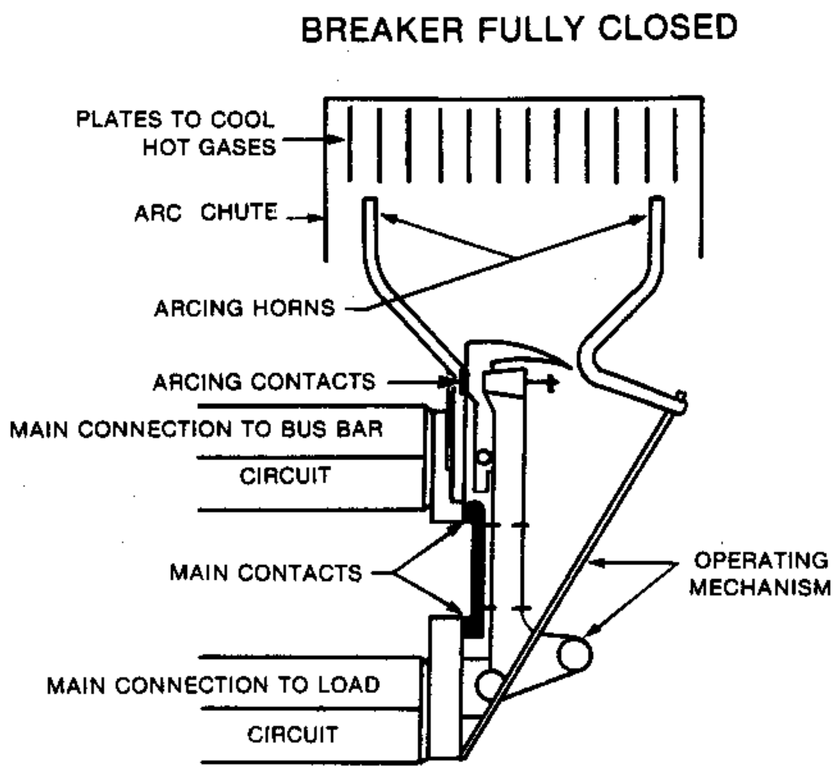


Figure 4(A): Breaker Fully Closed

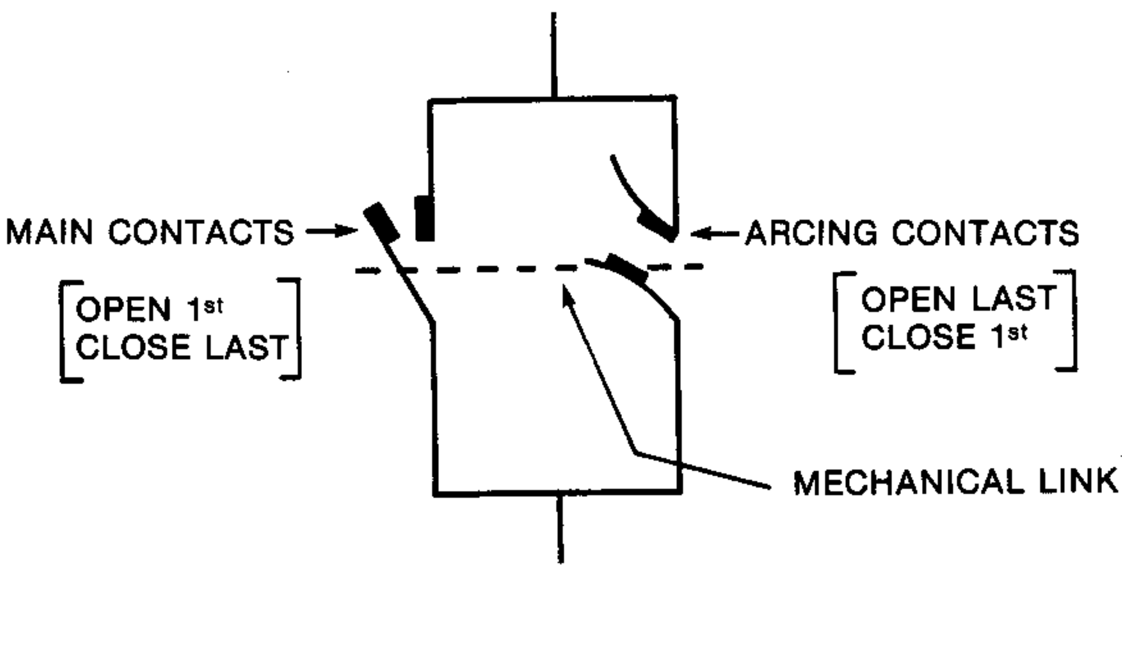


Figure 4(B): Breaker Contacts Opening

3.2.1 Air Circuit Breakers (continued)

(a) Construction

Each phase of a 3 phase air circuit breaker consists of three types of contacts, namely; main contacts, arcing contacts and the arcing horn. Their operating mechanisms are shown in Figure 4(A).

(i) The main contacts carry the load current under normal operation. Main contact resistance, at the point of contact, must be low to prevent overheating, when current is flowing through it. The main contacts are therefore made of a good conducting material such as copper, silver or copper with silver plating. Since these metals have relatively lower melting points, they can be damaged if arcing occurs. To prevent this damage, the main contacts do not make or break the current.

(ii) Arcing Contacts

Since no arcing must occur at the main contacts, arcing contacts are provided, which make or break the circuit current. This causes the arcing to occur at the arcing contacts. These contacts are constructed of a harder material with a higher melting point (eg. tungsten). Arcing contacts and the main contacts are connected in parallel, as shown in Figure 4(B).

(iii) Arcing Horns

Arcing horns are made from hard copper. After the arc is established on the arcing contacts, it is transferred to the arcing horns during the opening of the arcing contacts. Their shape is designed to stretch and weaken the arc.

(iv) Arc Chute

The arc chute is a cooling chamber located at the top end of the breaker. It cools the hot gases which are produced when arcing occurs.

(v) Operating Mechanism

The operating mechanism is designed to actuate the moving parts of the air circuit breaker during the opening or closing operation. The operating mechanism can be operated manually or electrically

3.2.1 Air Circuit Breaker (continued)

(by energizing a close coil for closing or a trip coil for opening). The push button controls for the electrical operation of circuit breakers may be located in the control room.

(b) Operation

To understand the sequence of operation of various contacts in the air circuit breaker, one must realize that arcing must never occur at the main contacts.

(i) Opening Cycle

Refer to Figure 5.

When the breaker is closed, the load current passes through the low resistance main contacts. See Figure 5(a).

As the breaker opens, the main contacts open first, transferring the current to the arcing contacts. See Figure 5(b).

The arcing contacts open and an arc is established across them through the air medium. See Figure 5(c).

As the arcing contacts continue to open, the arc is transferred to the arcing horns. The arc rises to the top of the arcing horns. This is because hot gases rise due to the convection principle. At the same time the arc is being lengthened, the arc enters the arc chute, see Figure 5(d), where it is rapidly cooled by the cooling plates. Cooled gases are deionized and cannot conduct electricity, and consequently the arc is extinguished.

(ii) Closing

For the breaker closing cycle, the arcing contacts touch first, making the circuit. The main contacts close a short time afterwards, completing the closing operation.

3.2.1 Air Circuit Breaker (continued)

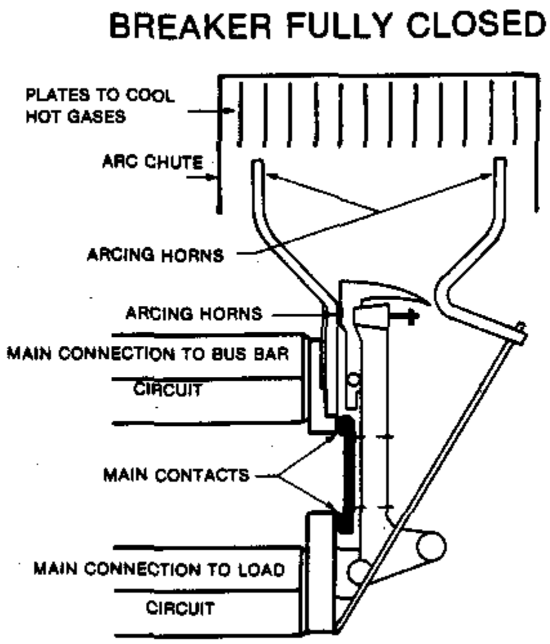


Figure 5(a)

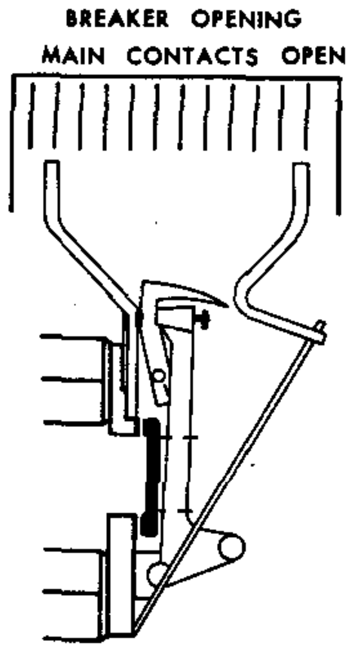


Figure 5(b)

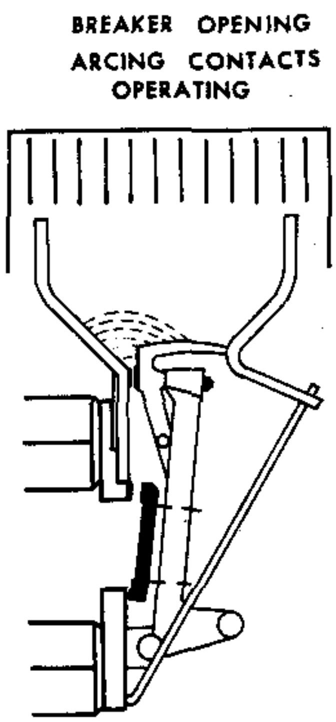


Figure 5(c)

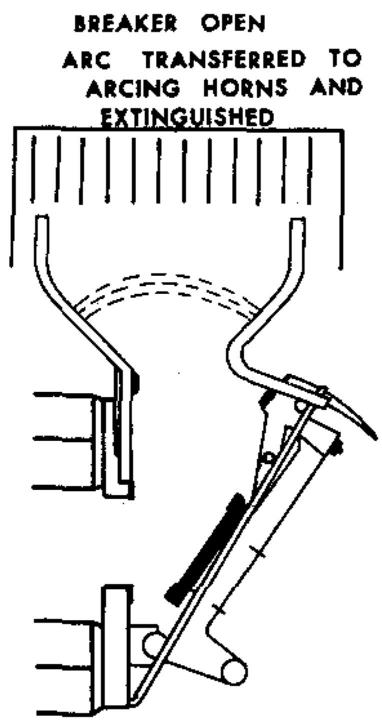


Figure 5(d)

Figure 5: Air Circuit Breaker Operating Sequence

3.2.2 Circuit Breaker Ratings

In common with fuses, circuit breakers also have three basic ratings. They are:

(a) Voltage Rating

Breakers are supplied by the manufacturer to operate at a specified voltage. This voltage rating indicates the maximum application voltage, at which arcing will not occur between the contacts, when the circuit breaker is open.

(b) Continuous Current Rating

Breakers are constructed to operate continuously at a specified value of load current. The current carrying components are designed to be able to carry the load current continuously, without overheating.

(c) Interrupting Current Rating

This is the mazimum fault current which can be safely interrupted. A breaker must have the capability to interrupt a large value of short circuit or fault current without damage. Typically, the fault current is 20 times the continuous current rating. Because of the large amount of heating associated with 20 times normal current, it follows that the breaker can only be subjected to this value of current, for a very short time. Therefore, the breaker must be able to rapidly clear a fault or short circuit. Typical fault clearance times are 5 to 8 cycles, at 60 Hz (80-100 milliseconds).

In addition to the three basic ratings as mentioned, theinterrupting capacity rating of a circuit breaker is sometimes mentioned. (ie - the MVA rating)

$$\text{Interrupting Capacity [MVA]} = \sqrt{3} \times \frac{\text{Rated Voltage [KV]} \times \text{Rated Interrupting Current [KA]}}{10^6}$$

(Do not memorize)

3.2.3 Advantages and Disadvantages of Air Circuit Breakers

Advantages

(a) Relatively inexpensive.
(b) Simple construction.
(c) Simple maintenance requirements.

Disadvantages

(a) Normally limited to a maximum voltage rating of 15kV.
(b) Normally limited to an interrupting capacity of about 1000MVA.

Type of Circuit Breaker	Nominal Voltage Class	Nominal Three Phase Interrupting Capacity (rounded off)	I Continuous	I Interrupting
Air	13.8kV	890MVA	2000	37.5kA
	4.16kV	208MVA	2000	29kA
	600V	43MVA	1600	42kA
	600V	25MVA	600	25kA
Airblast	230kV	25000MVA	2500	63kA
	500kV	69000MVA	4500	80kA
Oil	242kV	26000MVA	3000	63kA

Typical Rating of Air, Air Blast & Oil Circuit Breakers Used at NGD

Table 2

3.3 Air Blast Circuit Breaker

The medium used to extinguish the arc created in airblast circuit breakers is a blast of very dry, clean air, at a high pressure. The air pressure is high enough to actually open or close the contacts.

3.3.1 Types and Construction

There are two types of air blast circuit breakers:

(a) Fully Pressurized Type

In this type, the moving contacts after opening, are kept open by maintaining the air pressure in the main chamber (interrupting head). The contacts in this type of breaker make or break the line current and also provide isolation, provided no loss of air pressure occurs. However, if air pressure is lost the contacts will close and a disasterous situation may occur. To prevent this, a motorized disconnect switch is used to ensure that isolation is safely maintained under all circumstances. This type of breaker is used at Bruce NGS "A" & "B". Figure 6 shows a simplified diagram of this type of circuit breaker. Figure 6 is repeated in Figure 7 and the major breaker components are identified.

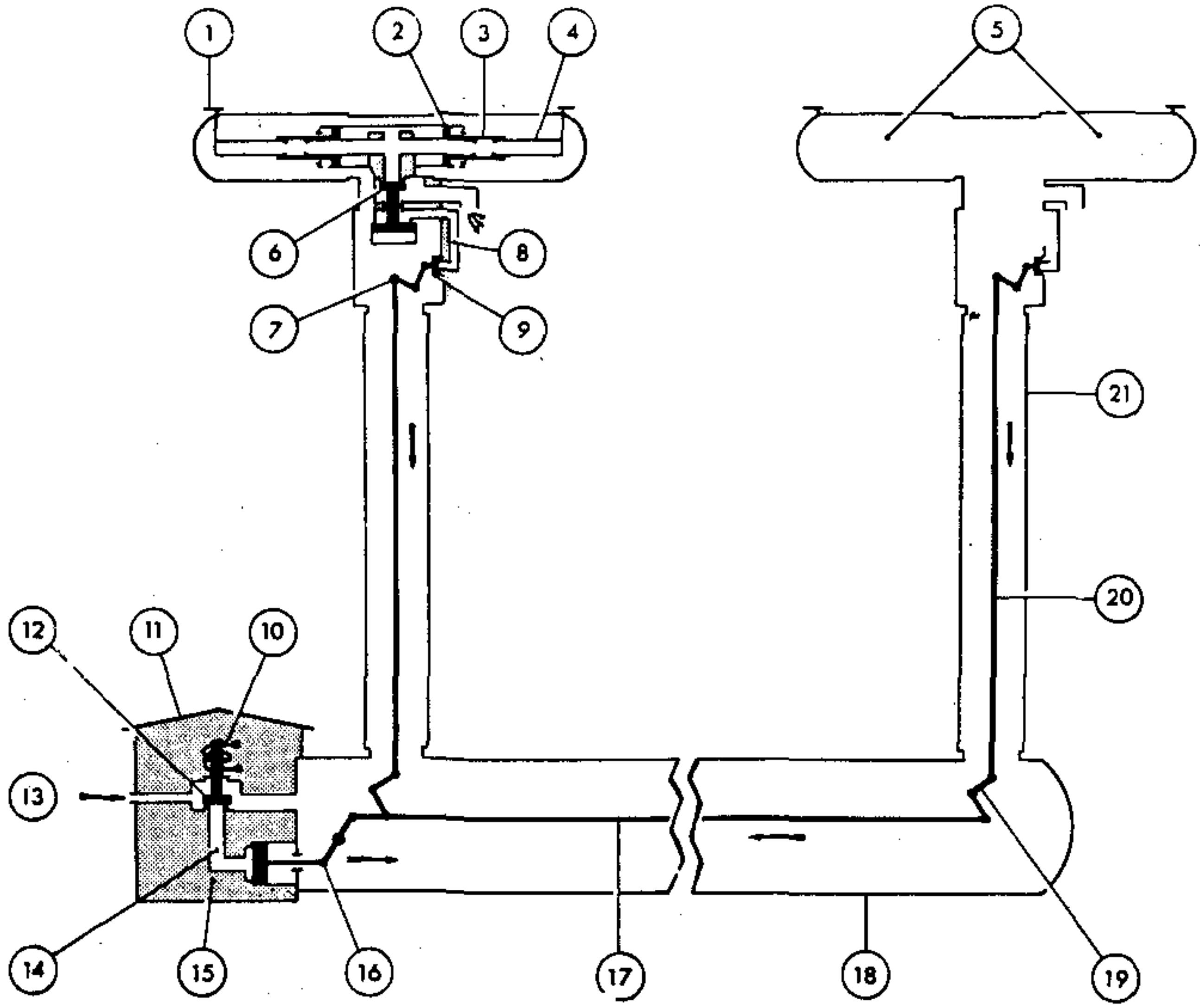


Figure 6: Air Blast Circuit Breaker - Fully Pressurized Type

3.3 Air Blast Circuit Breaker

(a) Fully Pressurized Type (continued)

The circuit breaker is shown in a closed position. The closing and tripping mechanisms are identical. To simplify the diagram, only the tripping mechanism is shown.

Figure 8 is a chart which identifies various breaker components. (Do not memorize diagram).

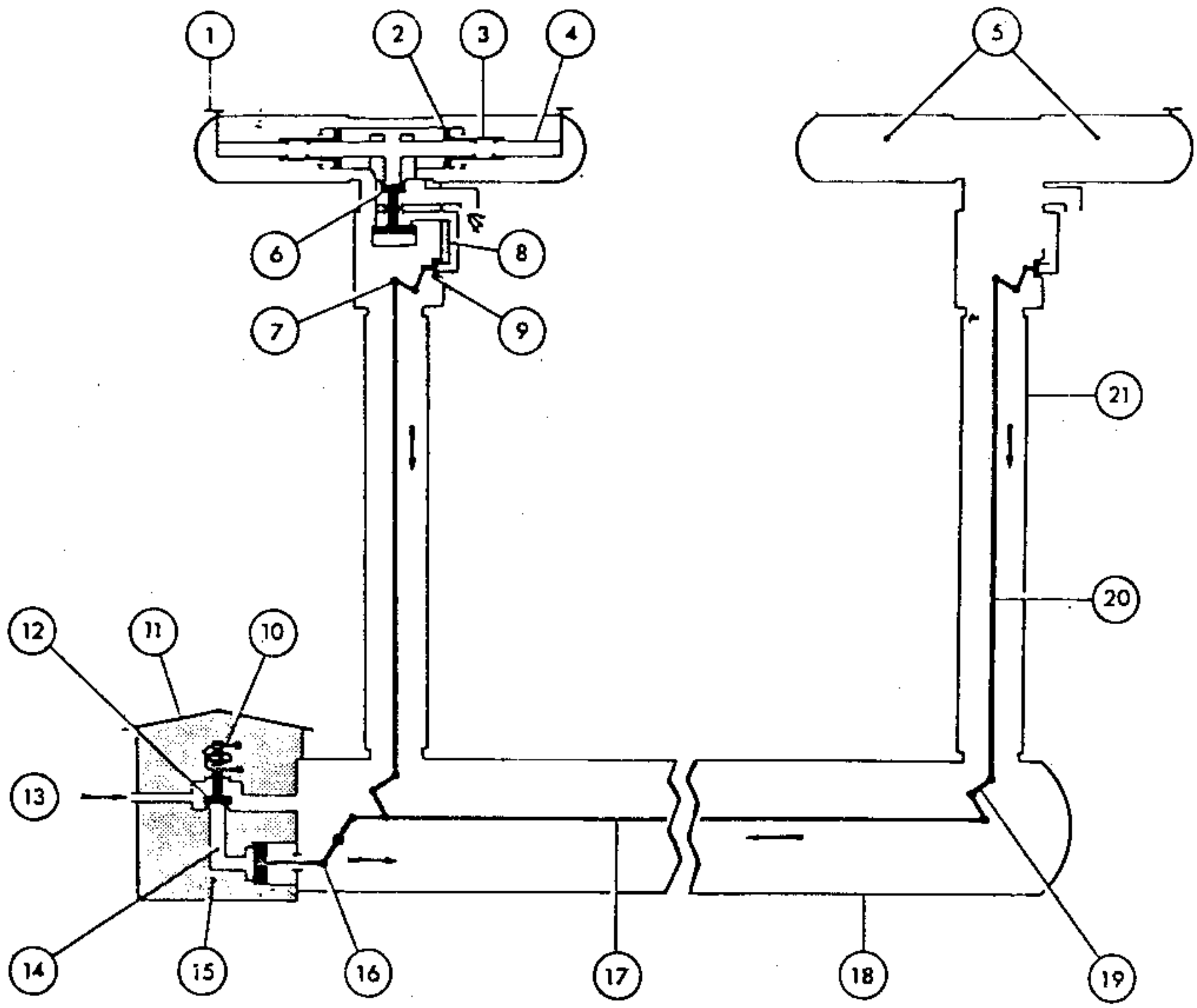


Figure 7: Air Blast Circuit Breaker - Fully Pressurized Type

Item	Designation
1	Terminal
2	Moving contact piston (see 3)
3	Moving contact of main chamber
4	Fixed contact of main chamber
5	Main chamber (extinguisher chamber)
6	Tripping control valve
7	Upper countershaft
8	Control valve channel (see 6)
9	Pilot valve of control valve (6)
10	Electro-valve
11	Single-pole control cubicle
12	Pilot valve of pneumatic control block
13	Intake of compressed air
14	Rod control channel (see 16)
15	Pneumatic control block
16	Rod control system
17	Horizontal metallic rod
18	Frame-tank
19	Lower countershaft
20	Vertical insulating rod
21	Insulting supporting column

Figure 8: Fully Pressurized Type Air Blast Circuit Breaker Components.

3.3 Air Blast Circuit Breaker

3.3.1 Types and Construction (continued)

(b) Non-pressurized Type

In this type of air blast circuit breaker, the fault current is interrupted by the contacts in the interrupting heads and the isolating heads, but isolation is maintained only by the isolating contacts. The isolation contacts are an integral part of the circuit breaker. Figure 9 shows such a circuit breaker.

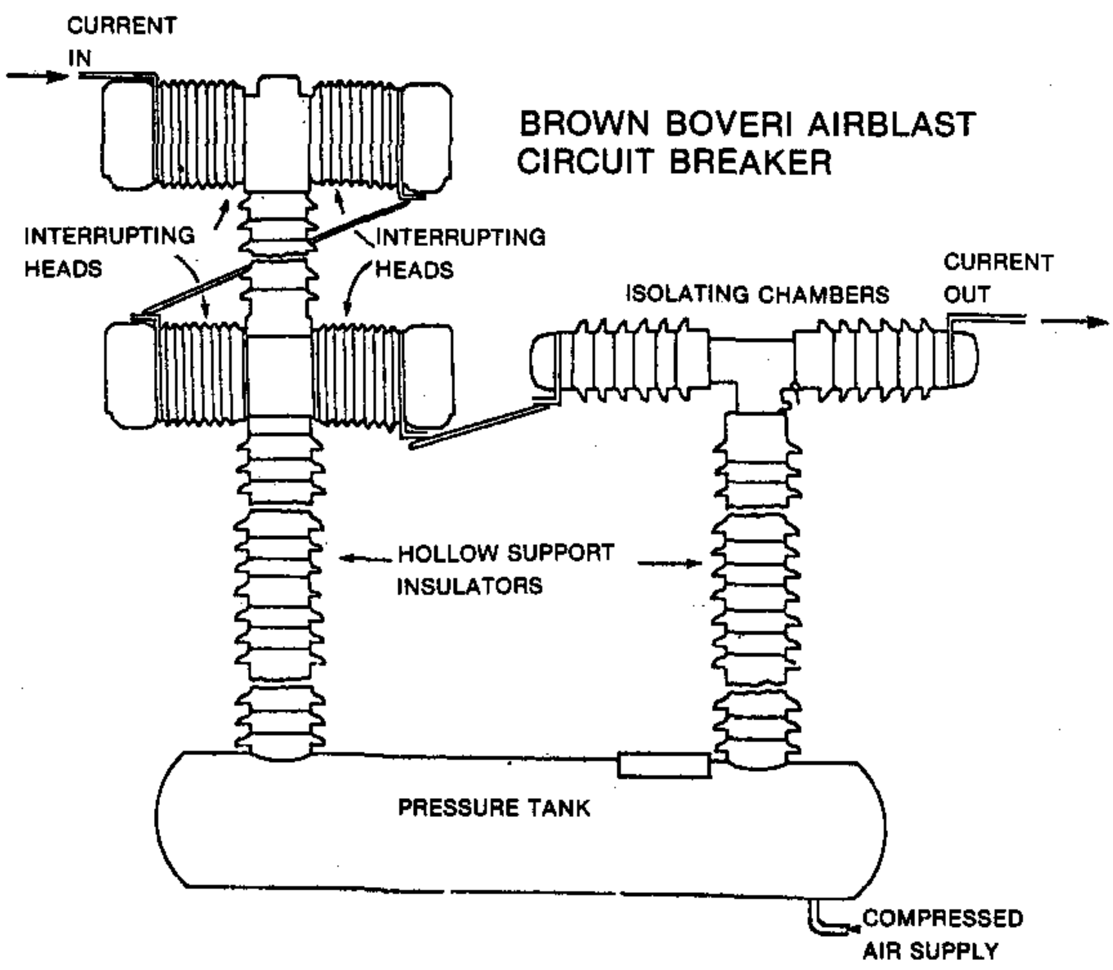


Figure 9: Non-Pressurized Air Blast Circuit Breaker

3.3.2 Operation of Fully Pressurized and Non Pressurized Air Blast Circuit Breakers

The operation of both of these circuit breaker types can be reviewed in Appendix A, which is situated at the end of this chapter. While reviewing this material, the reader should appreciate that both designs incorporate complex air pressurizing systems resulting in necessary extensive and costly maintenance. Other points worthy of note are discussed in the next section.

3.3.3 Advantages and Disadvantages of Air Blast Circuit Breakers

Advantages

(a) By connecting several breaker heads in series the voltage rating of the breaker can be increased.

(b) By careful design, the interrupting capacity rating can be increased to over 50,000 MVA.

(c) Fast clearance of fault currents. Breakers used at Bruce NGS can clear a fault within 2 cycles.

Disadvantages

(a) Expensive.

(b) Complicated construction, requiring air receivers and high pressure pipework.

(c) Maintenance is time consuming, as access is difficult.

(d) A supply of **very dry**, compressed air is required to ensure no condensation or ice formation on the insulators or contacts.

(e) The breaker, when opened, unless fitted with silencers, is very noisy and consequently cannot be used in built-up residential areas.

3.4 Oil Circuit Breakers

3.4.1 Construction

Refer to Figure 10 for the following discussion.

(a) Tank

Houses the electrical contacts, insulated pot and the oil.

(b) HV Bushings and Connectors

HV bushings are insulators made of ceramics. They prevent short circuiting between the current carrying conductors and the tank. HV connectors are the conductors which are conneced to the power lines, via disconnect switches.

(c) Electrical Contacts

Electrical contacts have two parts:

(i) Fixed contact.
(ii) Moving contact.

The fixed contacts are stationary and do not move. The moving contacts can be moved by an operating rod, sometimes referred to as a push-and-pull rod. The operating rod is actuated by an electrically driven, opening and closing mechanism that has both local and remote (control room) controls.

(d) Pots

The pots enclose the electrical contacts, holding them in the arc cooling oil. The pots are made of insulating material and also act as a pressure chamber when the arc is developed. Breather holes are provided in the pots to allow fresh oil to enter the pot.

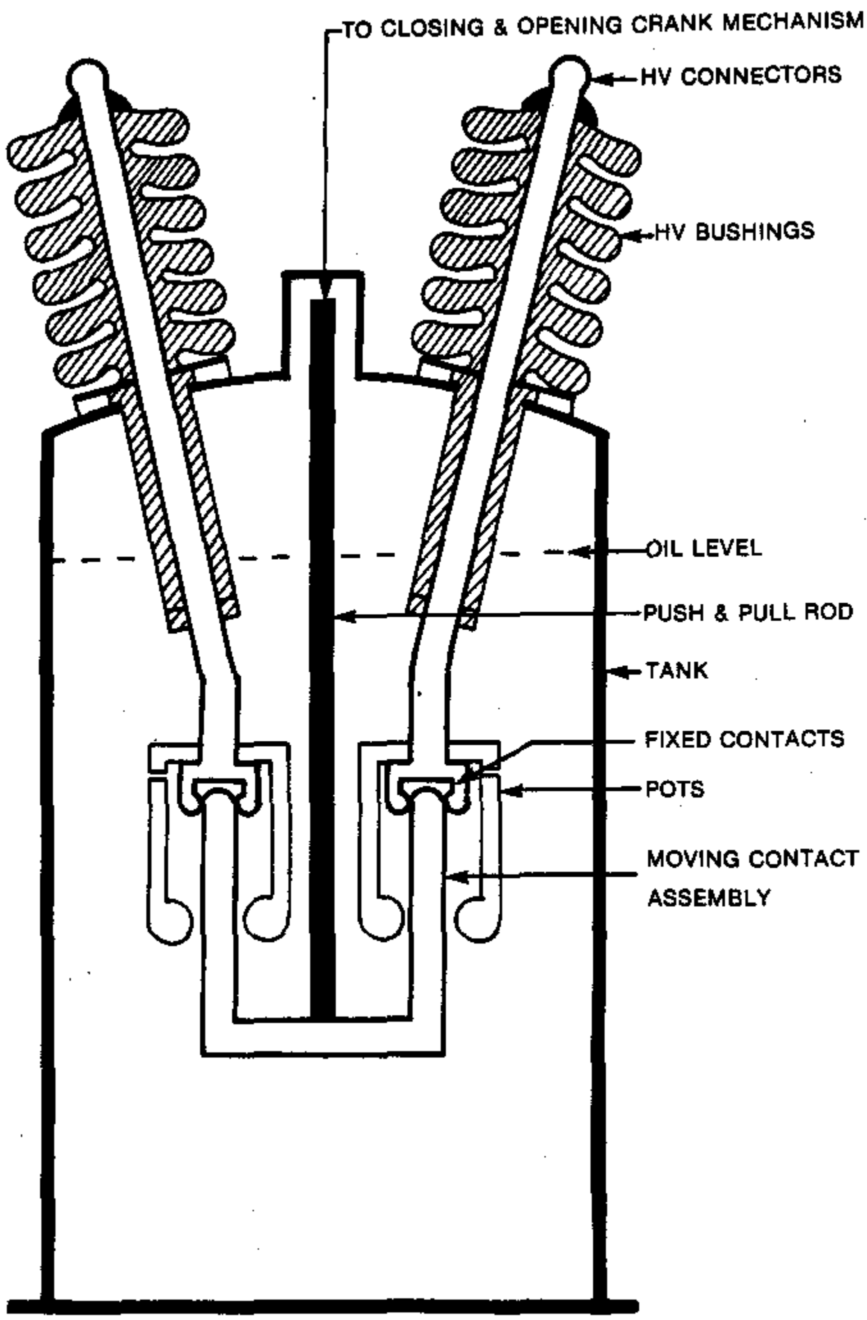


Figure 10: High Voltage Oil Circuit Breaker - Shown in the CLOSED Position

3.4.2 Operation

Refer to Figure 11(a) and 11(b). In Figure 11(a) a breaker pot is shown with the moving contact in the closed position. When a fault occurs or when it is required to open the breaker, an electrical signal is given to the operating mechanism causing the crank mechanism to move forwards. This action causes the moving contact to move away from the fixed contact and an arc is developed.

The process of arc extinguishment in an oil circuit breaker is as follows:

(a) As the moving contact moves away from the fixed contact an arc is developed.

(b) High temperature arc causes the oil in the pot to break down and form gas.

(c) Production of gas pressurizes the pot. Hence, oil in the pot is forced past the electrical contacts and provides cooling. This extinguishes the arc.

(d) Cool, fresh oil from the tank enters the pot, via breather holes.

(e) Gases produced, recombine into oil, or become dissolved in it.

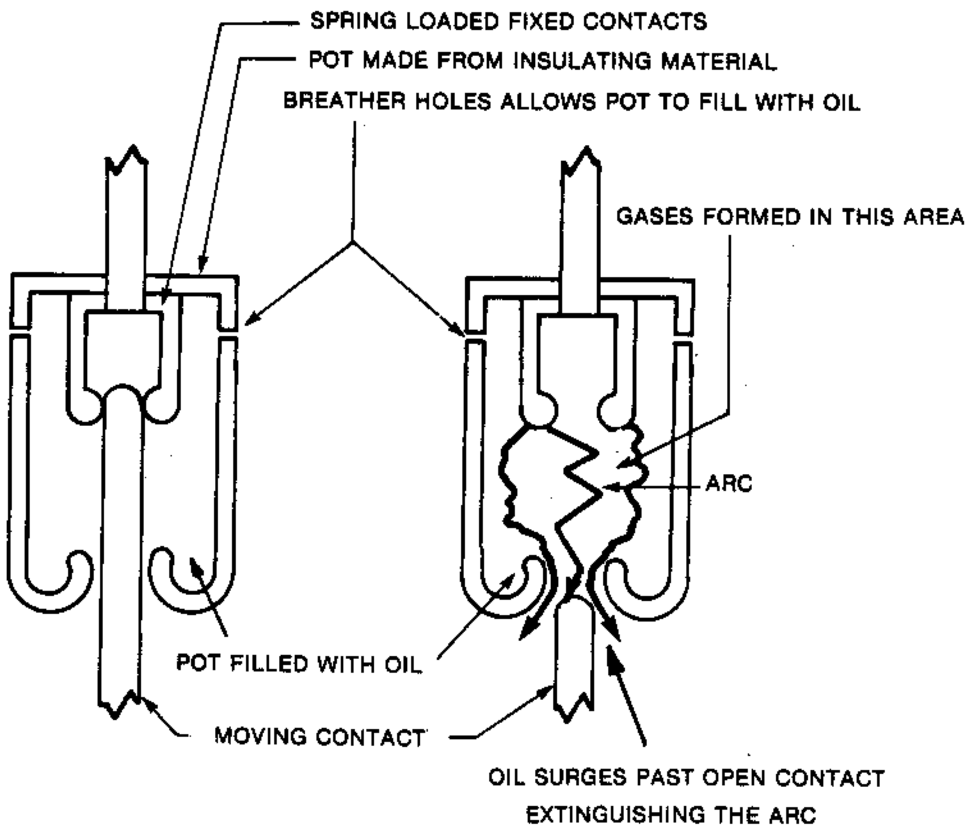


Diagram Showing An Oil Breaker Pot With Contacts in the Closed Position

Figure 11(a)

Diagram Showing How the Arc is Extinguished in an Oil Circuit Breaker

Figure 11(b)

3.4.3 Advantages and Disadvantages of Oil Circuit Breakers

(a) Advantages

(i) By connecting several interrupting mechanisms in series, the voltage rating of the breaker can be increased.

(ii) By careful design the interrupting capacity rating can be increased up to 26,000 MVA.

(iii) Quiet operation.

(b) Disadvantages

(i) The breaker contains flammable oil, consequently it should be located outdoors.

(ii) Oil breakdown at high temperatures forms carbon which gets dissolved in the oil. This increases the oil conductivity. To keep the oil insulating properties at an acceptable level, it must be purified after a predetermined number of breaker operations. This requires oil treatment equipment on site.*

(iii) may become an environmental hazard if spillage occurs.**

* Oil purification standards for the breakers are the same as for the transformer oil.

** Askerol is both an environmental and a health hazard.

Notes

3.5 Vacuum Circuit Breakers

3.5.1 Construction and Operation

A vacuum circuit breaker consists of a sealed vacuum "pot" or flask which contains the contacts. A vacuum provides the insulation and arc extinguishing medium. The moving contact is moved by some moving mechanism and the arc is extinguished at the first "crossing of current" through zero amplitude. Figures 12 and 13 show a vacuum circuit breaker in the OPEN and CLOSED positions, respectively. This design is relatively new and gaining acceptance.

3.5.2 Advantages and Disadvantages of Vacuum Breakers

(a) Advantages

(i) Small size.

(ii) Requires little maintenance as they are "sealed for life".

(iii) Can be operated many tens of thousands of times before replacement is required.

(b) Disadvantages

(i) Loss of vacuum can be dangerous and difficult to detect.

(ii) Normally, no repairs can be done to the breaker. Faulty units are usually discarded.

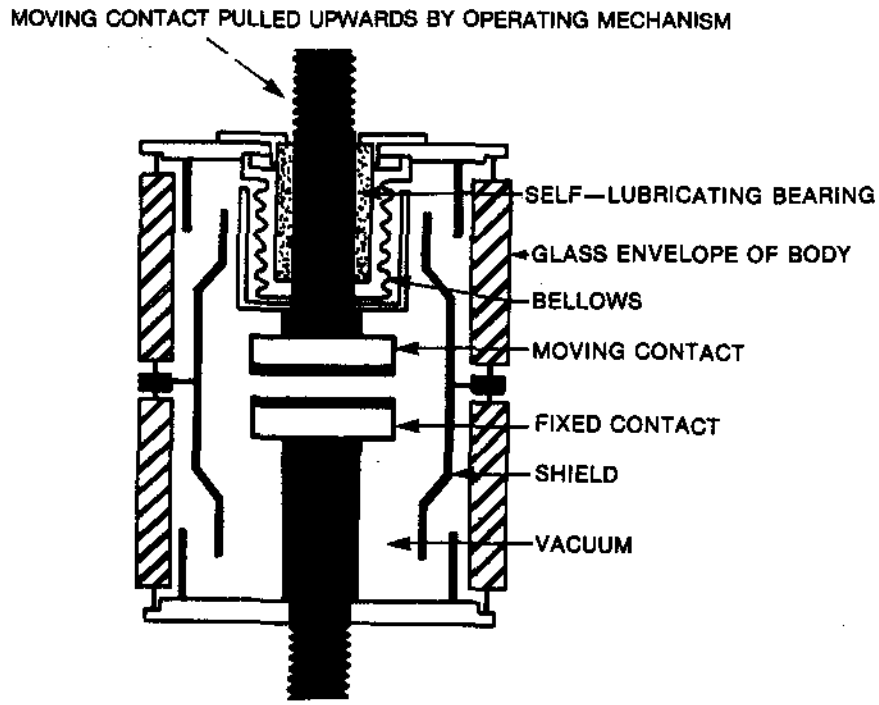


Figure 12: Vacuum Breaker: Open Position

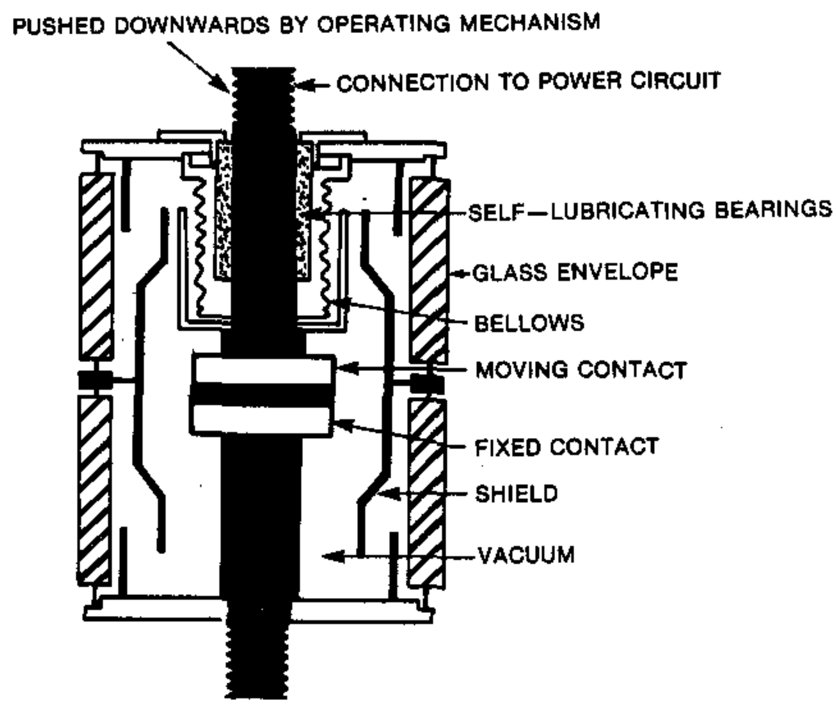


Figure 13: Vacuum Breaker: Closed Position

3.6 Sulphur Hexa Floride (SF_6) Circuit breaker

3.6.1 Construction and Operation

SF_6 gas is a very stable compound. It has high insulating qualities and good interrupting properties. SF_6 gas is inert, nonflammable, non toxic and odorless. It is used as an arc quenching medium in circuit breakers up to 500 kV.

The SF_6 has high pressure gas which blasts out at the electrical contacts when the breaker is opened. Since the gas is at high pressure, to prevent liquification of the gas, a gas heater is provided. High arc temperatures cause the gas to decompose into atoms, electrons and ions. However, most of it recombines quickly. Before the gas is recompressed, it is filtered, by passing it through activated aluminum to remove gaseous florides.

Figure 14 shows a 230 kV, SF_6 circuit breaker.

3.6.2 Advantages and Disadvantages

(a) Advantages

(i) Relatively smaller size.

(ii) Can be housed in a building to complement the area (environmentally desirable).

(iii) High interrupting capacity.

(b) Disadvantages

(i) Expensive.

(ii) Relatively new development.

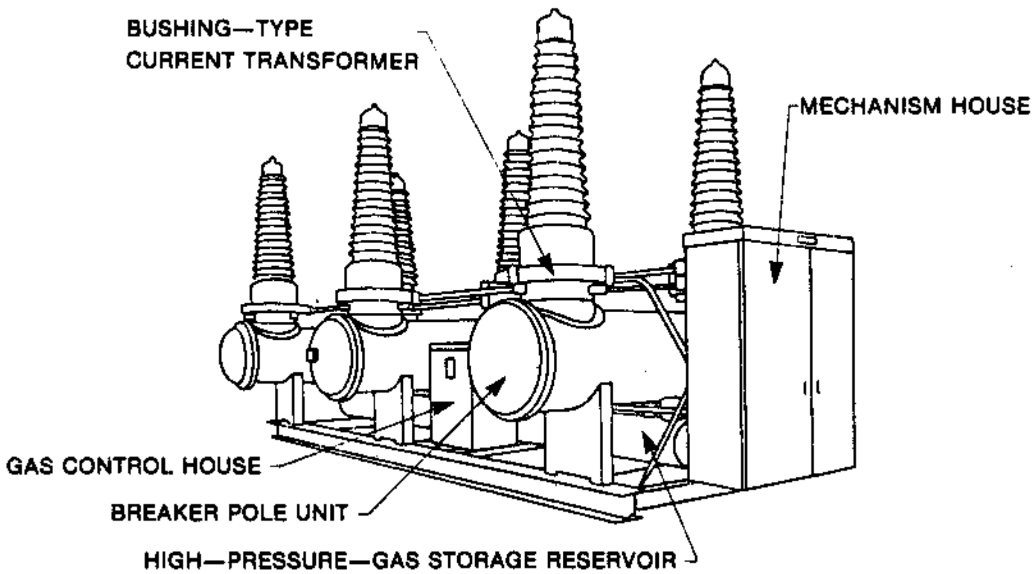


Figure 14: 150kV Sulphur Hexa-Floride (SF_6) Circuit Breaker

ASSIGNMENT

1. Can a disconnect switch be used for making or breaking a fault or load current. Explain (section 2.2).

2. What is the purpose of a disconnect switch in Ontario Hydro applications? (Section 2.2)

3. Complete the following table: (Table 1)

Circuit Breaker	Medium Used for arc Quenching	Voltage at Which it is used in NGD
Air		
Air Blast		
Vacuum		
Oil		
SF_6		

4. For an air circuit breaker:

   (a) List the three sets of contacts used. (Section 3.2.4)

   (b) Give the purpose of each set of contacts. (Section 3.2.1)

   (c) For each set of contacts, what metal is used to make them and why? (Section 3.2.1)

4. For an air circuit breaker (continued):

   (d) List the sequence of operation for opening and closing cycle. Section (3.2.1, ii)

5. What do the following ratings of a circuit breaker mean: (Section 3.2.2)

   (a) Voltage rating

   (b) Continuous current rating

   (c) Interrupting current rating

   (d) Interrupting capacity.

6. List three advantages and two disadvantages of an air circuit breaker. (Section 3.3.3)

7. List two types of airblast circuit breakers and briefly explain what the difference between them is. (Section 3.3.1)

8. For the two types of air blast circuit breakers which are used at Bruce N.G.S. and what additional isolation feature is provided along with them and why? (Section 3.3.1, a and b).

9. What is the purpose of interrupting contacts and of isolating contacts in a nonpressurized air blast circuit breaker? (Section 3.3.1, b).

10. List three advantages and five disadvantages of an airblast circuit breaker. (Section 3.3.3, a,b,)

11. Using diagrams explain how the arc is quenched in an oil circuit breaker. (Section 3.4.2).

12. List three advantages and three disadvantages of an oil circuit breaker. (Section 3.4.3)

13. List the advantages and disadvantages of:
    (a) a vacuum circuit breaker (section 3.5.2).

    (b) SF_6 circuit breaker (Section 3.6.2)

14. Complete the following table by indicating which piece of equipment is suitable for each of the three functions listed. Also state any constraints which may limit that piece of equipment in a specific function. (if any).

Equipment	Interrupt Current	Isolation	Protect Against Fault Current
Fuse			
Disconnect Switch			
Circuit Breaker			

S. Rizvi

Notes

Appendix A

Fully Pressurized Type

Refer to Figure 1. The main chambers (5) are permanently pressurized because they are connected directly to the air tank (18) via the insulating support column. Piston (2) drives the moving contacts (3). Normally, the pressure on the two sides of the piston (2) is the same. Piston (2) is actuated by creating a difference of pressure, between its two faces.

Sequence of Operation

(a) Opening Cycle

An opening signal to the coil of electro-valve (10) causes the opening of pilot valve (12).

Pressure is then established in the channel (14) to actuate the piston controlling the rod assembly (16).

The movement of the piston causes the horizontal metal rods (17) to be pulled, as well as the vertical insulating rods (20), through the counter shafts (19).

On being pulled, the rods (20) open the pilot valve (9). Pressure is then established in the channels (8) and on the piston of each of the opening control valves (6) causing them to open. There is one opening control valve in each main chamber.

As the valves (6) open, the inside of the tubular moving contacts (3) is open to the atmosphere, as well as the annular space on the rear face of the pistons (2).

The pressure on the front face of the piston (2) is greater than the rear face. This causes the contacts to open.

(b) Closing Cycle

For the closing of this type of air blast circuit breaker, there is another set of valves called closing valves (not shown). The principal of operation is similar to the opening cycle, except the closing value will exit the other side of the piston (2) to atmosphere.

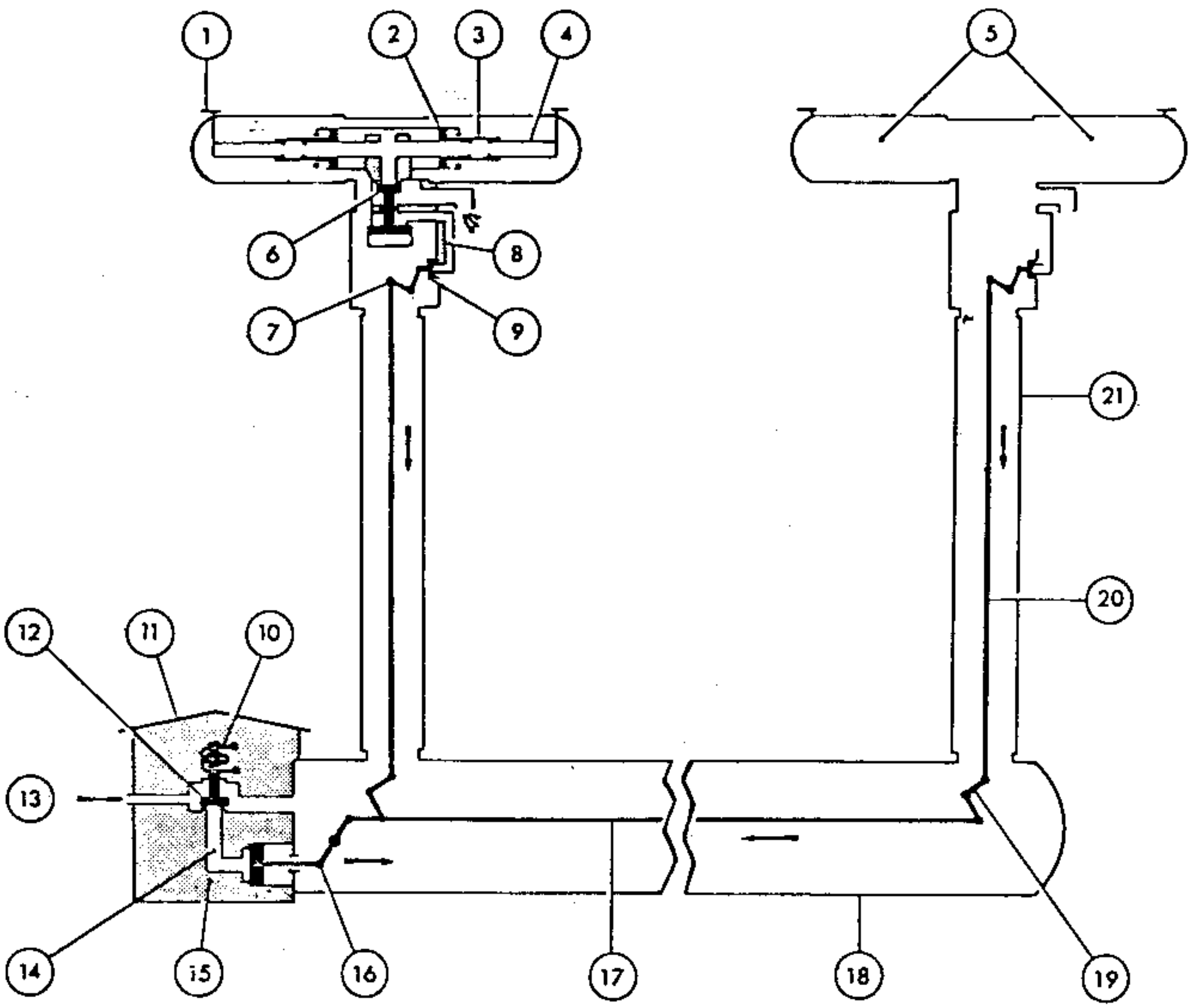


Figure 1: Air Blast Circuit Breaker - Fully Pressurized Type

The circuit breaker is shown in the closed position.

Non-Pressurized Type

Sequence of Operation

Figure 2 shows the operation of this type of circuit breaker. Each interrupting head contains a fixed and a moving contact.

(a) Opening Cycle

An electrical signal to the blast valve opens the valve. Air pressure acts on the lower part of the moving contact and depresses the spring causing the moving contact to move in the cavity. Figure 2(B) shows the interrupting head of an AECB in closed position.

As the moving contact moves away from the fixed contact and arc is developed, Figure 2(C).

A blast of air from the air reservoir rushes past the moving contact and provides cooling. This extinguishes the arc, Figure 2(D).

After the contacts in all of the interrupting heads are open the isolating head contact opens. After the isolating contact has opened, the interrupting contacts reclose. Circuit isolation is maintained by the isolation contacts remaining open.

(b) Closing Cycle

To close a non-pressurized type of air blast circuit breaker, only the isolation contacts need to be closed (with an air blast). Isolation contacts, as well as the interrupting contacts are designed to make or break large currents.

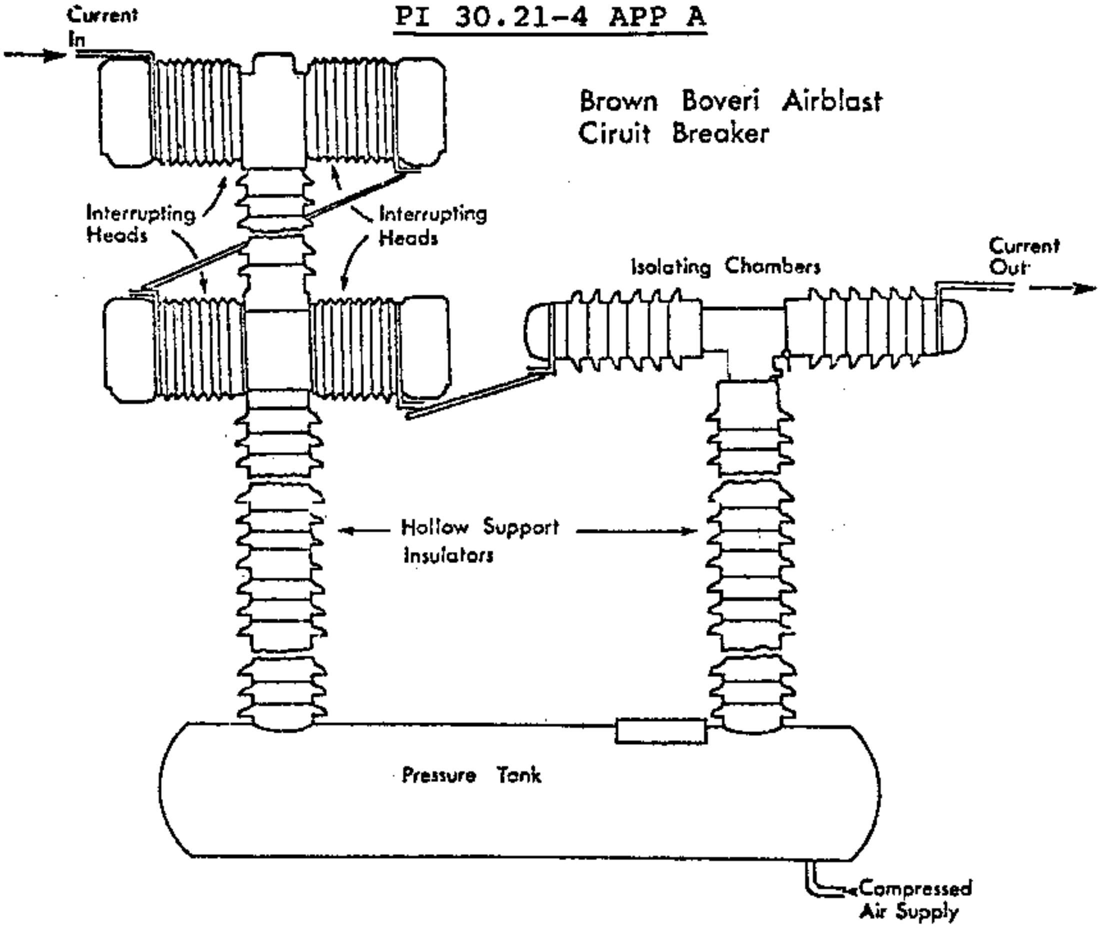


Figure 2(A): Non-Pressurized Air Blast Circuit Breaker

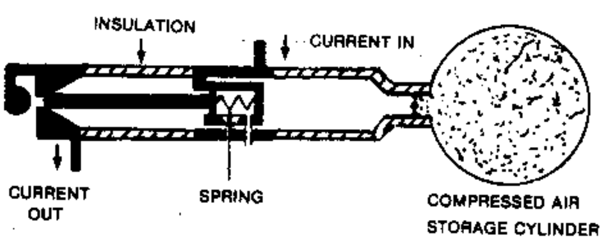


Figure 2(B)
Contacts: Closed

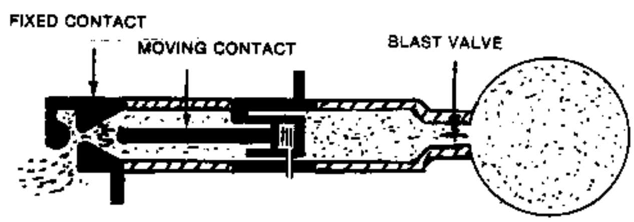


Figure 2(C)
Contacts: Open

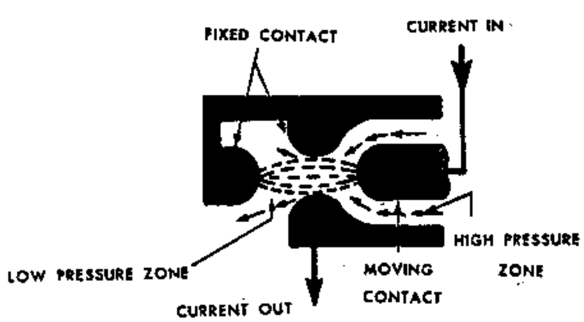


Figure 2(D): Air Blast Extinguishing An Arc

Figure 2: Non-Pressurized Air Blast Circuit Breaker

Electrical Equipment - Course PI 30.2

TRANSFORMERS

OBJECTIVES

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

1. Briefly explain, in writing, the terms "hysterisis loss" and "eddy current loss".
2. Recall, in writing, two factors which make it necessary for a transformer to be cooled.
3. Briefly, state, in writing, two consequences of insufficient cooling in transformers.
4. Given a diagram, identify and briefly explain in one or two sentences the purpose of each component in a power transformer.
5. Briefly state, in writing, the methods used for the cooling of transformers.
6. In writing, identify which transformers within NGD, use oil-water heat exchanger cooling.
7. Briefly explain, in writing, the operation of an oil-water heat exchanger type of cooling system.
8. a) Recall, in writing, one problem which may occur with an oil-water heat exchanger type of cooling system;
   b) Explain, in writing, what causes this problem to develop and how it can be eliminated.
9. Recall, in writing, two advantages and two disadvantages of using mineral oil for transformer cooling.
10. Recall, in writing, four contaminations which may occur in transformer oil.
11. Briefly explain, in writing, how each of four contaminants affects transformer performance.
12. Briefly explain, in writing how each of four contaminants in transformer oil is detected.
13. Briefly, in writing, explain the function of a tap changer and how a tap changer performs this function.
14. If given a tap changer schematic and a set of voltage variations, select the correct tap to be used.

1. Introduction

This lesson will introduce the reader to:

(a) A short review of transformer theory.
(b) Methods used for the cooling of transformers.
(c) A sectional view of a power transformer.
(d) The common problems associated with transformer insulating oil and the their respective detection methods.
(e) Tap changers.

2. Transformer Theory Review

For a detailed discussion on transformer theory, refer to the PI 263 course notes.

$$\text{Turns ratio (a)} = \frac{\text{Primary number of turns } (N_1)}{\text{Secondary number of turns } (N_2)} = \frac{\text{Primary Voltage } (V_1)}{\text{Secondary Voltage } (V_2)}$$

$$= \frac{\text{Secondary current } (I_2)}{\text{Primary current } (I_1)}$$

Total core loss = Eddy current loss + Hysteresis loss. Core loss is a constant quantity. It does not vary with changes in the load current.

$$\text{Total copper loss} = \text{Primary copper loss}(I_1{}^2R_1) + \text{Secondary copper loss}(I_2{}^2R_2)$$

Copper loss is not a fixed quantity, it changes with the load current.

3. Transformer Cooling

3.1 Why Cooling is Needed

In the transformer, heat is produced by the following two factors:

(a) Core loss (considered to be fixed).
(b) I^2R loss, which is also referred to, as copper losses. The I^2R loss changes as the load current changes.

If the heat produced by the above two factors is not removed effectively then:

(i) insulation failure will occur, or
(ii) transformer will have to be derated to prevent damage to the transformer.

Since both of these circumstances mentioned are undesirable, effective cooling methods must be employed to remove this heat from the transformer.

3.2 Cooling Methods

The common cooling methods used in NGD are listed below.

(a) For dry type transformers.

(i) Self-air cooled: The transformer is placed in its housing and the heat is removed by the natural convection of surrounding air and through heat radiation. This method is used for the transformers rated up to 3MVA.

(ii) Forced air cooled: The transformer is placed in its housing and air is circulated through it, by means of blowers. This method is used for transformers rated up to 15 MVA in size.

3.2 Cooling Methods (continued)

(b) Oil-immersed type: In the oil immersed type, the transformer windings and the transformer core are immersed in a mineral oil which has good electrical insulating and thermal conductivity properties.

(i) Oil-immersed self cooled: Cooling in this type of transformer is provided by mineral oil, which is circulated by natural convection through a radiator that is cooled by the surrounding air. This type is normally used for distribution transformers.

(ii) Oil-Immersed forced air cooled: Cooling is provided by mineral oil, which in turn is cooled by forced air circulation. A bank of fans/blowers are used to force air through the cooling fins of the transformer radiator. This cooling method is normally used for large transmission transformers, which are situated outdoors, in power plants, or in transformer stations.

(iii) Oil-immersed, water cooled: Cooling is provided by mineral oil, which in turn is passed through an oil-water heat exchanger. This method is used on very large transformers. The main transformers in NGD are of this type. This method will be discussed in greater detail, later in this lesson.

Notes

4. Components of a Power Transformer

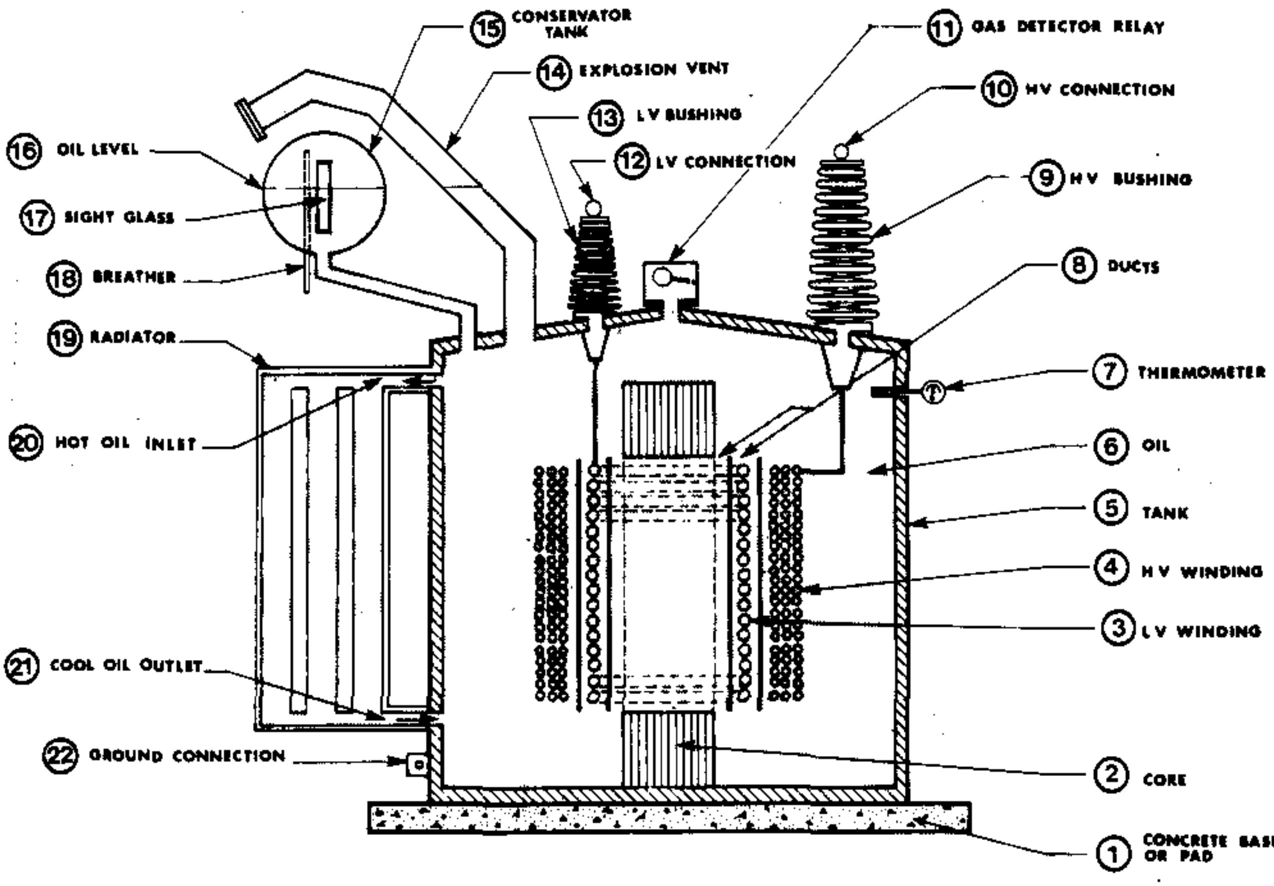


Figure 1: Cross Section of a Power Transformer

4. Components of a Power Transformer (continued)

ITEM	DESCRIPTION	REMARKS
1	Concrete base	Needed to provide proper support for the large weight of the power transformer. Base must be solid, properly levelled & fire resistant.
2	Core	Provides a path for the magnetic flux. Provides mechanical support for the windings.
3	LV Winding	It has fewer turns, as compared to HV windings. The conductor diameter is relatively larger, since it carries more current, as compared to the high voltage winding.
4	HV Winding	High voltage winding has a larger number of turns. Its conductor diameter is relatively smaller, since it carries less current. The HV winding is usually wound over the low voltage winding.
5	Tank	The transformer tank acts as a housing for the windings, core and the oil. It must be mechanically strong enough to withstand high gas pressures and electromagnetic forces that develop when a fault occurs.
6	Oil	It is high quality mineral oil. Provides an insulation between the windings, core and transformer tank. It also removes heat from the windings and the core.

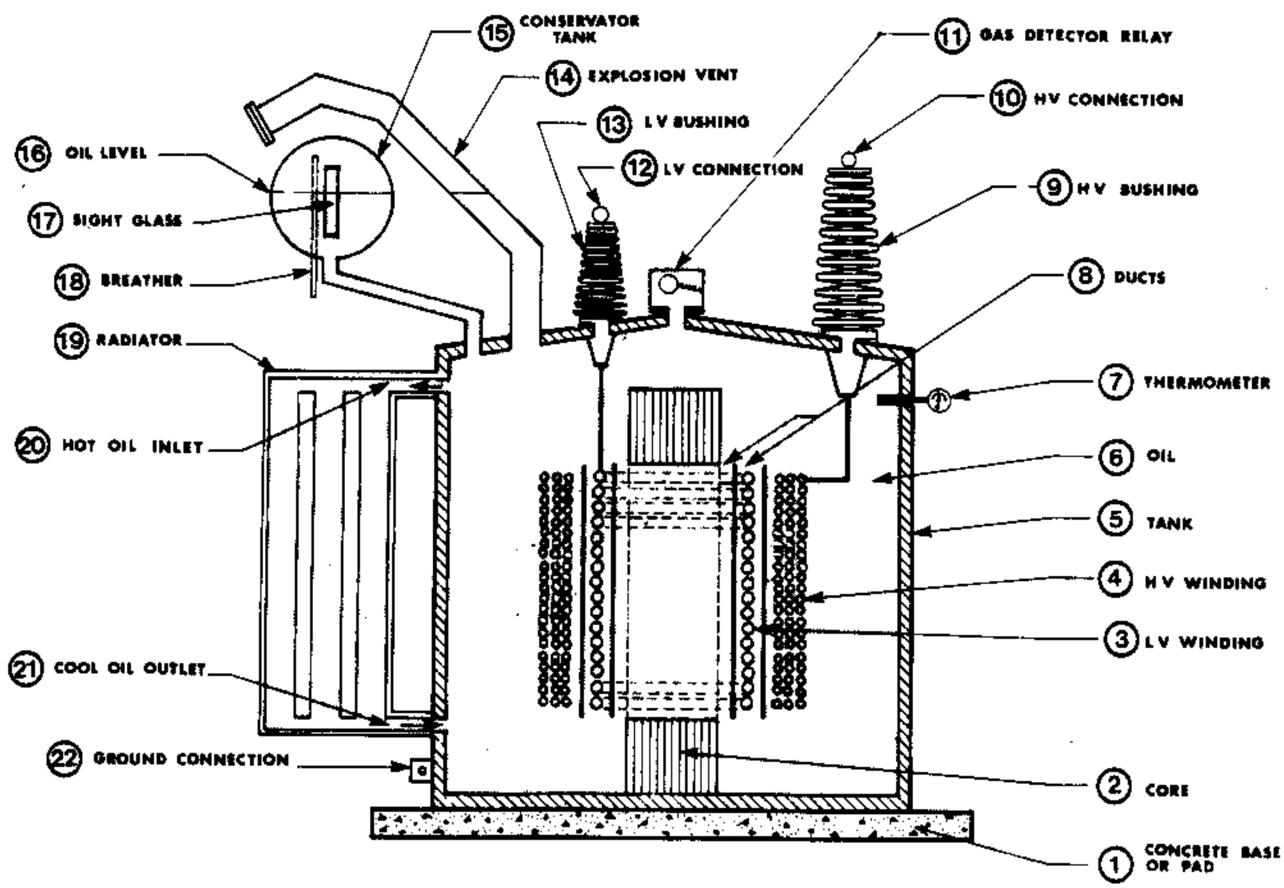


Figure 2: Cross Section of a Power Transformer

4. Components of a Power Transformer (continued)

ITEM	DESCRIPTION	REMARKS
7	Thermometer	Monitors the oil temperature and initiates an alarm, if the temperature exceeds a predetermined level.
8	Ducts	Remove heat from inside of the windings, to improve the cooling.
9	HV Bushing	Ceramic bushing which carries the HV conductor. It also insulates the HV conductor from the tank.
10	HV connections	Connects the HV winding to the HV side of the circuit.
11	Gas Detector relay	Detects gas buildup in the tank. It has two sections. One detects large rate of gas production, which may be produced due to a major fault and the other detects the slow accumulation of air/gases which are released from the oil, when it gets warm or from minor arcs. It can initiate an alarm or trip the transformer off the line, if excessive gas pressure is detected.
12	LV connection	LV conductor which connects the LV winding to the circuit.
13	LV bushing	Ceramic bushing which carries the LV conductor & insulates it from the tank which is at ground potential.

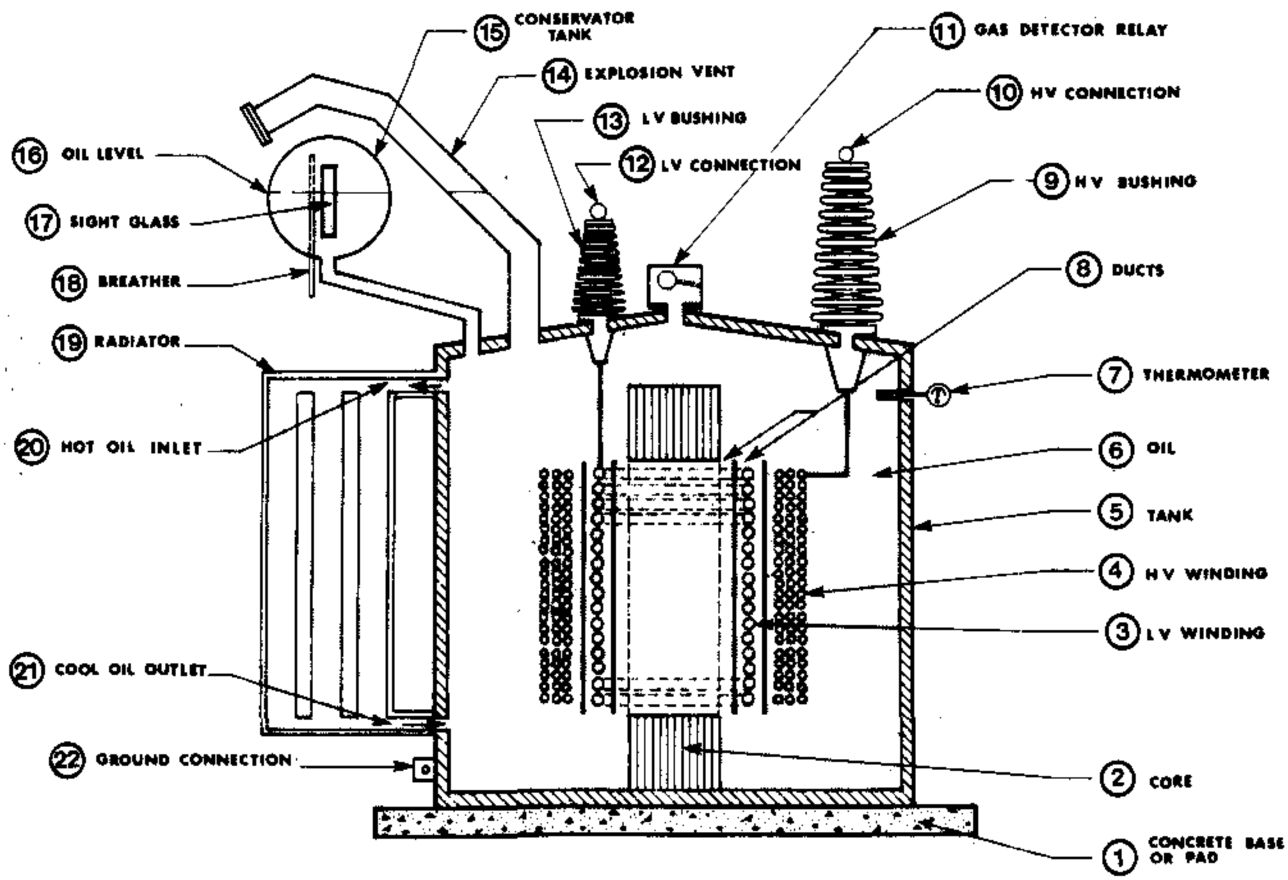


Figure 3: Cross Section of a Power Transformer

4. Components of a Power Transformer (continued)

ITEM	DESCRIPTION	REMARKS
14	Explosion vent	Explosion vent prevents buildup of high pressure in the tank. When a fault occurs, oil disintegrates and forms gases. If the gas pressure is above a predetermined value, the relief diaphragm at the end of explosion vent, ruptures and vents the tank to atmosphere.
15	Conservator tank	It acts as a reservoir of oil. When the oil is hot it expands and the excess oil goes in the conservator tank. When oil cools, it contracts and returns to the transformer tank. This maintains the transformer tank fully filled with oil.
16	Oil level	Oil level in the conservator tank varies depending on the expansion or the shrinkage of oil volume. Oil must always immerse the core and the windings, to ensure there is adequate cooling and insulation.
17	Sight glass	Provided as a visual means to check the level of oil in the conservator tank.
18	Breather	Allows the air to get in or out of the conservator tank upon the shrinkage or expansion of oil. It is fitted with an air drier (silica gel) to remove the moisture from the air going into the conservator tank.

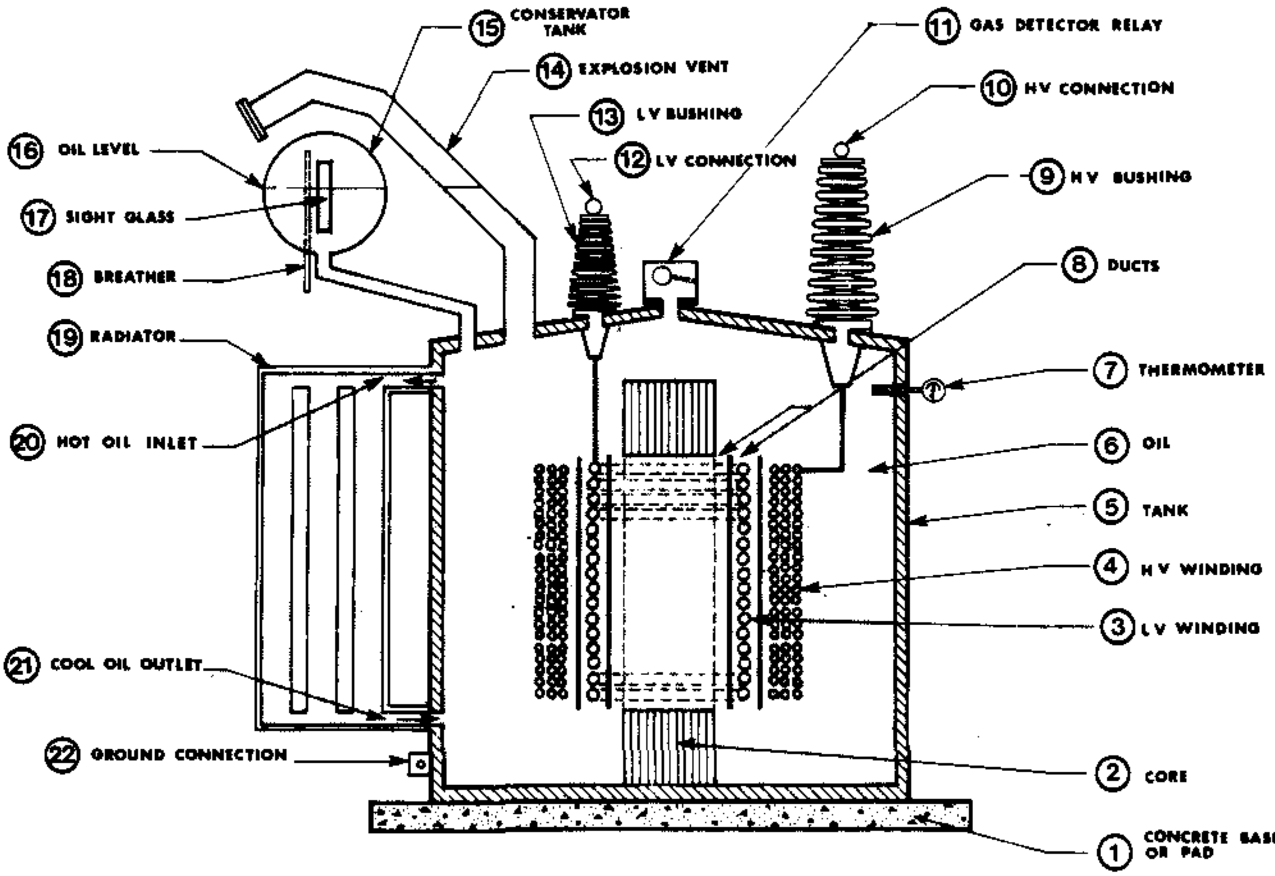


Figure 4: Cross Section of a Power Transformer

4. Components of a Power Transformer (continued)

ITEM	DESCRIPTION	REMARKS
19	Radiator	This is a type of heat exchanger which is used to provide cooling for the hot oil. Hot oil circulates through the cooling fins and air circulation around the radiator provides the cooling.
20	Hot oil inlet	Hot oil enters the radiator here from the transformer tank, due to convection.
21	Cool oil outlet	After oil circulates through the radiator it becomes cool and returns to the tank at this point.
22	Ground connection	Transformer tank is connected to the ground(earth) at this terminal, to provide safety to personnel.

5. Oil-Water Heat Exchanger Cooling

In NGD the main transformers are cooled by oil-water heat exchangers. Figure 5 shows a functional arrangement for such a system.

5.1 Operation (Refer to Figure 5)

(a) Hot oil from the transformer is circulated through the heat exchanger by two, 100% capacity oil circulation pumps. Each pump is operated at 50% capacity.
(b) Service water is circulated through two 100% duty heat exchangers. Each is operated at 50% capacity.
(c) Heat transfer occurs from oil to water in the heat exchanger.
(d) Flow switches (FS) are provided to detect an absence or reduction of service water flow. If the flow of water is lower than a predetermined set value, a flow switch initiates an alarm in the control room. The transformer can still be operated at 100% capacity, if one cooler is out of service. However, if both coolers are inoperative, then immediate action is required to trip the transformer and prevent overheating. Station instructions are provided to deal with such circumstances.

5.2 Problems and Precautions

A problem that may occur with the coolers is freezing and bursting of the water cooling tubes, during winter months. (These tubes are located outdoors). This can occur due to two conditions.

(a) If water is allowed to stand still in the cooling lines, during cold weather, it may freeze and burst the piping. To prevent this, the coolers must be drained of water, if the transformer is removed from service for an extended period of time. Station Instructions must be followed.
(b) If oil at subzero temperatures is allowed to circulate through the coolers, the cooling water may also freeze. The oil temperature in the tank can be below zero if the transformer is removed from the line for extended period of time in the cold weather. To prevent this when the transformer is brought back on the line the oil must be allowed to warm up through normal copper and core loss heat before water is circulated through the coolers.

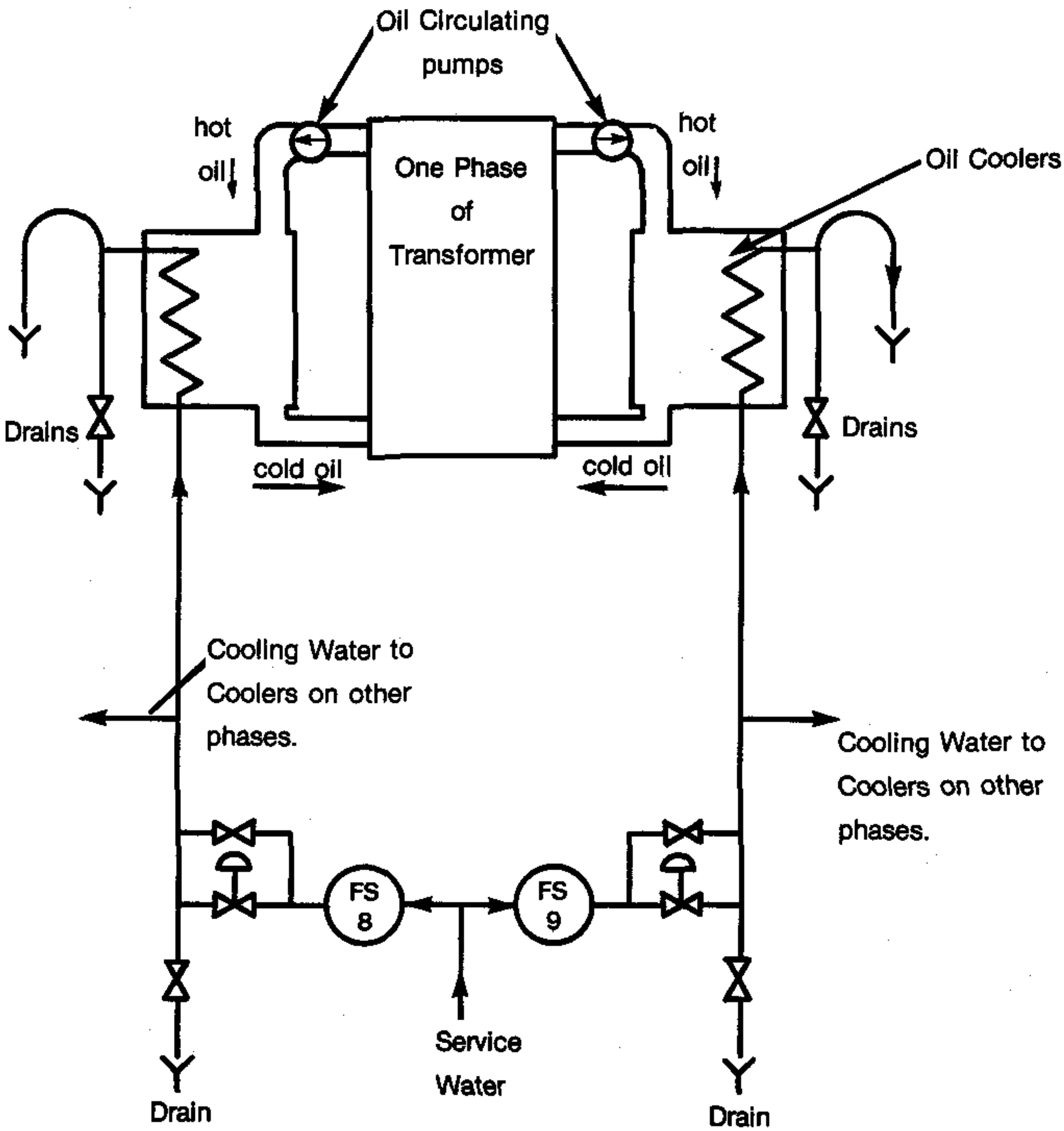


Figure 5: Cooling System for Main Transformers at Bruce "A" NGS.

Note: Only One Phase is Shown

6. Advantages and Disadvantages of Transformer Oil

(a) Advantages:

(i) Transformer oil is a good electrical insulator.
(ii) Transformer oil has good thermal conductivity which allows efficient removal of heat.

(b) Disadvantages:

(i) Mineral oil is a fire hazard, hence, indoor transformers should not be of the oil immersed type.
(ii) Oil is a polution hazard. Any leaks in the tank or during oil handling can result in pollution of the of the environment.
iii) Synthetic oil, called "Askerel", is non-flammable, but it is linked to serious health problems. Its use has been banned and restricted to existing installations, only.

7. Oil Contamination and Detection Methods

Oil must be kept clean and free of contamination in order for it to perform as an insulator. The following factors will affect oil performance.

7.1 Moisture

Moisture is a major problem with oil which is used as an insulation for in electrical equipment. An excess of moisture greatly reduces the insulating properties of oil. Moisture contents of 0.06% reduce the insulating ability of oil to half. The maximum acceptable moisture level in oil is 35 parts per million. Extensive care is taken to prevent moisture contamination. Some of these are listed below;

(a) During shipping and assembly, care is taken to prevent moisture from getting into the tank, or the windings, or the oil.
(b) Air dryers are installed on the breather of the conservator tank. These dryers can be of a chemical or dehumidifier type.
(c) In an oil-water heat exchanger, oil pressure is maintained above the water pressure to prevent the water from leaking into the oil.

(d) Regular checks are made on oil samples in order to detect moisture. One method uses a dielectric tester. During this test the oil sample is subjected to a fixed potential difference for a given amount of time. If arcing does not occur, then the oil is considered to be satisfactory.

7.2 Oxidation of Oil

When oil is heated above 75°C and exposed to oxygen, it oxidizes and forms sludge. Oxidation presents the following problems.

(a) Sludge formed in the oil restricts the flow of oil in the cooling ducts and reduces the cooling efficiency.
(b) Oil becomes acidic which reduces its insulation quality and life.

Oxidation is detected by an acidity test of the oil. The result of this test is compared to the value found in a previous test. A progressively increasing acidity content indicates that oxidation of the oil is taking place. Once the acidity increases over a set, acceptable limit, the oil must be refiltered or replaced.

7.3 Dissolved Gases

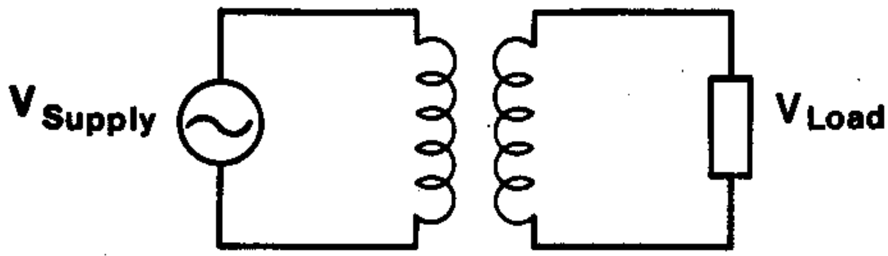
Localized hot spots, due to the burning of insulation or sparks causes oil temperature, in localized areas, to become high enough to cause oil disintegration. The formation of carbon and other gases occurs. Some of this gas is dissolved in the oil and causes the conductivity of oil to increase. In order to determine if localized hot spots are present in the transformer, a chemical analysis of the oil is performed. The presence of carbon and other gases can thus be detected. A presence of these, indicates localized burning of insulation and the transformer tank must be opened to correct this problem.

7.4 Oil Level

Oil level in the transformer may drop due to evaporation or leaks. A low oil level can damage the transformer. A sight glass or level indicator is provided on the transformer tank or the conservator tank. Regular checks are made on the oil level.

8. Transformer Tap Changes

8.1 What is a Tap Changer



A Transformer with No Tap Changer

Figure 6

On the load side of a transformer, it is desired to have voltages which are constant, or as close to the required voltage, as possible. However, load voltages can change if there is a change in the load current or the supply voltage.

Secondary voltage = Supply voltage/turns ratio "a".

In this condition, to maintain a constant secondary voltage or as close to the desired value as possible, the turns ratio is changed. **A tap changer on a transformer performs the job of changing the turns ratio.** A tap changer can be located on the primary or the secondary side. However, it is normally on the high voltage side because:

(a) The HV winding is usually wound over the low voltage winding. Hence, it is easier to access the turns in the HV winding.
(b) Current through the high voltage winding is lower. Hence, there is less "wear" on the tap changer contacts.The size of the tap changer contacts can be smaller.

Taps are normally provided at ±2.5% intervals. Some fine adjustment tap changers, on distribution transformers, could have taps at ±1% intervals.

8.2 Tap Changer Operation: Tap Changer in Primary

Consider the tap changer in Figure 7(A) and follow the steps below.

(a) When the supply voltage is nominal, the tap changer will be at the tap marked 0%.

(b) Consider the secondary voltage increasing 2-1/2% above its nominal value. To maintain the secondary voltage constant, the tap changer shifts to the tap marked + 2-1/2%. This increases the number of turns in the primary by 2-1/2%. Hence, the turns ratio increases. The secondary voltage therefore decreases.

(c) Consider the load voltage decreasing by 2-1/2% from nominal. The tap changer shifts to the - 2-1/2% tap. This decreases the number of turns in the primary by 2-1/2%. The turns ratio, "a" decreases. Hence, the secondary voltage increases.

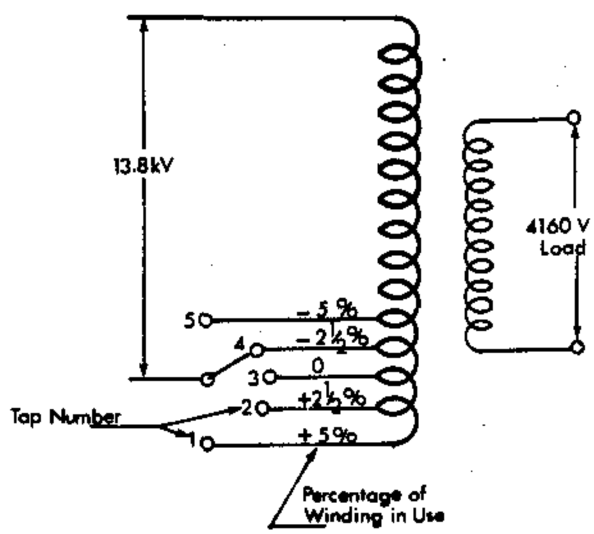


Figure 7(A): Tap Changer in the Primary

Note: If the tap changer is on the secondary side the shifting of taps will be reversed as compared to the above discussion.

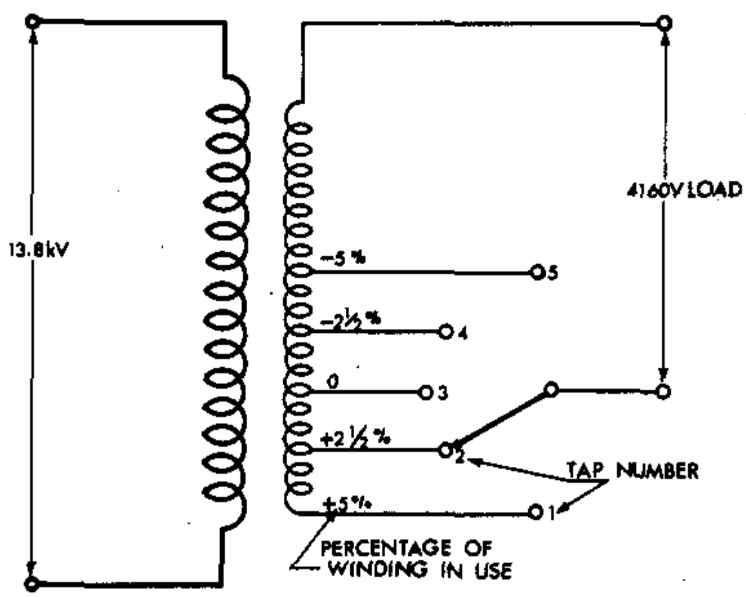


Figure 7(b): Tap Changer in Secondary

8.3 Types of Tap Changers

There are two types of tap changers.

(a) Off-load tap changer

In NGD, most of the tap changers in transformers are of the off-load type. Off-load tap changers, have contacts which are not designed to break any current, including the no-load current. Transformers with this type of tap changing mechanism must be electrically disconnected from the circuit before the tap is changed. Tap changing can be manual or motorized.

(b) On-Load Tap Changer

In on-load tap changers, the taps can be changed while the transformer is supplying the load. Mechanisms are provided to prevent damage to the transformer or to the tap changer.

ASSIGNMENT

1. Explain why cooling is required in transformers (section 3.1)

2. List two consequences of inefficient cooling in transformers. (Section 3.1)

3. List two cooling methods used for dry type transformers and briefly explain each. (Section 3.2)

4. List three cooling methods used for oil-immersed type transformers and briefly explain each. (Section 3.2)

5. List the components of a power transformer and give the function of each. (Section 4 Figure 1)
Use separate sheets.

6. State what type of transformers, in NGD, use an oil-water heat exchanger for cooling. Briefly explain the operation of such an arrangement. (Sections 5, 5.1)

7. What problem may develop with oil-water heat exchangers, what factors contribute to it and how can it be eliminated? (Section 5.2)

8. List two advantages and two disadvantages of transformer oil. (Section 6).

9. List three contaminants which may be detected in transformer oil. State how each affects transformer performance and how each is detected. (Section 7.1, 7.2, 7.3)

10. State what a tap changer does and how it achieves this. (Section 8.1)

11. From Figure 7(B) indicate the tap position to be used if:
    (a) the secondary voltage increases by 5%.

    (b) the secondary voltage decreases by 5%.

12. List the two types of tap changers used and differentiate between them. (Section 8.3)

S. Rizvi

Notes

Electrical Equipment - Course PI 30.2

AC GENERATORS

OBJECTIVES

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

1. Briefly explain how "relative motion" is obtained in a large ac generator.

2. Briefly explain, how a magnetic field is produced in a large ac generator.

3. Given a simplified diagram of a large AC generator;
   a) Identify the flagged components;
   b) Briefly state the purpose of each flagged component.

4. State that for a large AC generator:
   a) The magnetic field circuit, consists of:
      i) the rotor;
      ii) the air gap;
      iii) the stator iron.

   b) The armature, consists of:
      i) the stator bars;
      ii) the stator iron.

5. Briefly explain, for large AC generators, three reasons for having the magnetic field circuit situated in the rotor.

6. Briefly explain four factors which produce heat in an AC generator.

7. List three sources of turbine-generator shaft voltage.

8. For a large AC generator, briefly explain:
   a) the need for:
      i) a shaft grounding brush;
      ii) Pedestal/bearing and hydrogen seal insulation
   b) The consequences of shorting an insulated generator pedestal to ground.
   c) How the damage identified in b) may occur.

1.0 INTRODUCTION

This module will provide the trainee with:

(a) A brief review of ac generation theory.

(b) An explanation of why large ac generators require cooling.

(c) The names, a brief description and the purpose of the major components of a large ac generator.

(d) An introduction to generator shaft voltages, grounding and insulation.

2.0 ELECTRICAL THEORY REVIEW

2.1 What is a Generator

A generator is an electromechanical device which converts mechanical energy into electrical energy.

2.2 Magnetic Effects of Current

When conventional current, I, flows through a conductor a magnetic field is produced around the conductor as shown in Figure 1.

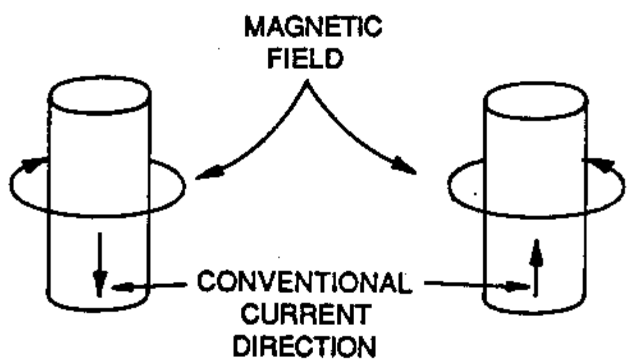


Figure 1: Magnetic Fields Around Conductors Carrying a Current

The magnetic field thus produced has the following characteristics:

(a) Its polarity or direction changes with the change in the direction of current as shown in Figure 1.

(b) The strength of this magnetic field depends on the magnitude of the current. Within limits an increase in current produces a stronger magnetic field, and a decrease in the current causes the magnetic field to weaken; ie, fewer magnetic field lines per unit area.

From the above it can be seen that, a large constant dc current will produce a large, constant magnitude magnetic flux which has a fixed polarity.

This principle will be applied when the rotor or field of the generator is discussed.

2.3 Electromagnetic Induction

In order to induce a voltage on a conductor, the following three conditions as shown in Figure 2 must be met:

(a) There must be a conductor. (L).

(b) There must be a magnetic field. (B).

(c) There must be relative motion between the conductor and the magnetic field. (V).

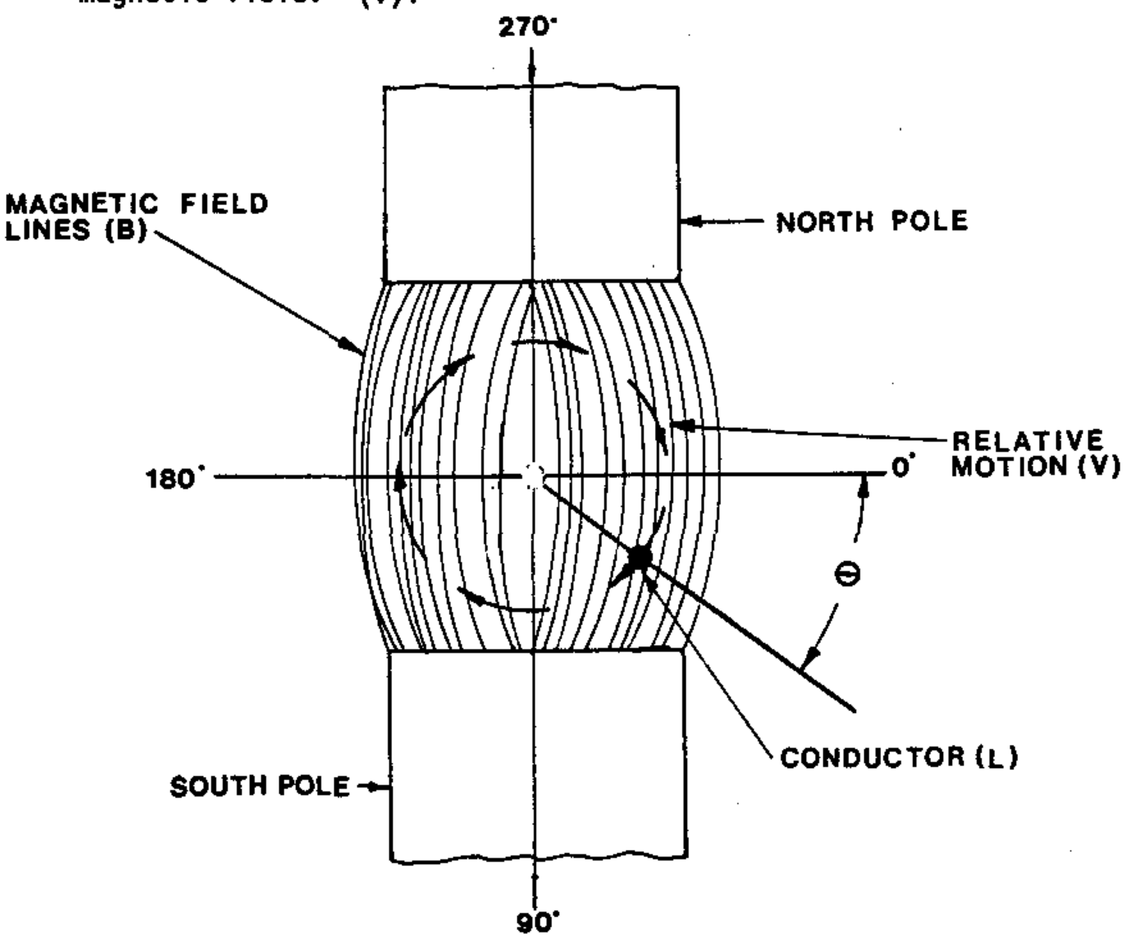


Figure 2: Conditions Required to Induce a Voltage on a Conductor

Whenever these three conditions are met, a voltage is induced on the conductor. The magnitude of the induced voltage is given by the following expression:

$e(\text{volts}) = B \cdot L \cdot V \cdot \sin(\theta)$ (do not memorize)

where: e is the instantaneous induced voltage on the conductor.
B is the magnetic flux density in Teslas.
L is the length of the conductor in the magnetic field, in meters.
θ is the angle that the direction of travel of the conductor makes with a line that is perpendicular to the magnetic field at any given time.
V is the relative velocity, in meters per second.

From this expression, it can be seen that induced voltage is increased or decreased by:

(a) Changing the flux density, B. The generator flux or magnetic field is produced in the rotor and is varied by changing the rotor or field current.

(b) Changing the length, L, of the conductor in the magnetic field. However, once a generator has been constructed, the length of the conductor is fixed. There are practical limitations to the maximum conductor length.

(c) Changing the relative velocity, V. In a generator, the rotor velocity determines the frequency. Since the frequency of the Ontario Grid is held constant at 60 Hz the velocity of the rotor of any generator on the grid is kept constant.

If the expression $e = B \cdot L \cdot V \cdot \sin\theta$ is plotted for various values of θ, between zero and 360°, the waveform would be a sinewave, as shown in Figure 3.

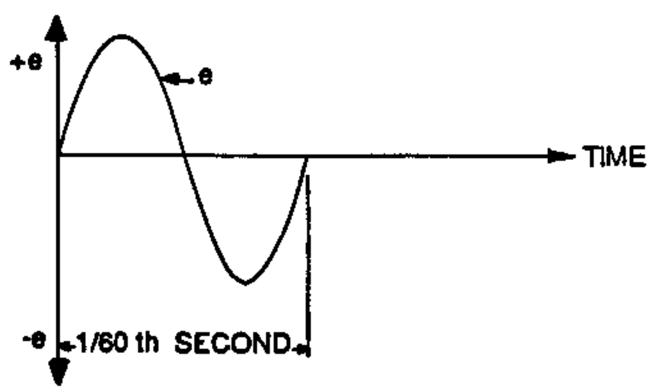


Figure 3: ac Wave Form

Note that the instantaneous voltage e rises to a maximum positive peak, falls to zero, and then rises to a maximum negative peak and returns to zero 60 times a second.

This is the 60 Hz ac wave form.

3.0 LARGE AC GENERATORS

The physical size and format of a large ac generator is determined primarily by the magnitude of its output power.

3.1 The Practical ac Generator

From the three conditions specified for electromagnetic induction in Section 2.3, it can be seen that two physical format possibilities exist for a practical ac generator. These are:

(a) The magnetic field can be stationary and the conductors can be moved through it

OR

(b) The conductors can be held stationary and the magnetic field can be swept past them.

While some small generators utilize the stationary field option, in the large ac generators used in CANDU systems it is always the conductors that remain stationary and the magnetic field that is moved past the conductors.

The stationary conductors or stator bars are rigidly mounted in a slotted iron core called the stator iron. This assembly is referred to as the stator or armature.

The magnetic field is produced in the rotor which consists of a set of four coils mounted in slots in the steel shaft which runs through the armature. The dc field current is fed to the rotor coils via slip rings and brush gear. Each coil produces a magnetic field having a north and south pole. The result is that the rotor now has four distinct electromagnetic poles consisting of two south poles at 180° to each other and two north poles at 180° to each other and displaced 90° from the south poles. When the rotor rotates, these magnetic fields sweep past the stator bars providing the required relative motion.

The rotating magnetic field configuration is used to accommodate:

(a) Physical Size Limitations

The armature currents of up to 30 000 amps ac are much larger than the field currents of approximately 4 000 amps dc. Therefore, the armature conductors are more massive than the field conductors.

(b) Cooling

The armature conductors (stator bars) must be water cooled. It is easier to provide leak proof connections to a stationary conductor.

(c) Brush Gear

It is preferable to have the smaller field current on the rotor, since the current carrying capacity of the slip rings and brushes is limited by I^2R heating effects.

3.2 Large ac Generator Components - Description and Purpose

Figure 4 is a simplified sectional diagram identifying major generator components. Some of these are also shown in Figures 5 and 6, which are photographs of a partially assembled generator.

Drive Coupling

The drive coupling is a bolted hub assembly which connects the generator shaft to the turbine shaft.

Bearings

The sleeve type babbited bearings are located outside of the generator. They provide support and low friction rotation for the generator rotor.

Outer Pressure Casing or Yoke

The yoke supports the stator assembly and end covers. It is also a pressure vessel which contains the pressurized hydrogen used to cool the generator rotor and stator iron. It also carries the hydrogen coolers.

End covers

The end covers are sealed and bolted onto the ends of the yoke. They carry the hydrogen seals and the connection points for the hydrogen coolers. They form part of the pressure vessel containing the hydrogen.

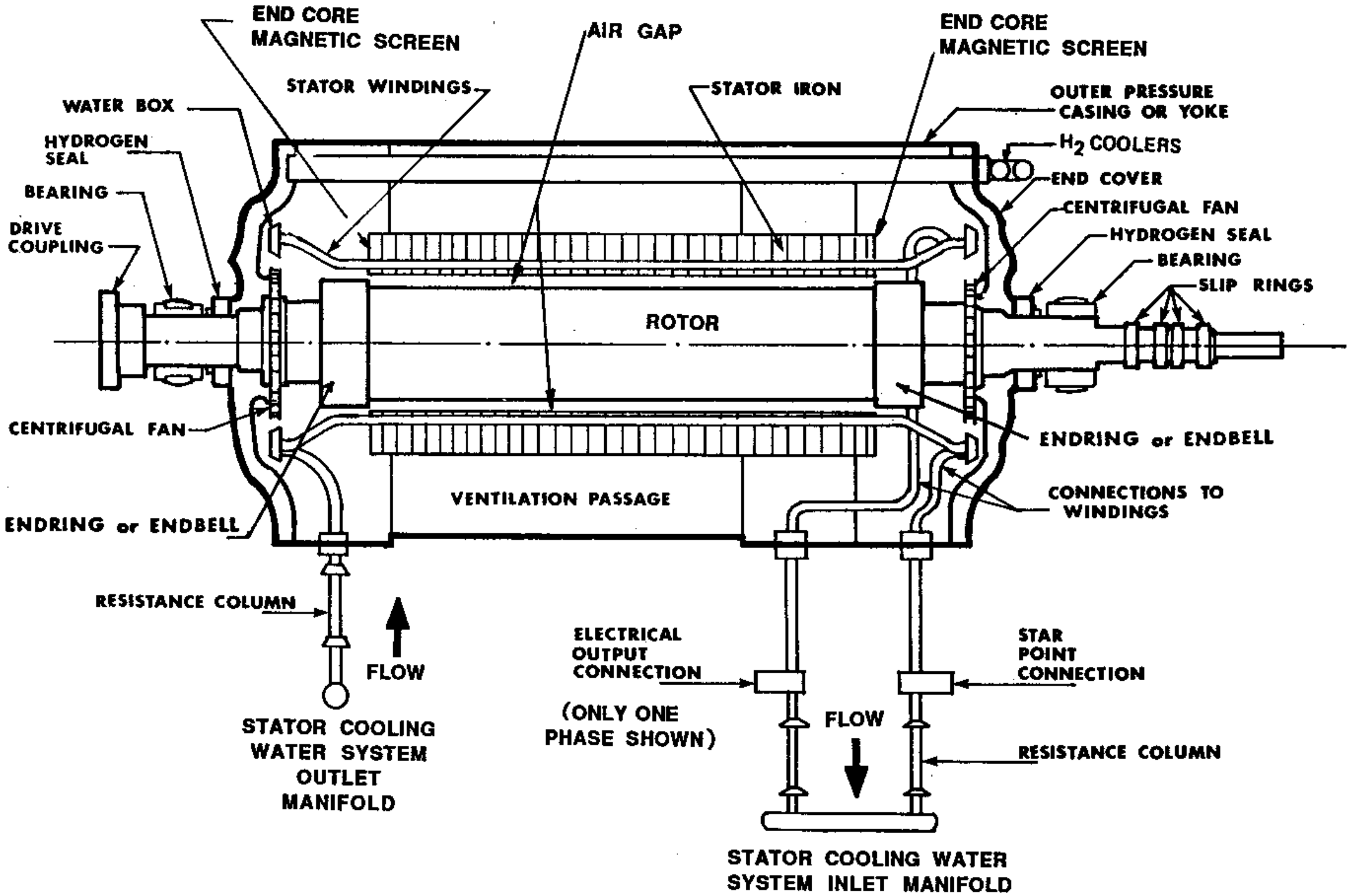


Figure 4: Simplified Sectional Diagram of a Large AC Generator

Hydrogen Seals

The hydrogen seals provide the moving seal, between the generator end covers and the rotor shaft, that keeps the hydrogen in the generator at working pressures. They also keep air out of the generator at working pressures.

Hydrogen Coolers

The hydrogen coolers mounted in the generator yoke use low pressure service water to cool the hydrogen gas which is circulating continuously inside the generator.

Stator Iron

The stator iron carries the 144 stator bars wedged tightly in 72 slots running axially along the inner circumference of the iron. The stator iron also acts as part of the magnetic field circuit and concentrates the magnetic flux produced by the rotor around the stator bars.

The stator iron is composed of "low-hysteresis" alloy laminations. Each laminate is insulated from the others by a glass or varnish coating. The laminates are assembled in packets with spaces to provide for circulation of cooling hydrogen throughout the stator assembly.

End Core Magnetic Screen

At each end of the stator iron package there is a water cooled copper annulus called the end core magnetic screenplate. These magnetic screens minimize flux losses from the ends of the stator iron.

Stator Bars or Windings

The stator bars are bundles of partially flattened small diameter copper tubes, which have a voltage induced in them by the rotating magnetic field. They carry the ac load current demanded by the grid and/or station load and therefore are cooled by demineralized water flowing through them. The stator bars are series-parallel connected to form the required three-phase star-wound configuration. The combination of stator iron and the stator bars is called the armature.

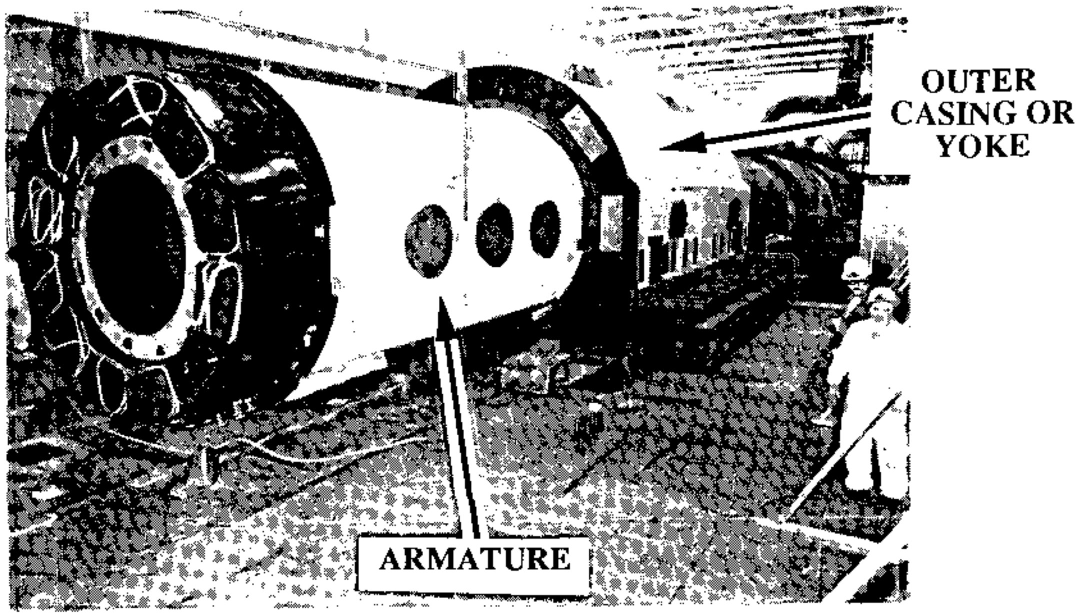


Figure 5: Generator Yoke and Armature

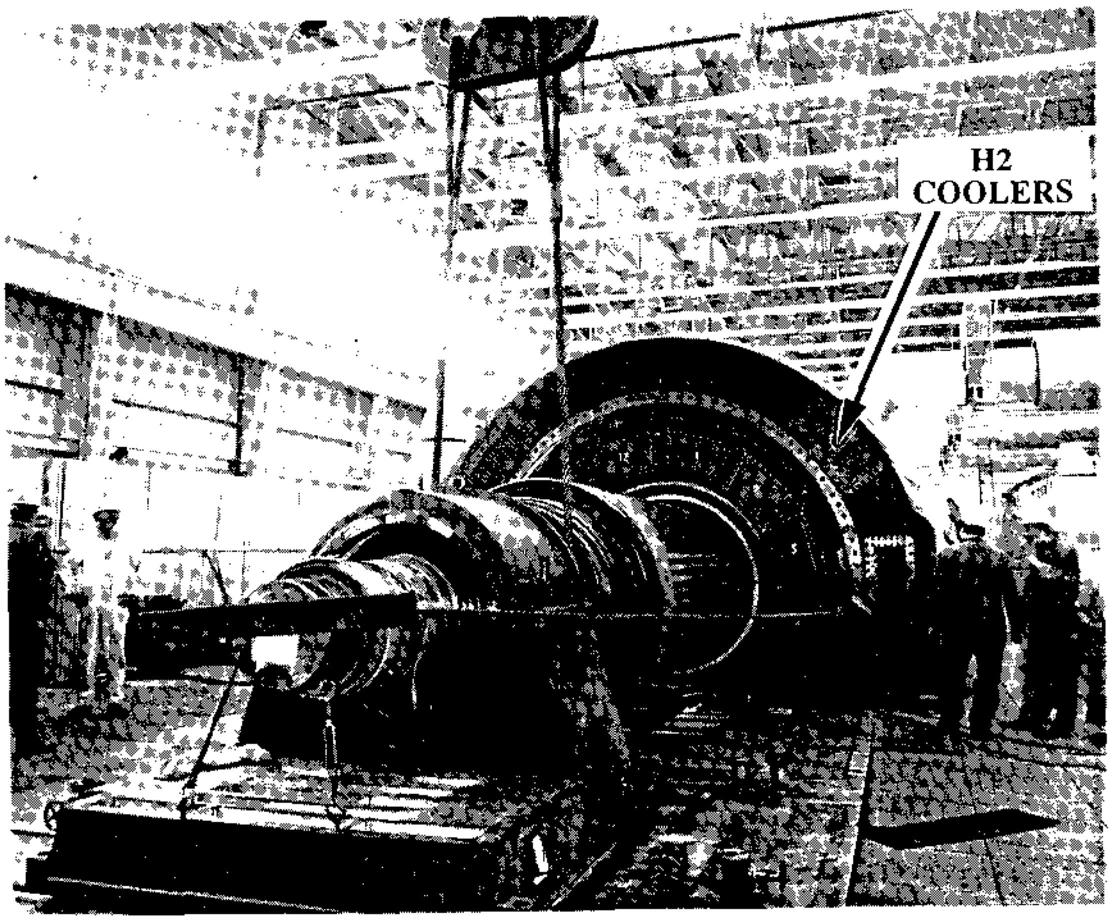


Figure 6: Rotor Being Inserted into Yoke/Armature Assembly

Water Boxes

The 12 water boxes feed the demineralized cooling water to and from the stator bars. They also provide for the series/parallel electrical interconnections of the stator bars needed to achieve the required terminal voltage and load current output. In most units the water boxes have been replaced with feeder rings and teflon hose connections to individual stator bars.

Resistance Columns

The resistance columns are epoxy resin tubes which carry the stator cooling water to the stator bars from the cooling water system and vice versa. They isolate the high voltage generator stator bars electrically from the cooling water system.

Stator Cooling Water System Outlet Manifold

This manifold is the point from which the demineralized cooling water enters the generator from the cooling system. It is located at the turbine end of the generator.

Stator Cooling Water System Inlet Manifold

This manifold is the point at which the demineralized water leaves the generator and is returned to the cooling system. It is located at the outboard end of the generator.

Star Point Connection

The star point connection is located just above the resistance columns, at the cooling water system inlet manifold. It is the point at which the neutral ends of the red, white and blue phases are joined together and taken to ground, via a grounding transformer.

Electrical Output Connections

The red, white and blue phase electrical output connections are located just above the resistance columns at the cooling water system inlet manifold. Only one of these is shown in Figure 4.

The Rotor

The rotors in the main generators at all CANDU stations are four-pole, and therefore rotate at 30 r/s (1 800 RPM). The rotor is a massive, single, solid forging of high grade steel, into which are machined four sets of slots for the rotor "windings or coils". The rotor windings are copper bars having a "U" cross-section, and holes along their length. These bars are wedged firmly into the rotor slots to prevent moving or chaffing during operation. Electrically the rotor bars are connected to form four coils in series with each other.

End Bells or End Rings

The end bells mounted on each end of the rotor support the rotor windings against centrifugal forces. They also direct the flow of cooled hydrogen into both ends of the rotor windings.

Centrifugal Fans

The fans, mounted at each end of the rotor move heated hydrogen out of the air gap, through the coolers and back into ducts or passages in the stator iron and rotor.

The Air Gap

The air gap is the space (≈ 6 cm) between the outside diameter of the rotor and the inside diameter of the stator iron. The air gap permits the rotor to spin, at all speeds, without touching the stator iron. Heated hydrogen flows from both the rotor and the stator iron into the air gap. The air gap is also part of the magnetic field circuit.

Slip Rings

The slip rings are mounted on the outboard end of the generator shaft. They work in conjunction with the brush gear to feed the dc field or excitation current to the rotor windings.

3.3 Summary

The magnetic flux produced in the rotor windings travels through the magnetic field circuit which consists of the rotor, the air gap and the stator iron.

Figure 7 shows a much-simplified but typical large turbo-generator to illustrate the following points:

- To have an ac voltage generated, there must be a conductor, a magnetic field, and relative motion.
- The dc field current is fed from a dc source to the rotor via slip rings and brushes. This creates a four-pole magnetic field which rotates when the rotor rotates.
- The stator windings are the conductors on to which the ac voltage is induced and in which the ac load current will flow when the generator is connected to the grid.
- A steam turbine is the prime mover providing the relative motion between the rotor magnetic field and the stator conductors.
- As a result, an ac voltage is induced on the stator conductors. These conductors are brought out and connected to the transmission lines via a step-up transformer.

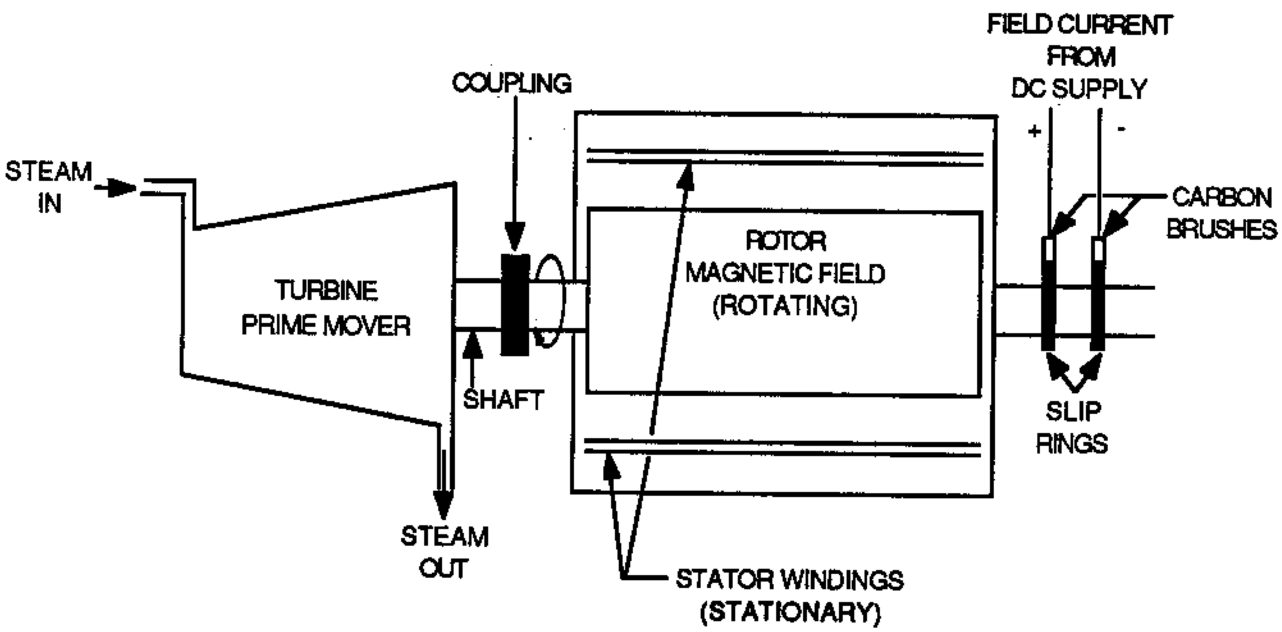


Figure 7: A Simplified Turbo-Generator

4.0 HEAT PRODUCED IN A GENERATOR

Although a large modern ac generator is a very efficient machine (≈ 98.5% efficiency), heat is produced within the generator during all phases of its operation. The following factors contribute to the production of heat in the generator:

(a) I^2R Losses in the Stator Windings

Heat produced by this process is related to the square of the current supplied to the grid by the generator. Maximum current can be 16 500A at Pickering, 24 600A at Darlington, or 30 000A at Bruce. Heat produced by this method can be as high as 3.0 MW.

$[(30\ 000)^2 \times \approx 0.0033\ \Omega \approx 3\ \text{MW.}]$

(b) Eddy Current and Hysteresis Losses

Eddy current and hysteresis losses occur in the iron of the stator core and in the end core magnetic screen plates at each end of the stator iron. they can be as high as 1.0 MW.

Some eddy current heating also occurs in the copper stator bars or conductors, whenever the generator is excited.

(c) I^2R Losses in the Rotor

The dc current flowing through the rotor windings can be as high as 4 000A. This produces a large I^2R loss in the rotor windings. Rotor I^2R losses can be as high as 1.2 MW. $[(4\ 000)^2 \times \approx 0.08\ \Omega \approx 1.2\ \text{MW.}]$

(d) Windage and Frictional Losses

The ≈ 6 cm clearance or "air gap" between the rotor and the stator is filled with the hydrogen gas which is circulating within the generator. When the rotor rotates, the gas is also in motion. This causes a rubbing action between the rotor-gas-stator interfaces and produces heat which is referred to as windage loss.

Although the rotor is mounted on well lubricated sleeve bearings at each end, friction between the rotor and the bearings produces heat referred to as frictional loss.

Windage and frictional losses together can be as high as 1.5 MW.

The 6-7 Megawatts of heat produced by the above sources must be continuously removed to prevent damage to the insulation, the bearings, the lubricating oil and the conductors. The systems for removing this heat are described in the next module "Generator Auxiliary Systems," PI 30.23-2.

5.0 SHAFT VOLTAGE AND GROUNDING

This section introduces the causes of "shaft voltages" and the need for properly grounding the generator shaft.

5.1 Shaft Voltage

When the turbine generator is running, it is found that a voltage appears on the shaft. There are three major sources of this voltage:

(a) Magnetic - because of asymmetries in the magnetic field (for example, the rotor is not perfectly round) a voltage is induced, along the rotor body and shaft.

In small machines, this voltage may be negligible but with large generators the voltage can range from a few millivolts up to 50 Vac.

(b) Electrostatic - with generators that have sleeve or journal type bearings, the oil film forms an effective electrical insulation between shaft and ground. Electrostatic charges are generated by the brushing effect of the wet steam with the blades of the turbine (LP stage). Hence, the whole shaft is raised to a potential above ground.

(c) Static Exciter - in generators which have a static exciter, the solid state switches cause "spikes" in the applied field voltage which lead to "spikes" appearing in the induced shaft voltage.

5.2 Shaft Grounding, Pedestal and Bearing Insulation

If the shaft voltage described in Section 6.1 is not discharged continuously to ground it may build up to a level at which it will discharge from the shaft, through the bearing oil film, to the bearing surface. Pitting of the bearing and shaft surfaces by spark erosion will occur and the bearing surfaces will be seriously damaged if this condition is allowed to continue. In order to preclude this problem, shaft voltages are continuously discharged to ground via a carbon or copper brush and flexible lead as shown in Figure 8.

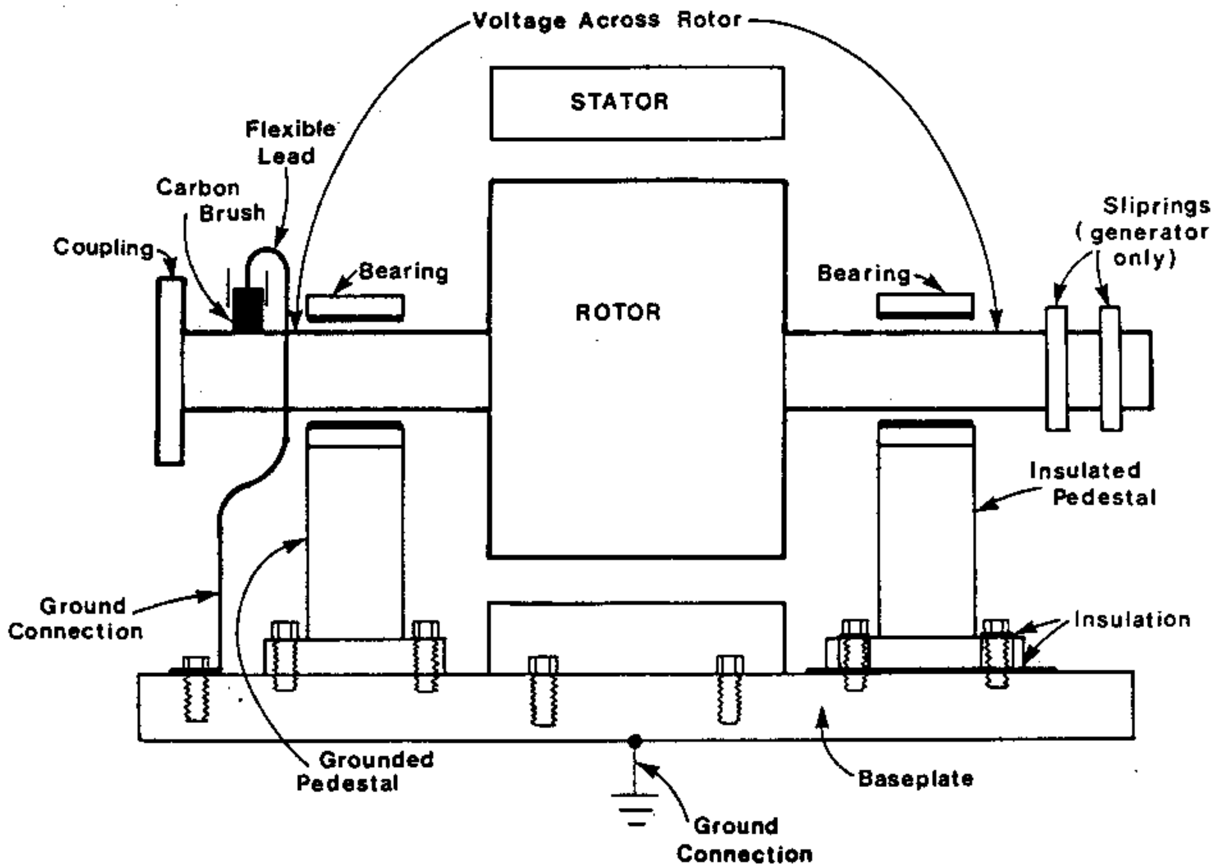


Figure 8: Grounding and Insulation Arrangements for a Large Motor or Generator Rotor

Figure 8 also shows that one bearing pedestal is insulated from ground. This insulation is required to prevent current from circulating from the shaft, the bearing and the baseplate, and back to the shaft via the flexible lead and brush.

Figure 9 shows how current produced by induction can circulate through the bearings if the pedestal insulation is bypassed. Bypassing can be caused by an uninsulated flange on an oil pipeline, an uninsulated instrumentation connection, or by any metallic object (eg, metal barrier, stand, ladder) forming a direct link from the insulated pedestal to ground.

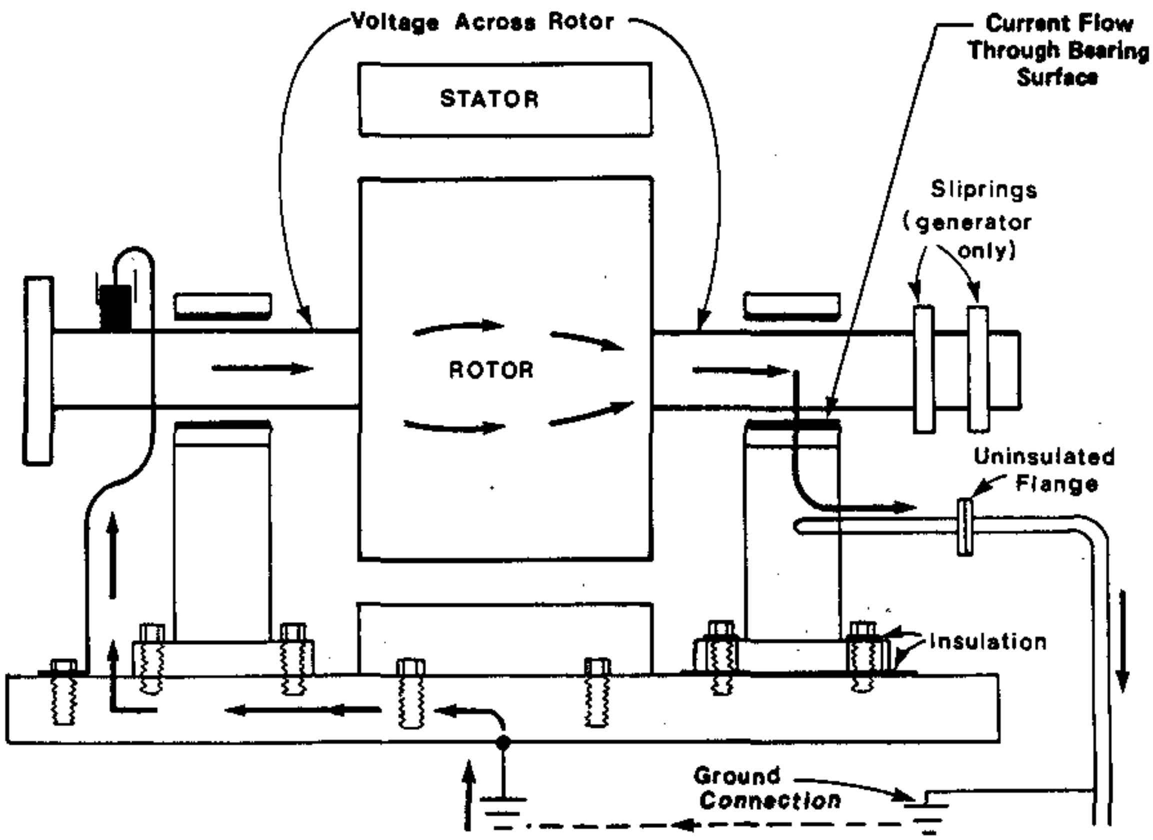


Figure 9: Current Flowing Through Bearings and Uninsulated Flange

Bearing failure due to pitting will occur in a few minutes if current is allowed to circulate through the bearing surfaces. Also, the arcing across the oil film can ignite the hot oil causing a serious fire.

In some stations, as an alternative to pedestal insulation, the bearing itself is of the insulating type.

5.3 Hydrogen Seal Insulation

The Hydrogen seals which seal the generator casing to the shaft, must also be insulated in a similar manner to prevent spark erosion of the seal face. The electrical insulation points of a typical seal are shown in Figure 10.

Again, should current flow through the seal faces, failure due to pitting will occur in a few minutes.

This problem is precluded in the newer radial seals described in the next module.

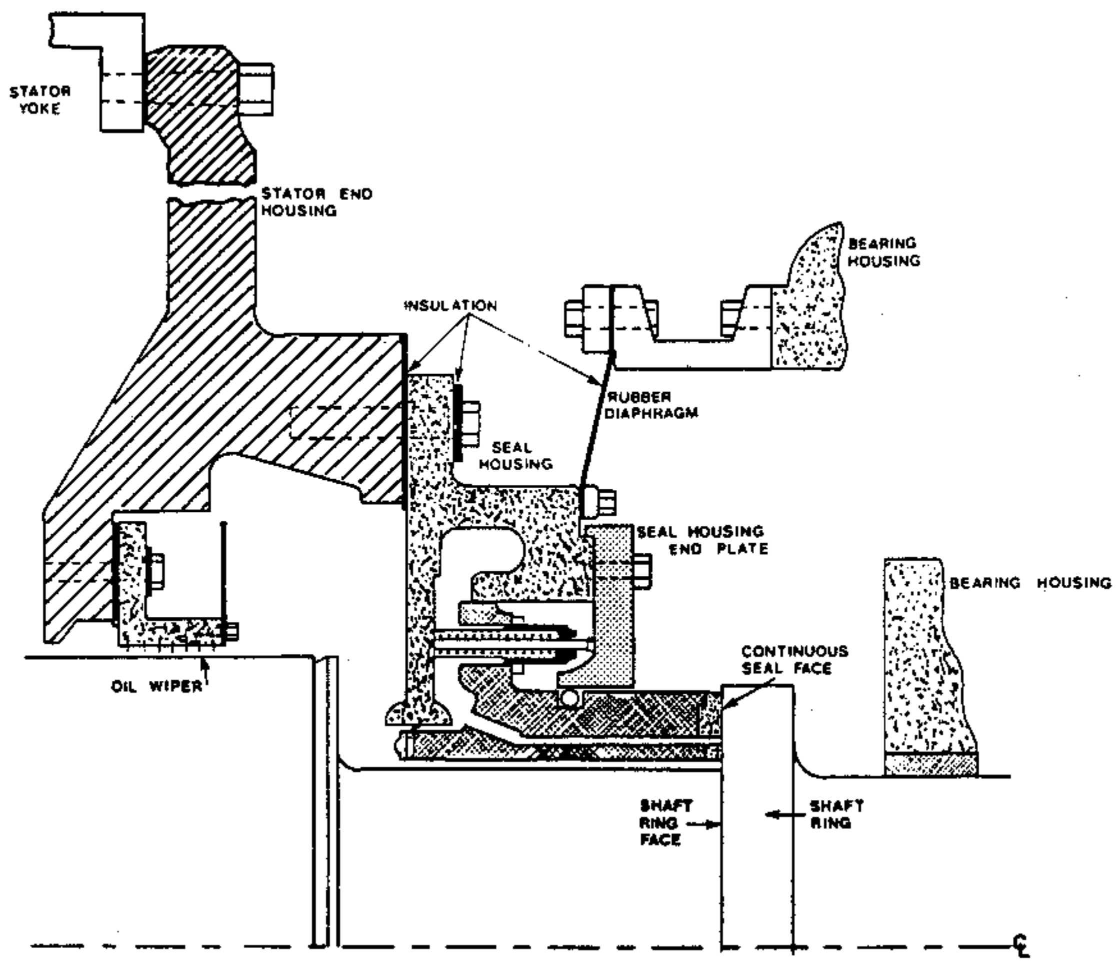


Figure 10: Section of a Generator Hydrogen Seal Showing Insulation

ASSIGNMENT

(1) What is a generator? (Section 2.0)

(2) List three requirements which must be met to have an induced voltage? (Section 2.3)

(3) For a large ac generator, state the components of:

(a) The magnetic field circuit. (Section 3.3)

(b) The armature. (Section 3.2)

(4) Explain briefly how "relative motion" is obtained in a large ac generator. (Section 3.1)

(5) List the three reasons for having the magnetic field as the rotor? (Section 3.1)

(6) Explain briefly how a magnetic field is produced in a large four-pole ac generator. (Section 3.1)

(7) Given the attached simplified diagram of a large ac generator: (Section 3.2)

(a) Identify the flagged components.

(b) Briefly state the purpose of each component.

(8) List and briefly explain the four major causes of heat production in a large ac generator. (Section 4.0)

(9) List three sources of turbine/generator shaft voltage. (Section 5.1)

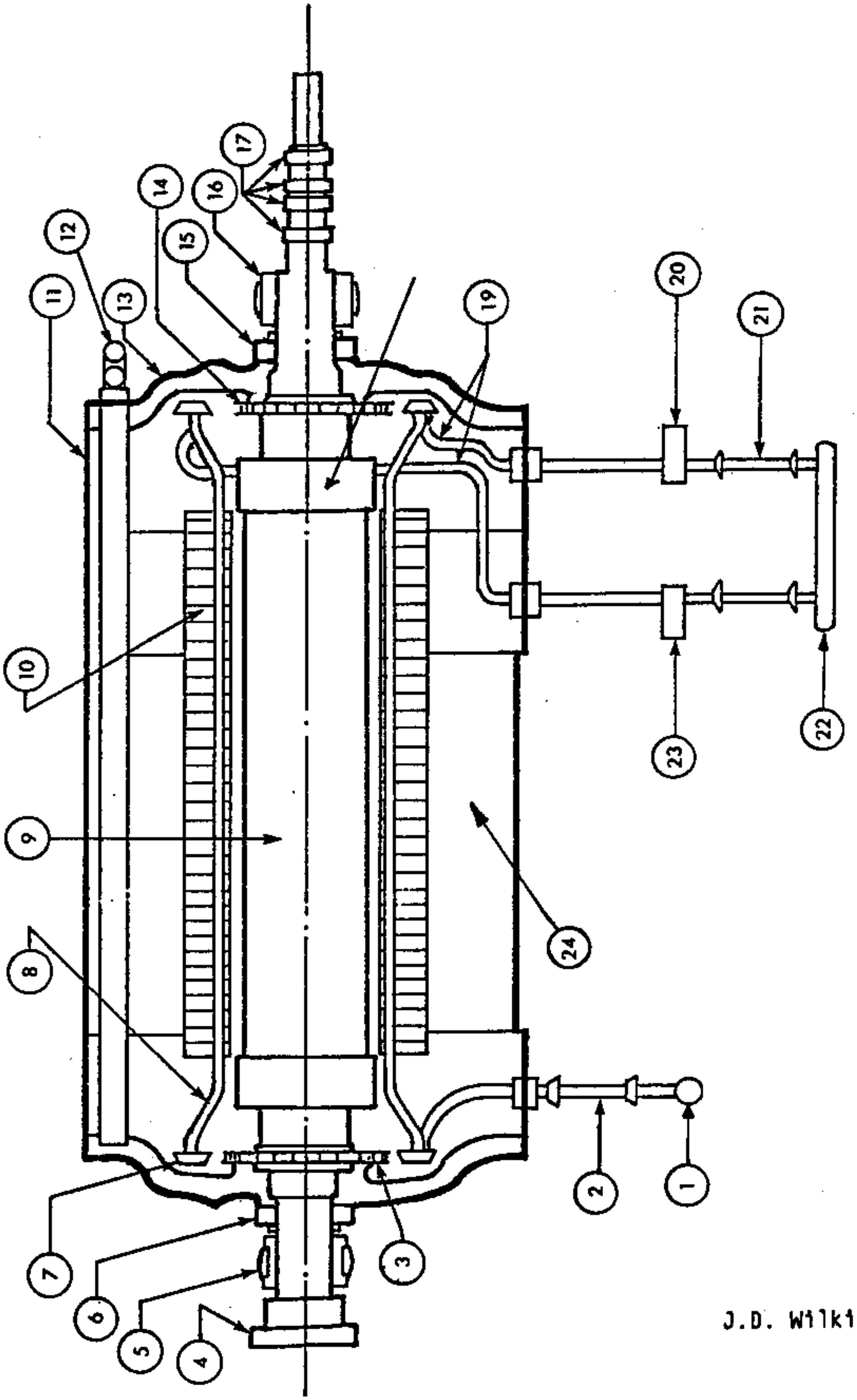
(10) Briefly explain the need for:

(a) A shaft grounding brush. (Section 5.2)

(b) Pedestal/bearing and hydrogen seal insulation. (Section 5.2, 5.3)

(11) Briefly explain the consequences of shorting an <u>insulated</u> generator pedestal to ground, describing how damage may occur. (Section 5.2)

Question #7



J.D. Wilkinson

Electrical Equipment - Course PI 30.2

GENERATOR AUXILIARY SYSTEMS

OBJECTIVES

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

1. State the purpose of the generator stator cooling system.
2. List and briefly explain five operational requirements of the generator stator cooling system.
3. Given a simplified diagram of a typical stator cooling system:
    a) Label each flagged component;
    b) Identify the flow direction of the demineralized cooling water using arrows.
    c) Briefly explain the function of each component in a stator cooling system.
4. State the purpose of the generator hydrogen seal.
5. State three operational requirements of the generator hydrogen seal.
6. Given a cross-sectional diagram of a typical generator hydrogen seal:
    a) Briefly explain its operation;
    b) State the direction of flow of the seal oil within the seal.
7. State the purpose of the generator hydrogen seal oil system.
8. List and briefly explain six operational requirements of the generator hydrogen seal oil system.
9. Given a simplified diagram of a typical generator hydrogen seal oil system:
    a) Label the flagged components correctly;
    b) Briefly explain the function of each component.
10. State the purpose of the generator hydrogen cooling system.
11. List and briefly explain seven operational requirements of a generator hydrogen cooling system.

12. Given a simplified diagram of a large AC generator:

    a) Label the components related to, or cooled by the hydrogen cooling system;
    b) Briefly explain the function of each of the components you identified in (a).
    c) Indicate with arrows, the flow paths of the hydrogen gas.

13. List and briefly explain six precautions with respect to the generator auxiliary systems discussed in objectives 1 to 13 inclusive.

14. a) List and briefly explain five advantages of choosing hydrogen rather than air as a cooling medium for large generators;
    b) List and briefly explain two disadvantages of choosing hydrogen rather than air as a cooling medium for large generators.

1.0 INTRODUCTION

This module will introduce the trainee to:

(a) The generator stator cooling system.

(b) The generator hydrogen seal.

(c) The generator hydrogen seal oil system.

(d) The generator hydrogen cooling system.

(e) Precautions relating to generator cooling systems.

(f) The advantages and disadvantages of hydrogen, compared to air, as a coolant.

2.0 THE GENERATOR STATOR COOLING SYSTEM

2.1 Purpose of The Generator Stator Cooling System

The purpose of the generator stator cooling system is to maintain the copper stator bars and the end core magnetic screen plates within their proper operating temperature range under all operating conditions, by passing cooled, demineralized water through them.

2.2 Operational Requirements of the Generator Stator Cooling System

To ensure safe operation of the generator, five operational requirements must be met. These are:

(i) To provide demineralized cooling water to the generator stator windings and the end core magnetic screen plates, at a controlled pressure below that of the hydrogen pressure, thereby ensuring that any leaks which may occur will result in hydrogen gas entering the stator coolant rather than water entering the generator.

(ii) To detect and alarm if the conductivity of the demineralized water goes up to an unsafe level. The demineralized water must not allow any fault to ground.

(iii) To provide filtration to remove any particulates which could plug the very small bores of the stator tubes.

(iv) To provide venting to atmosphere for any hydrogen gas that becomes entrained in the stator coolant.

(v) To provide for addition of demineralized coolant into a head tank to make up for any loss due to leaks or evaporation from the stator cooling system.

2.3 A Typical Stator Cooling System

Figure 2 is a simplified diagram of a typical stator cooling system, showing typical system components and the direction of the coolant flow. The following are brief explanations of the functions of the major components of the system:

(i) ac Pumps - PM 1, PM 2

Two 100% duty pumps, operating on Class IV ac power, are provided. Either of these pumps can provide 100% of the required flow. Therefore, one pump is in service and the other is on standby.

(ii) Emergency Pump - PM 3

The emergency pump is a 50% duty pump, meaning it is capable of supplying only 50% of the required full power flow. It is powered from Class I and starts automatically if both ac pumps fail. Some stations may not have an emergency pump.

(iii) Check Valves - NV24 and Others

Various check valves are provided to prevent reverse rotation of the pumps and to ensure correct flow direction of the stator coolant.

(iv) Stator Water Coolers - HX1, HX2

In order to minimize demineralized water cost and to prevent ingress of impurities, the demineralized water is recirculated through the stator conductors and the cooling system in a closed loop. Two 100% duty heat exchangers, cooled by low pressure service water, are provided in a parallel configuration. These heat exchangers are vented at their high points.

(v) Strainer and Filter - STR1, FR1

A strainer and filter are provided to remove any particulates from the coolant. Both may be instrumented for differential pressure drop across them and bypassed for maintenance.

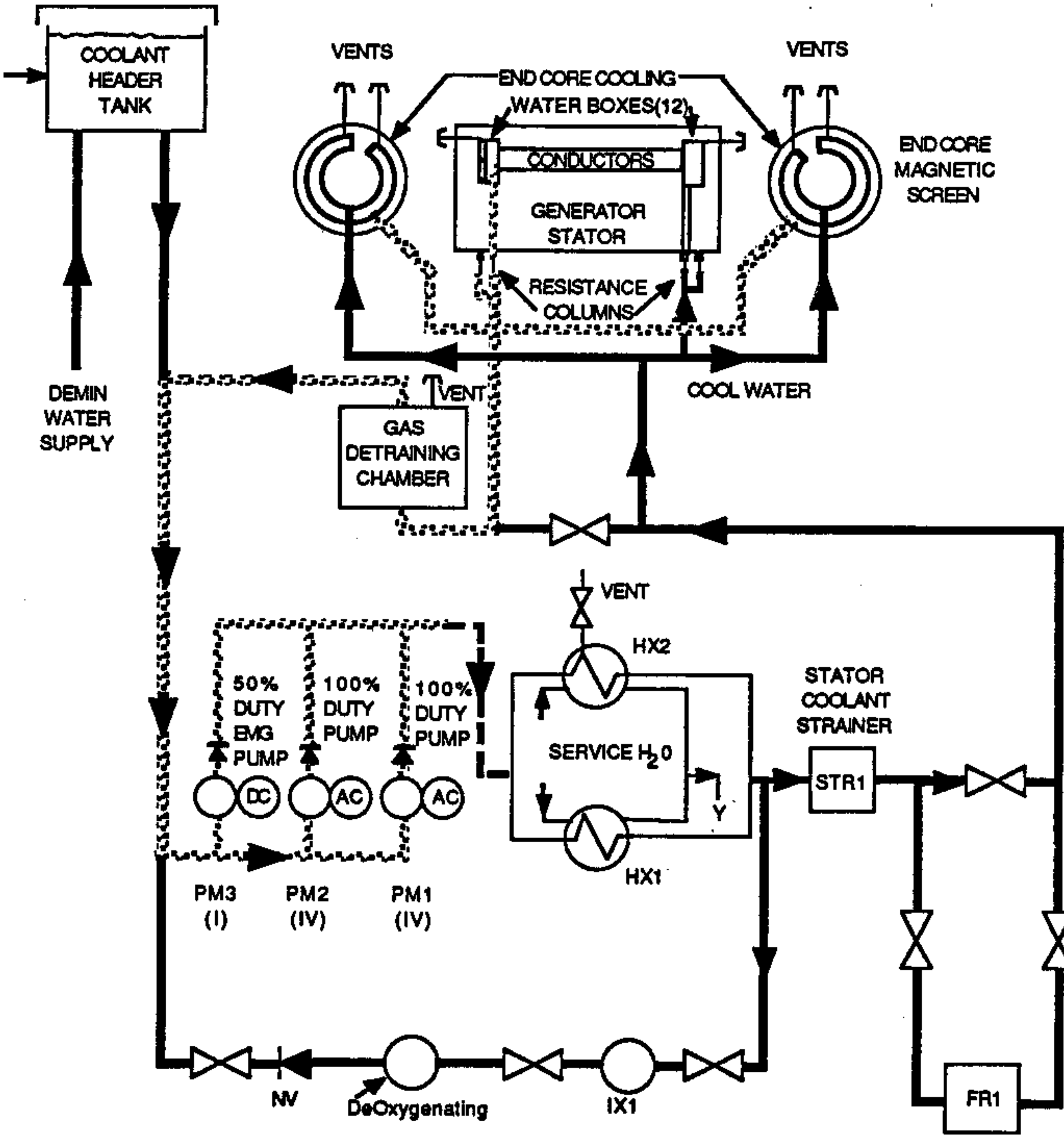


Figure 2: Simplified Diagram of a Typical Stator Cooling System

(vi) Deoxygenating Unit and IX Column - IX1

In order to provide the required insulating properties, the stator water conductivity must be held below preset limits. A typical operating conductivity is in the 0.5 μs/cm range. Since conductivity will tend to rise during operation, an IX column and deoxygenating unit are provided to scrub the demineralized water circulating in the stator cooling system.

(vii) Vents

Vents are provided as shown, at various high points in the stator cooling system, to permit bleeding off of any gases (O_2, N_2, H_2) that might accumulate and cause an "air-lock" to form.

(viii) Coolant Header Tank

The coolant header tank holds a supply of demineralized water at a relatively constant head pressure for the stator coolant system. It is important to keep the stator cooling system filled with demineralized water in order to minimize the corrosion and other forms of contamination that will arise if the stator cooling system is repeatedly opened to the atmosphere.

(ix) Resistance Columns

The resistance columns carry the stator cooling water into or out of the generator while electrically isolating the stator cooling system from the stator conductors. Stator conductor voltages are as high as 24 kV.

(x) Gas Detraining Chamber

The heated outflow from the stator conductors and the end core magnetic screen plates at each end of the generator goes to the gas detraining chamber. Any hydrogen that may have leaked into the demineralized cooling water ($P_{H2} > P_{H2O}$) is separated and vented to atmosphere.

3.0 THE GENERATOR HYDROGEN SEAL

3.1 Purpose of the Generator Hydrogen Seal

Hydrogen seals are provided at each end of the generator to ensure that there is a minimum of hydrogen leakage between the rotating generator shaft and the stationary end cover of the stator. This requires maintaining a continuous seal for operating periods of a year or more, at hydrogen working pressures of 300 - 400 kPa(g), at generator rotor speeds ranging from stationary to 1 800 RPM.

3.2 Operational Requirements of a Generator Hydrogen Seal

Three operational requirements of a generator hydrogen seal are:

(i) It must provide a seal between the generator rotor and the stationary end cover of the generator.

(ii) It must accommodate significant axial movement of the rotor shaft with respect to the generator end cover.

(iii) It must minimize the ingress of oil and/or air to the generator cavity.

3.3 A Typical Generator Hydrogen Seal

Figure 3 is a simplified sectional diagram of a typical generator hydrogen seal. The cool, clean seal oil is supplied to the stationary oil feed chamber at a pressure somewhat greater than the hydrogen pressure in the generator. A preset spring loading, aided slightly by the oil pressure provides an axial force which continuously holds the seal ring toward the shaft ring face. On the front of the seal ring is the soft metal continuous seal face. The oil pressure causes the seal oil to flow through the oil ports to the continuous seal face, where the majority of the oil flows outwards between the seal face and the seal ring and the remainder flows inwards toward the rotor shaft. This flow pattern results in a continuously oil wetted and cooled seal between the rotor shaft and the generator end cover.

Most of the oil flow is required for lubrication and cooling of the seal face. After flowing outwards to the low pressure side of the seal, it is discharged to the bearing drains in the bearing pedestal. Since the oil flow to the hydrogen side is small, the quantity of entrained air released into the hydrogen is very small. It is, therefore, not necessary to vacuum treat the seal oil to remove entrained air. Hydrogen purity is normally maintained without extensive make-up. The small amount of oil which flows to the hydrogen side is drained to the hydrogen detraining tank.

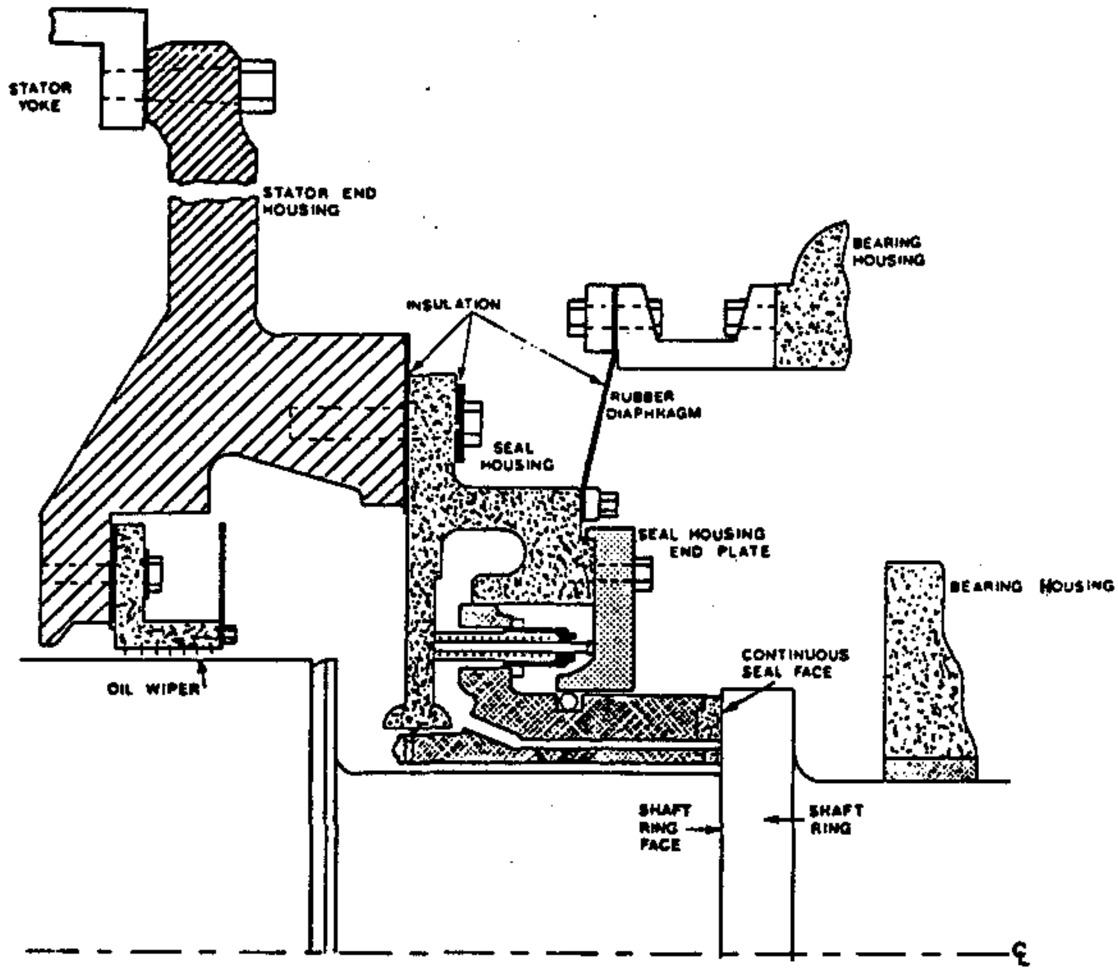


Figure 3: A Section of a Typical Generator Seal

3.4 Radial Hydrogen Seals

The radial oil seal shown in Figure 4 is a newer form of hydrogen seal having no soft metal seal faces. Oil is pumped toward the shaft from two sets of holes in a stationary ring surrounding the generator shaft, forming two rings of oil between the moving shaft and the stationary ring. A central vacuum ring extracts the oil from the seal area. These rings of oil accommodate both axial and radial shaft movement while continuously sealing the hydrogen within the generator.

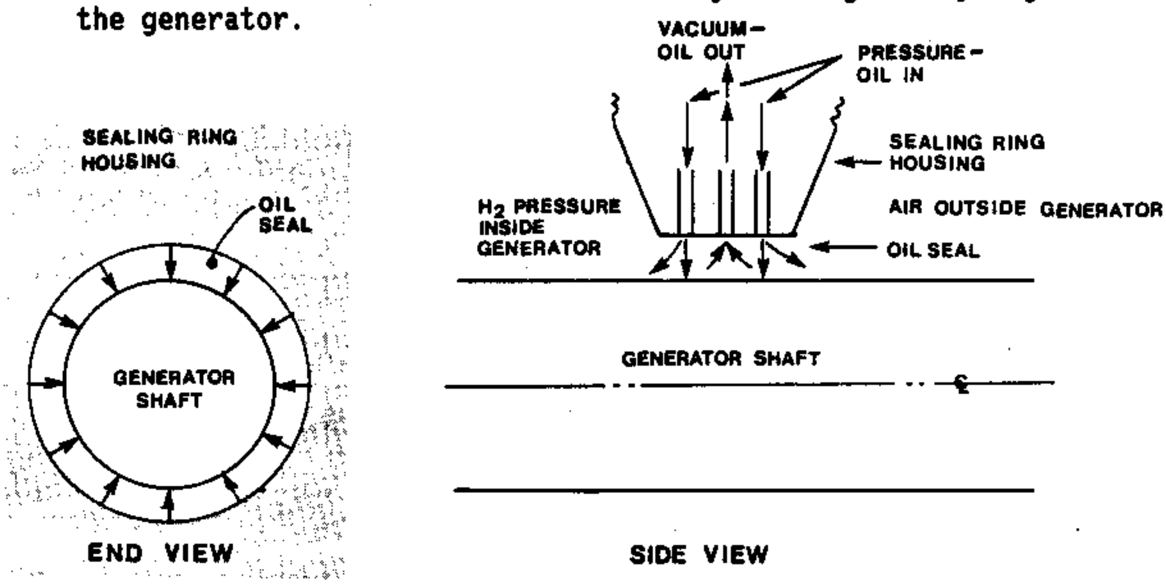


Figure 4: A Typical, Simplified, Radial Hydrogen Oil Seal

4.0 GENERATOR HYDROGEN SEAL OIL SYSTEM

4.1 Purpose of the Generator Hydrogen Seal Oil System

The purpose of the generator hydrogen seal oil system is to clean, lubricate and cool the hydrogen seal face while providing the required sealing pressure.

4.2 Operational Requirements of the Generator Hydrogen Seal Oil System

It was indicated in Section 3.3 above that the seal oil flows through the seal to the seal face in order to cool and lubricate the seal face and provide the dynamic, hydrogen seal. Six operational requirements of the seal oil system are:

(i) To provide sufficient oil flow to keep the seal face lubricated and cooled under all operating conditions.

(ii) To maintain the oil at a predetermined differential pressure, greater than the hydrogen pressure in the generator, and thereby provide the actual hydrogen seal.

(iii) To maintain the seal oil at the correct operating temperature under all operating conditions.

(iv) To provide filtration to remove any particulates which could score the soft metal seal face.

(v) To remove entrained hydrogen from the oil and vent the hydrogen safely to atmosphere.

(vi) To provide an emergency oil supply in the event of failure of the main seal oil pumps.

4.3 A Typical Generator Hydrogen Seal Oil System

Figure 5, is a simplified diagram of a typical generator hydrogen seal oil system, showing the system components and the direction of the oil flow. The following is a brief description of the function of the major components:

4.3.1 Oil From Main Turbine Oil System

The seal oil is normally supplied from the main turbine lubricating oil system via a turbine shaft driven pump and pressure relief valve (PRV).

4.3.2 AC Seal Oil Pump

If the turbine shaft driven pump is unable to provide suitable seal oil pressure, a Class IV ac pump is used. The combination of shaft driven and/or ac pumps will vary from station to station.

4.3.3 DC Seal Oil Pump

If the main oil pump and ac oil pump are unable to provide suitable seal oil pressure, a Class I dc pump starts automatically. The filters and coolers are bypassed by the oil which flows from the dc seal oil pump to the seals. Some stations will have alternate backup/emergency oil supplies.

Note that the provision of redundant oil pumps and different pump motor power supplies helps to ensure that the hydrogen seal will be maintained and kept properly cooled and lubricated whenever the generator is in any operating state other than shutdown and air filled.

4.3.4 Pressure Controls and Alarms

Various pressure controls and alarms are provided to maintain the seal oil pressure at a fixed differential above the hydrogen pressure, to provide alarms for low oil pressure and to start pumps when required.

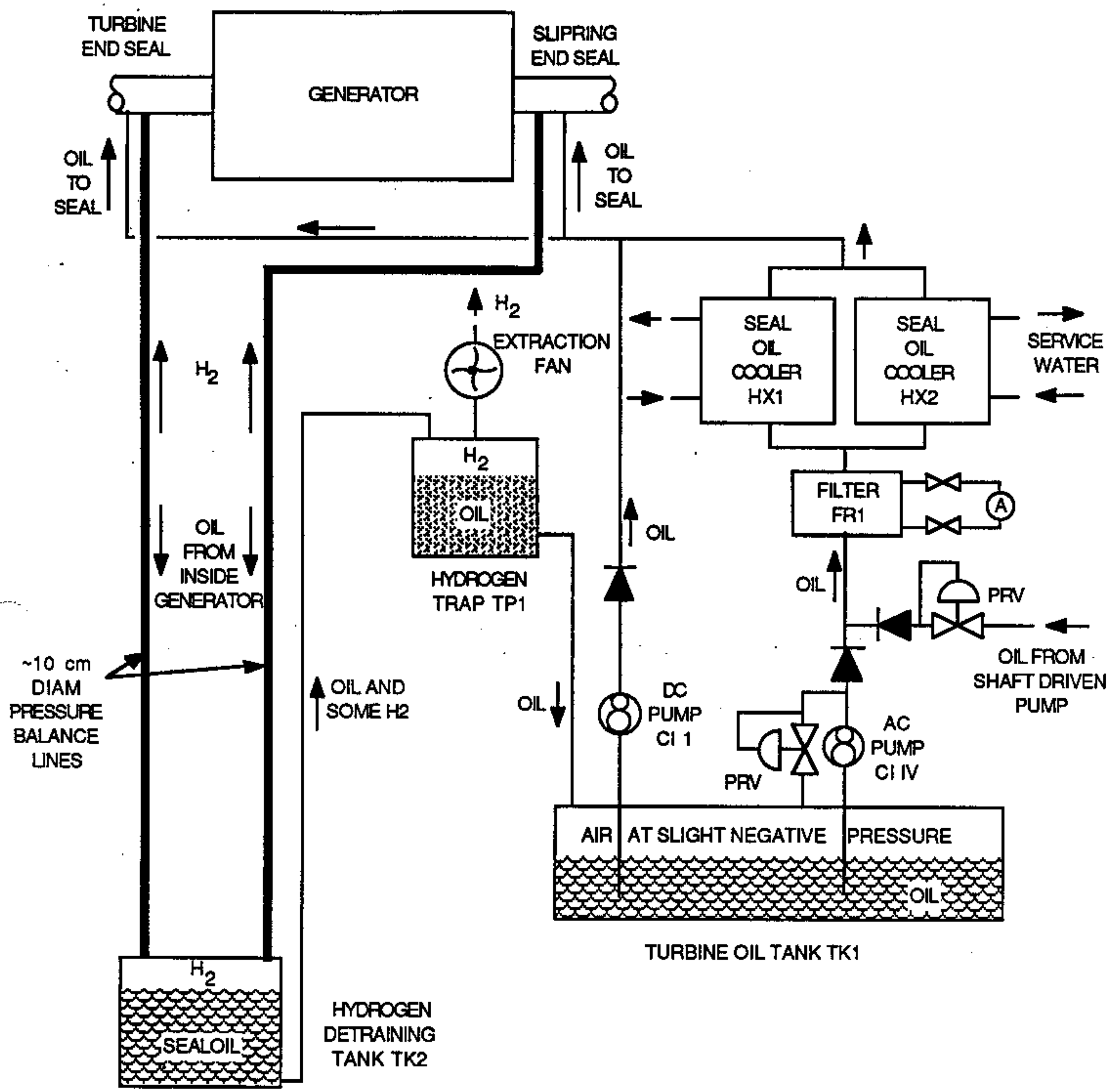


Figure 5: Simplified Circuit of the Seal Oil System

4.3.5 Seal Oil Filters and Coolers

The seal oil filters are provided to remove any particulates from the oil before it is supplied to the generator hydrogen seals. The filters are instrumented for high ΔP across the input/output lines. The coolers cool the oil before it flows through the seals, thereby maintaining the soft-metal seal faces within their operating temperature range. The seal oil temperature is controlled via the seal oil coolers which are supplied by manually operated service water valves. Thermocouples embedded in the seal face are used to monitor for high seal face temperatures.

4.3.6 Detraining Tank

The major portion of the seal oil flow drains to the bearing sumps and then to the turbine and seal oil tank.

The small amount of seal oil that flows inwards to the hydrogen side then drains down to the hydrogen detraining tank via a sight glass and $\approx$ 10 cm diameter pressure balance line. In the detraining tank, the entrained hydrogen separates from the oil. The oil is forced up to the hydrogen trap by the generator hydrogen pressure.

4.3.7 Hydrogen Trap and Extraction Fan

Any hydrogen remaining in the oil is removed in the hydrogen trap and is safely vented to atmosphere by an extraction fan. The seal oil flows by gravity down to the turbine and seal oil tank.

4.3.8 Turbine and Seal Oil Tank

This large tank provides a sump for all of the oil used in the turbine lubricating and seal oil systems.

5.0 GENERATOR HYDROGEN COOLING SYSTEM

5.1 Purpose of the Generator Hydrogen Cooling System

The purpose of the generator hydrogen cooling system is to maintain the generator rotor and the stator iron within their proper operating temperature ranges under all operating conditions.

5.2 Operational Requirements of the Generator Hydrogen Cooling System

As was indicated in PI30.23-1 heat is removed from the generator rotor and the stator iron by continuously passing hydrogen gas through them. Seven operational requirements of the generator hydrogen cooling system are:

(a) To continuously recirculate the hydrogen gas within the generator.
(b) To cool the hydrogen to the required temperature.
(c) To dry the hydrogen to the required dewpoint.
(d) To maintain the correct hydrogen gas pressure in the generator by providing make-up hydrogen to compensate for leaks.
(e) To provide an alarm for liquid oil or water within the generator cavity.
(f) To monitor the hydrogen gas purity.
(g) To provide CO_2, Air and H_2, for purging and charging the generator.

5.3 A Typical Generator Hydrogen Cooling System

Figure 6 is a simplified diagram of a typical, large generator showing the directions of the hydrogen flow within the generator. The following are brief explanations of the functions of the major components of the generator hydrogen cooling system.

5.3.1 Centrifugal Fans, Hydrogen Flow Paths

The centrifugal fans located at each end of the rotor draw hydrogen from the "air gap" between the rotor and stator and blow it through the coolers located within the generator yoke. From the coolers the hydrogen is directed to both the stator iron and to the rotor. The cool hydrogen passes through ducts in the stator iron and enters the air gap from the centre portion of the stator iron. The cooled hydrogen is also directed to the rotor ends by sheet metal shrouding and enters the end bells, percolates through and along the rotor windings and emerges into the air gap along the centre portion of the rotor.

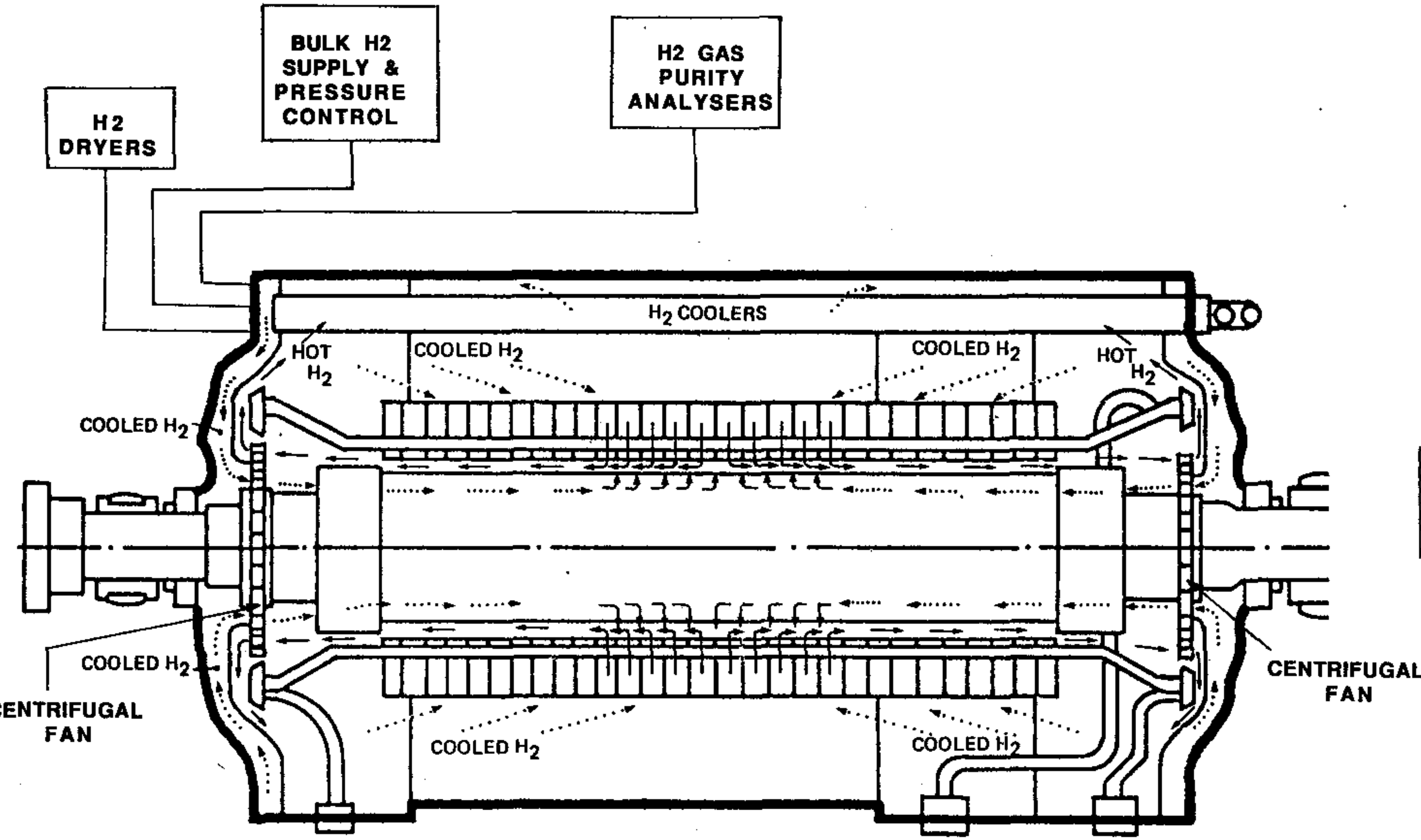


Figure 6: A Typical Generator Hydrogen Cooling System

5.3.2 Hydrogen Coolers

The hydrogen coolers are long, finned, U-tube units mounted axially in compartments located in the generator yoke. (Also, see Figures 5 and 6 of PI30.23-1). Service water is circulated through the cooler tubes. The hot hydrogen passes over the finned tubes, loses its heat to the service water and then flows on to cool the stator iron and rotor conductors. The hydrogen temperature is controlled by automatically regulating the flow of service water to the coolers, using RTDs within the stator to measure the hydrogen temperature.

5.3.3 Gas Supplies - H_2, CO_2 and Air

Hydrogen from a bulk storage system is fed to the generator via a pressure regulating valve. The H_2 pressure within the generator is held relatively constant by the hydrogen make-up system.

CO_2 from portable bottles is used to purge hydrogen or air from the generator when required. The CO_2 is then displaced by clean, dry air if the generator is to be opened for maintenance.

5.3.4 Hydrogen Dryer

Typically, the hydrogen dryer will be a twin tower type using beds of activated alumina. Cycle times are adjusted to suit the drying load. Refrigeration type driers are used in some stations.

5.3.5 Hydrogen Gas Analyzer

The gas analyzer unit analyzes the H_2 purity when the generator is at operating speed. A low purity alarm is provided. A portable gas analyzer is used when charging and discharging the generator.

The primary significance of hydrogen purity is the requirement to avoid an explosive H_2/Air mixture, ie, H_2 content must be above 96% or below 5%.

6.0 PRECAUTIONS

There are six major precautions related to the generator cooling systems discussed in this lesson. This section is a review and consolidation of the previous material.

(a) Stator Cooling Water Conductivity

Since the large generators used in NGS operate at 18 000 volts ac or above, it is absolutely essential that the stator cooling water conductivity be kept low enough to provide adequate electrical insulation. This is both a personnel and an equipment concern.

(b) Hydrogen/Air Concentrations

The hydrogen/air concentration must be kept outside the explosion range to avoid serious damage to equipment and possible fire injury to personnel.

(c) Hydrogen to Seal Oil Differential Pressure

The seal oil pressure must be greater than the hydrogen pressure to prevent leakage of hydrogen from the generator. Again the concern is for personnel and hardware.

(d) Hydrogen to Stator Water Differential Pressure

To prevent leakage of liquid water from the stator system into the hydrogen, the hydrogen pressure must be greater than the stator cooling water pressure. Liquid water inside the generator represents a physical impact hazard to the spinning rotor and is also potentially an electrical short circuit hazard if it picks up impurities.

(e) Hydrogen Dryness

To prevent condensation and possible ground faults within the generator, the hydrogen gas which is circulating in the generator must be kept dry enough to always be above the dewpoint. To assist in the prevention of condensation, the stator cooling water temperature must always be above the hydrogen temperature.

(f) Drains

Any leakage of liquid, oil or water into the generator can cause severe physical damage. The drains from the bottom of the generator must be operational.

7.0 HYDROGEN GAS AS A COOLANT

Five advantages relating to the choice of hydrogen rather than air as a cooling medium in large NGS generators are discussed very briefly below:

(a) Density

Hydrogen gas has a lower density than air, so windage losses are less and less fan power is required for circulation. This low density permits higher working pressures thereby increasing heat removal capability.

(b) Specific Heat Capacity

Hydrogen has approximately seven times the specific heat capacity of air.

(c) Mass Flow

The cooling capability and, hence, the output of the machine is significantly increased, without a corresponding increase in windage losses, by pressurizing the hydrogen.

(d) Insulation Life

When a machine is hermetically sealed and kept free of oxygen, the interior is less subject to contaminants. This prolongs insulation life.

(e) Fire

A fire hazard inside the generator is eliminated because the pure hydrogen atmosphere inside the generator will not support combustion.

Disadvantages relating to the use of hydrogen as a cooling medium are:

(a) Explosion Hazard

Hydrogen in air is explosive, between 5% and 96% concentration. The hydrogen/air ratio must not be permitted to reach the explosion range either inside or outside the generator.

Systems must be provided to achieve this criteria.

(b) Hydrogen Seals/Supply

The provision and maintenance of rotating seals increases both design complexity and maintenance requirements.

A bulk hydrogen supply is required to fill and pressurize the machine with clean, dry hydrogen.

ASSIGNMENT

(1) With respect to the generator stator cooling system shown in the attached diagram:

(a) State its purpose.

(b) List and briefly explain five operational requirements of the stator cooling system.

(c) Identify the numbered components.

(d) Briefly explain the function of each component identified in (c).

(e) Using arrows, identify the flow direction of the stator cooling water.

(2) With respect to the generator hydrogen seal shown in the attached diagram:

(a) State its purpose.

(b) State three operational requirements of the seal.

(c) Briefly explain its operation.

(d) State the flow directions of the seal oil.

(3) With respect to the generator hydrogen seal oil system shown in the attached diagram:

(a) State its purpose.

(b) List and briefly explain six operational requirements of the system.

(c) Identify the numbered components.

(d) Briefly explain the function of each component identified in (c).

(4) With respect to the generator hydrogen cooling system shown in the attached diagram:

   (a) State its purpose.

   (b) List and briefly explain seven operational requirements of the system.

   (c) Identify the numbered components.

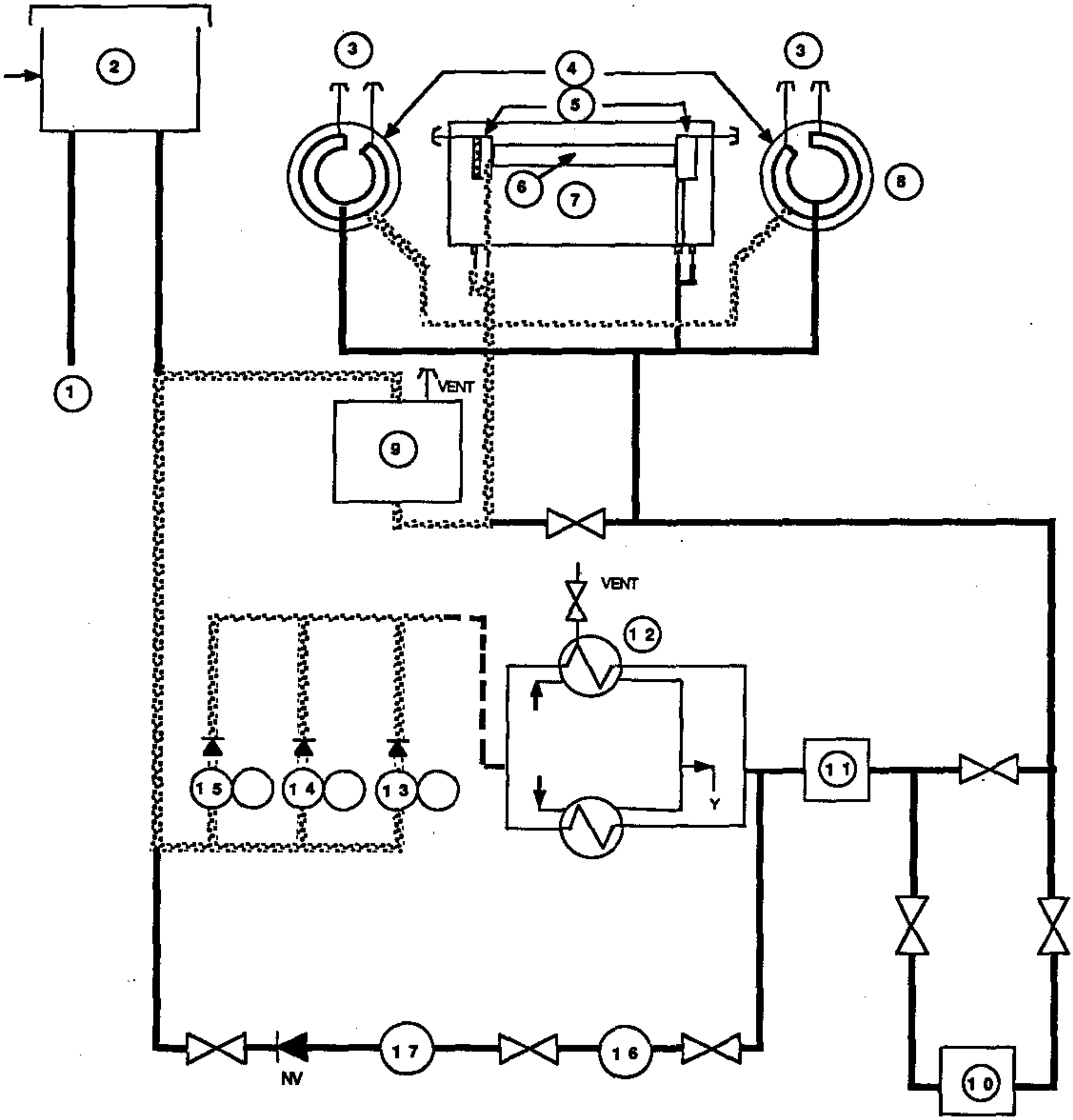
   (d) Briefly explain the function of each component identified in (c).

   (e) Using arrows, identify the flow paths of the hydrogen gas.

(5) List and briefly explain six precautions related to the generator cooling systems used with the large turbo-generators in NGS.

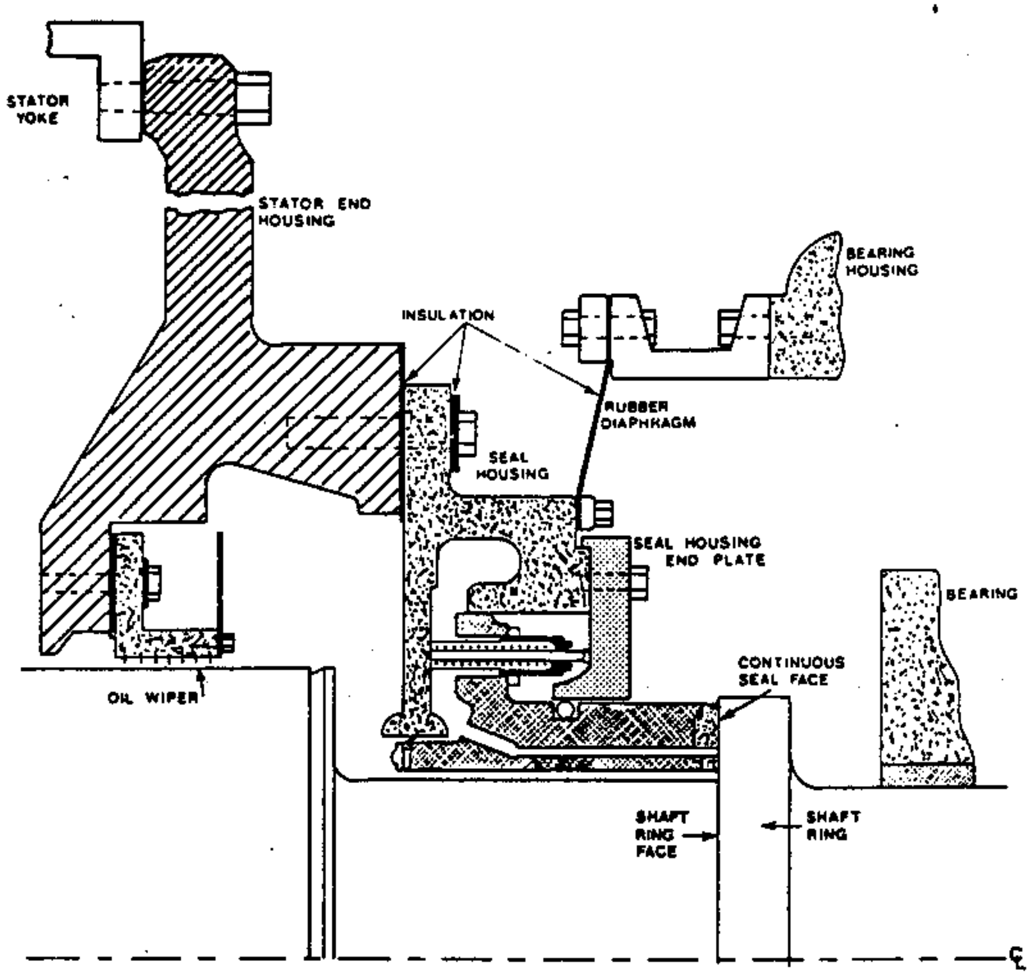
(6) List and briefly describe five advantages and two disadvantages related to the use of hydrogen as a coolant in large generators in NGS.

QUESTION #1



Simplified Diagram of a Typical Stator Cooling System

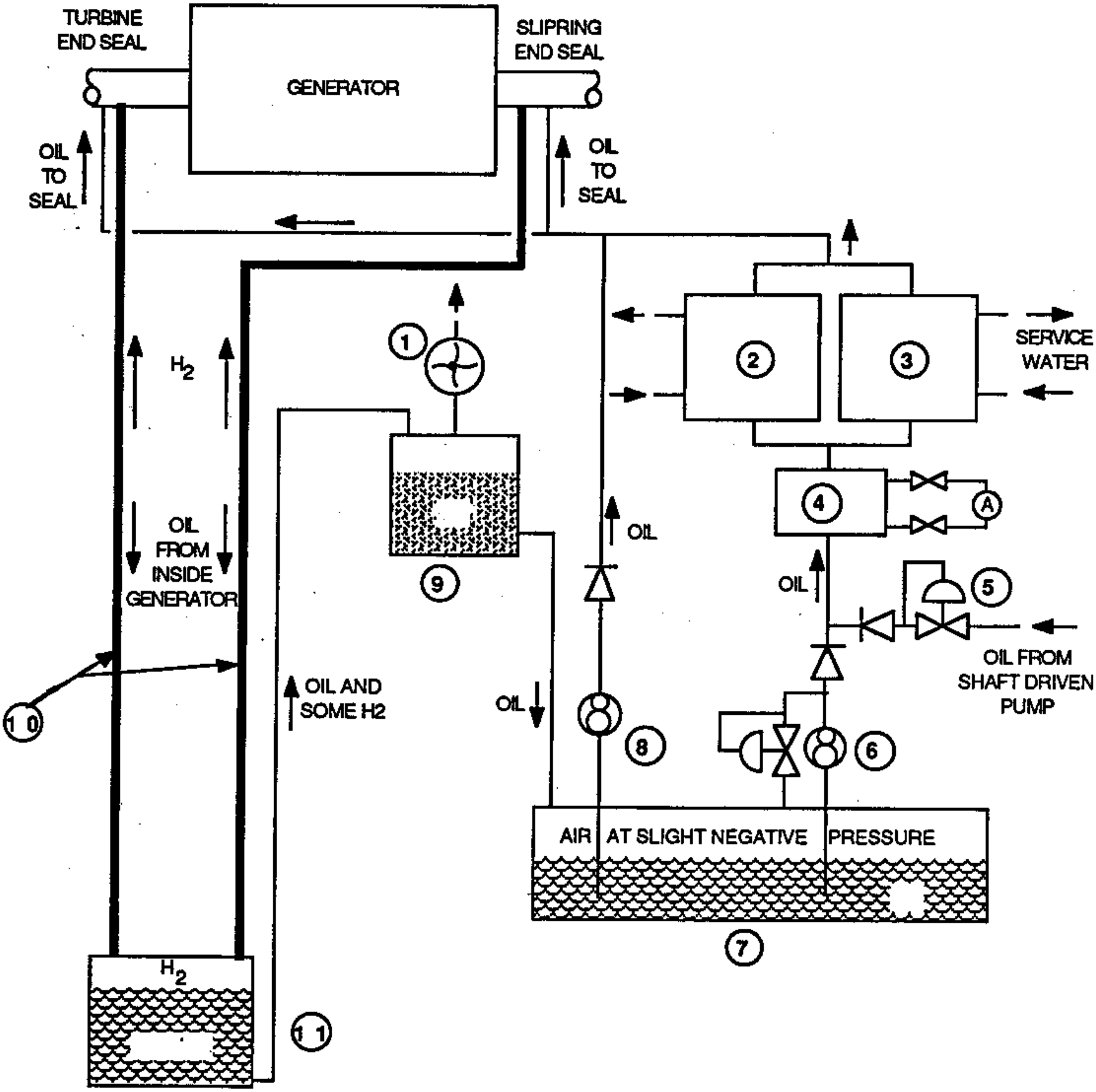
QUESTION #2



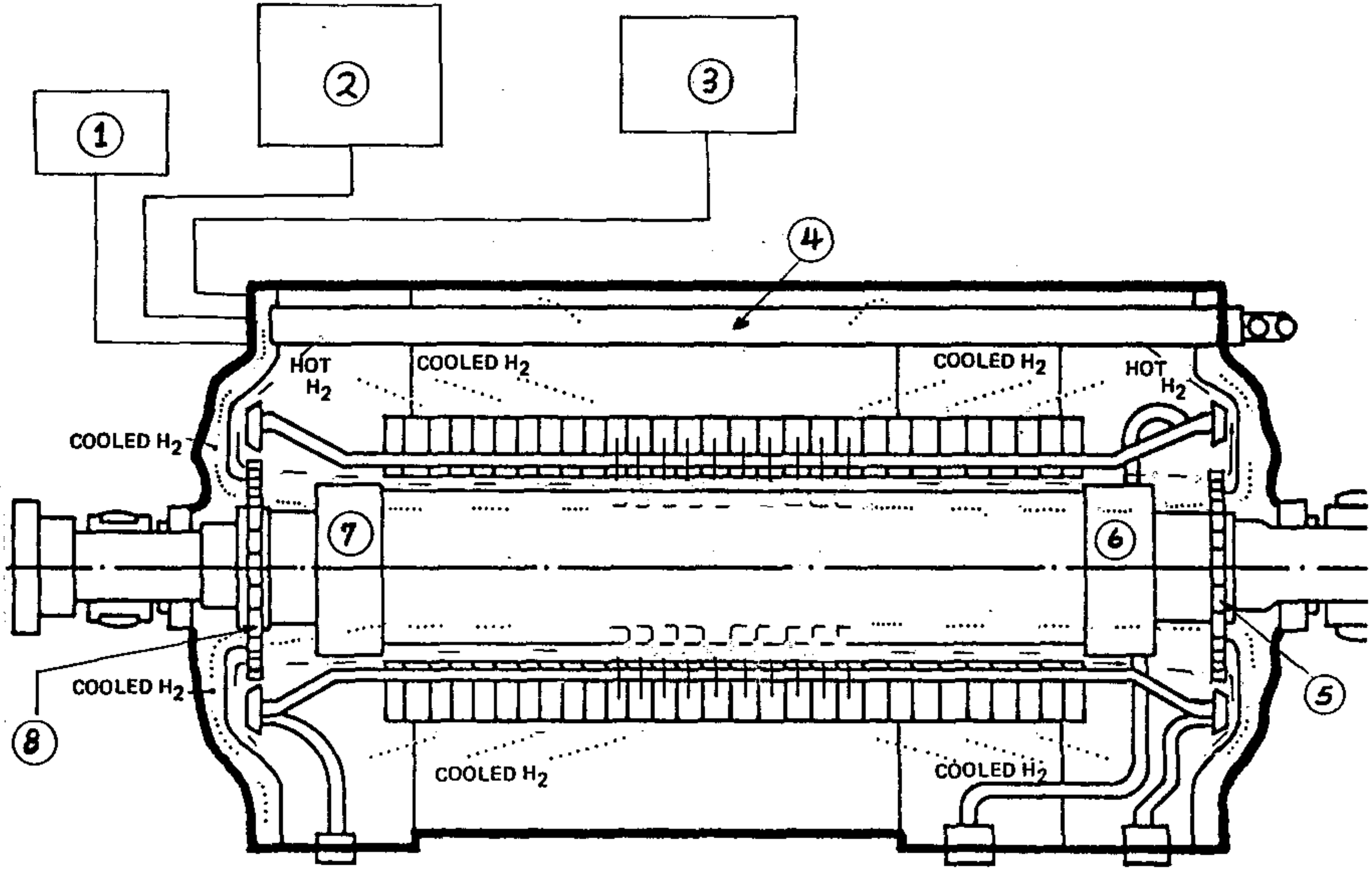
Section of a Generator Hydrogen Seal

Section of a Generator Hydrogen Seal

QUESTION #3



Simplified Circuit of a Typical Seal Oil System



A Typical Generator Hydrogen Cooling System

Electrical Equipment - Course PI 30.2

MOTORS

OBJECTIVES

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

1. Briefly explain, in writing, "shaft rotation" as an interaction of stator and rotor magnetic fields.

2. Draw and properly label the characteristic curves of the squirrel cage induction motor for:
   a) torque vs speed;
   b) current vs speed.

3. Explain briefly, in writing, the following terms, as related to a squirrel cage induction motor:
   a) Torque;
   b) Starting torque;
   c) Running torque;
   d) Pull out torque.

4. State, in writing, that the starting current is about = 6 x full load current.

5. Briefly explain, in writing, the following terms, as related to a squirrel cage induction motor:
   a) Motor full load current;
   b) Synchronous speed including the mathematical expression for synchronous speed;
   c) Slip speed, including the mathematical expression for slip speed.

6. Briefly explain, in writing, the meaning of the following nameplate data for a squirrel cage induction motor:
   a) HP
   b) RPM
   c) Volts
   d) Cycles
   e) Amps
   f) Phase
   g) Service Factor
   h) Time rating
   i) Insulation Class
   j) Maximum Ambient Temperature

6. k) CEMA Designation
   l) Frame
   m) Type.

7. Recall, and briefly explain the two basic types of enclosures for squirrel cage induction motors and give an application for each type.

8. In writing, briefly discuss the difference between the two methods of cooling used in each type of motor enclosure.

9. Briefly, in writing, state the consequence of changing the phase sequence, in a three phase induction motor.

1. Introduction

This lesson will introduce the reader to:

(a) What is a motor.
(b) Introduction to basic motor theory.
(c) Motor characteristics.
(d) Motor nameplate data.
(e) Motor cooling.

2. What Is a Motor

A motor is an electromechanical device which converts electrical energy into mechanical energy. Input to the motor is electrical energy. Output from the motor is rotation of the motor shaft, which delivers the required torque to a load. Load on the motor can be anything that needs to be rotated.

3. Motor Theory

Refer to the explanation of magnetic affects of electrical current and principle of electromagnetic induction, in the lesson on "Generators".

3.1 Electromagnetic Force

Consider a conductor through which a current is flowing. See Figure 1, below.

Current going away from the reader, into the page. Current direction is represented by '+' (tail of an arrow.)

Current coming towards the reader, out of the page. Current direction is represented by '.' (head of arrow).

Figure 1

3.1 Electromagnetic Force (continued)

Now consider a fixed magnetic field and a conductor carrying current placed in the magnetic field. See Figure 2.

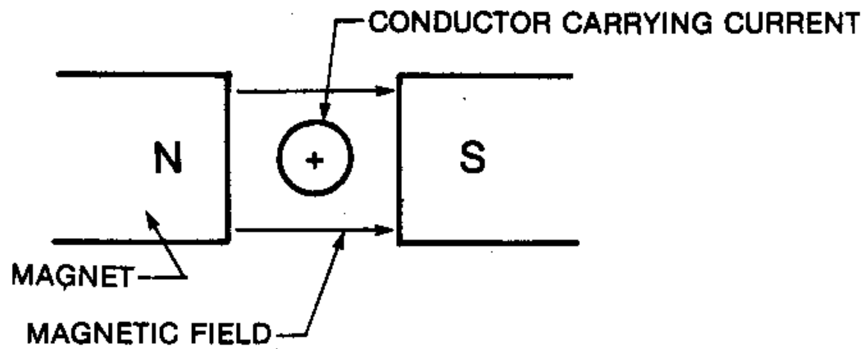


Figure 2: Current Carrying Conductor in a Magnetic Field

The direction of current in the conductor, as shown, is away from the reader, into the page.

When the current flows through the conductor, a magnetic field is developed around the conductor. The direction of the magnetic field can be determined by the right-hand rule. See Figures 3(A) and 3(B).

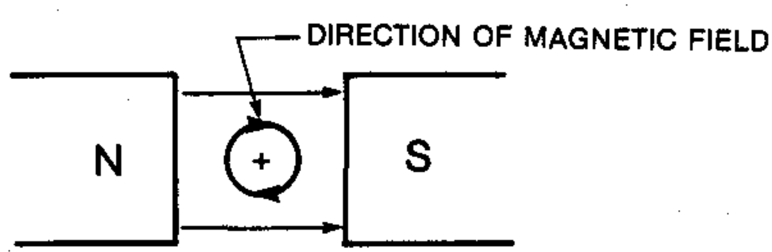


Figure 3(A): Magnetic Field Around the Conductor

3.1 Electromagnetic Force (continued)

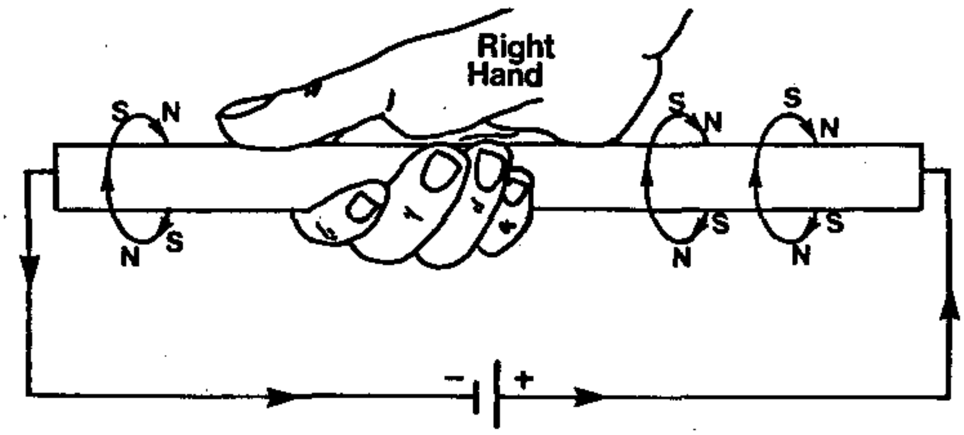


Figure 3(B): Right hand Rule for determining Direction of Magnetic Lines of Force around a Straight, Current-Carrying Conductor.

3.1 Electromagnetic Force (continued)

Now there are two magnetic fields (think of them as two forces) namely:

(a) Magnetic field from the permanent magnet.
(b) Magnetic field around the conductor due to the current flow through it. Interaction of the two magnetic fields is as follows:

- At the top of the conductor, the two fields are additive (in the same direction).
- At the bottom of the conductors, the two fields are subtractive (in the opposite direction).

As a result, the conductor, if free to move, will move in the downward direction. See Figure 4.

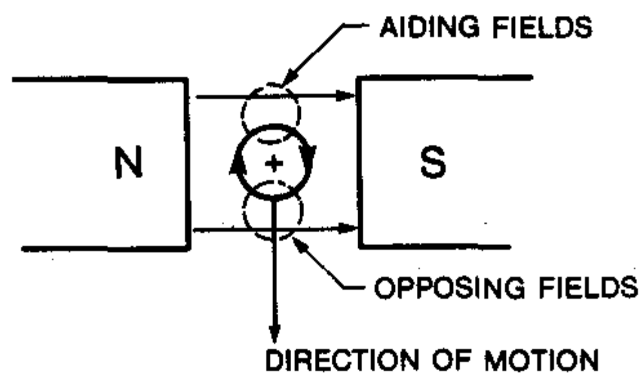


Figure 4: Interaction of the Two Magnetic Fields and the Resultant Direction of Motion

The above analysis can be applied, if the direction of the current through the conductor is changed. See Figure 5.

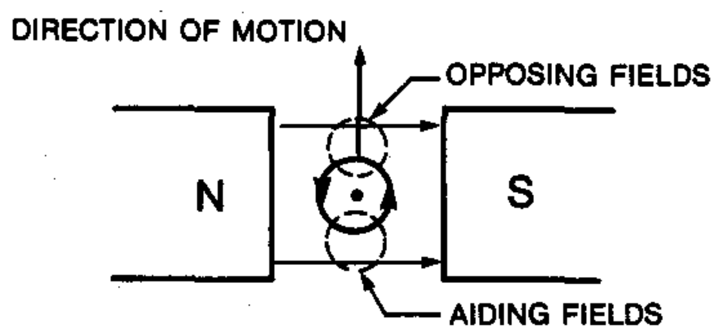


Figure 5: Upwards Motion of Conductor With a Change in Current Direction

Now consider a conductor in loop form. See Figure 6. Note the following:

- Current from the supply goes through one side of the loop and returns through the other side. Hence, the direction of current through each side of the loop is different.

- The direction of magnetic fields around each side are different.

- The direction of motion on each side is different.

If the conductor loop is mounted on a shaft through its centre as shown in Figure 6, and the shaft is mounted on bearings at the two ends, the conductor and the shaft will rotate.

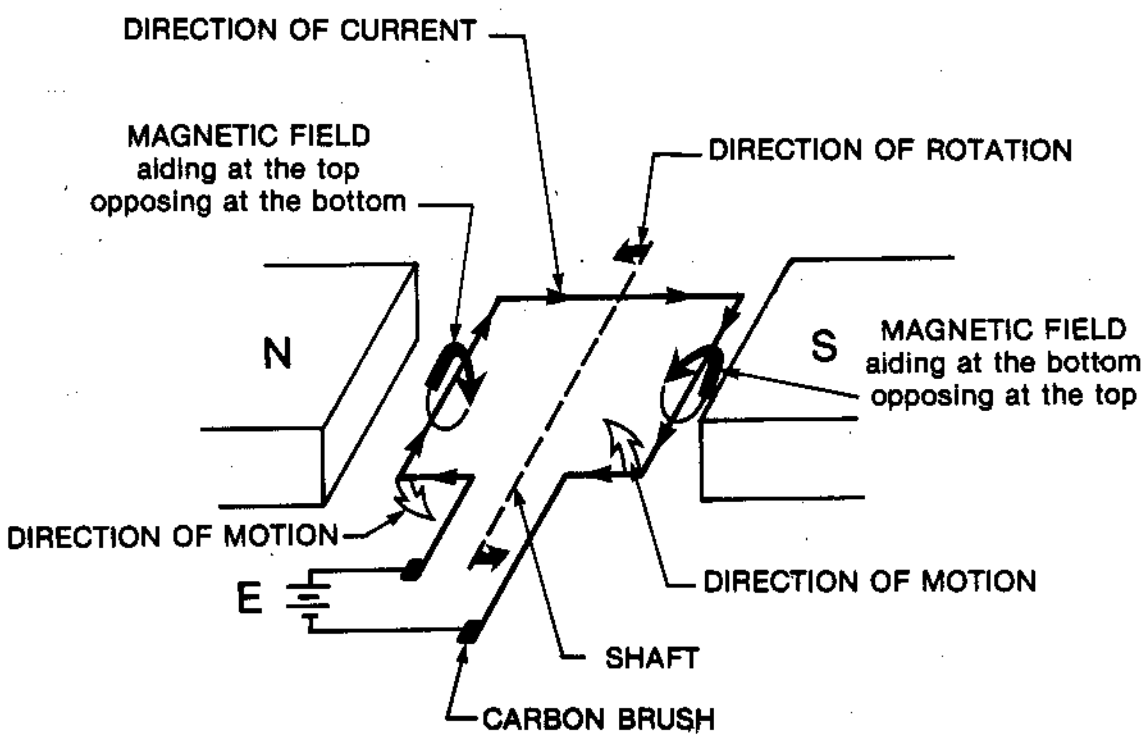


Figure 6: Current Supplied to a Loop and The Resulting Direction of Motion

3.1 Electromagnetic Force (continued)

The magnetic force produced, to cause the rotation of the shaft, is expressed below:

$$F(\text{newtons}) = B \cdot I \cdot L \text{ (do not memorize)}$$

where: F is the force produced by the interaction of the two magnetic fields, in Newtons.
B is the magnetic flux density of the permanent magnet, in Teslas.
L is the length of the conductor in the magnetic field, in metres.
I is the magnitude of current flow through the conductor in amperes.

The above presentation explains the operation of a DC motor.

3.2 AC Motor

Mechanical motion is still produced in an AC motor by the interaction of two magnetic fields. However, how the two fields are obtained is different and is explained in the sections below.

Rotating Magnetic Field

When a three phase supply is connected to the stator of an AC motor, a resultant rotating magnetic field, of constant magnitude is produced. For an explanation, see Appendix A, at the end of this lesson (for information only).

3.3 Rotor Construction

The rotor of an AC motor is made of conductors, which are shorted at the two ends by a short circuiting ring at each end. Figure 7 shows the basic construction of a **rotor of squirrel cage induction motor** (SCIM). This AC motor is referred to as a SCIM because it operates on the induction principle (discussed later) and the way its rotor is constructed.

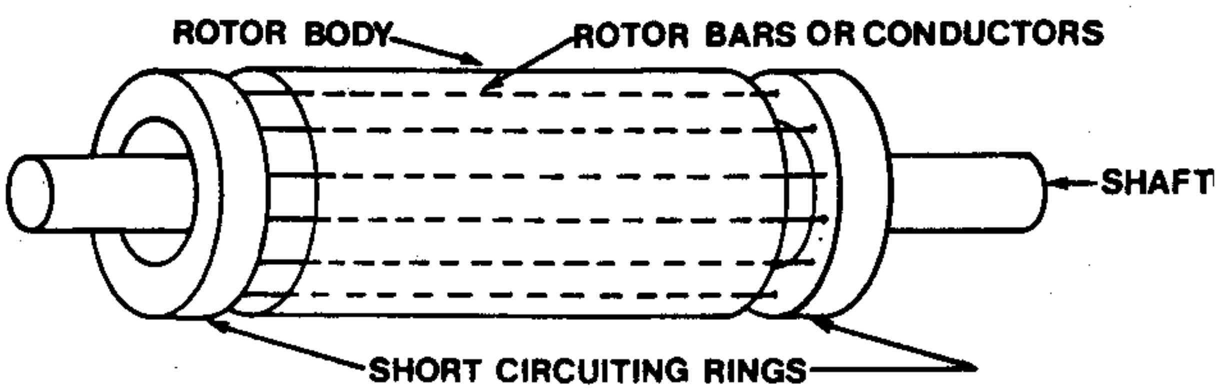


Figure 7: Rotor in an Inductor Motor

With smaller motors, the rotor windings and short circuiting rings are cast directly into the supporting rotor iron. The fan blades are cast onto the short circuiting rings. With large motors, the rotor winding consists of copper bars brazed to copper short circuiting rings. With this design, the fan is usually separate.

3.4 Stator

The induction motor stator windings are inserted and wedged in slots punched in the laminated stator iron. This is a similar arrangement to that used in a generator. The stator iron is securely clamped in the frame of the motor. The bearings are mounted in the end plates. Three phase input power lines are connected to the respective stator windings in a terminal box.

3.5 Rotation of Shaft in an AC Motor

When a three phase supply is connected to the stator windings of an AC motor, a rotating magnetic field is produced, which continually rotates 360°. The rotation of this magnetic field constitutes a "relative motion" between the motionless rotor conductors and the magnetic field. As a result, all the three requirements (conductor, magnetic field and relative motion) are met and a voltage is induced in the rotor conductors.

Since the rotor conductors are short circuited by the short circuiting rings at the two ends, a current flows through the rotor conductors and produces its own magnetic field.

Interaction of the rotor magnetic field and the stator magnetic field produces the rotation of the shaft the same way as explained in Section 3.1

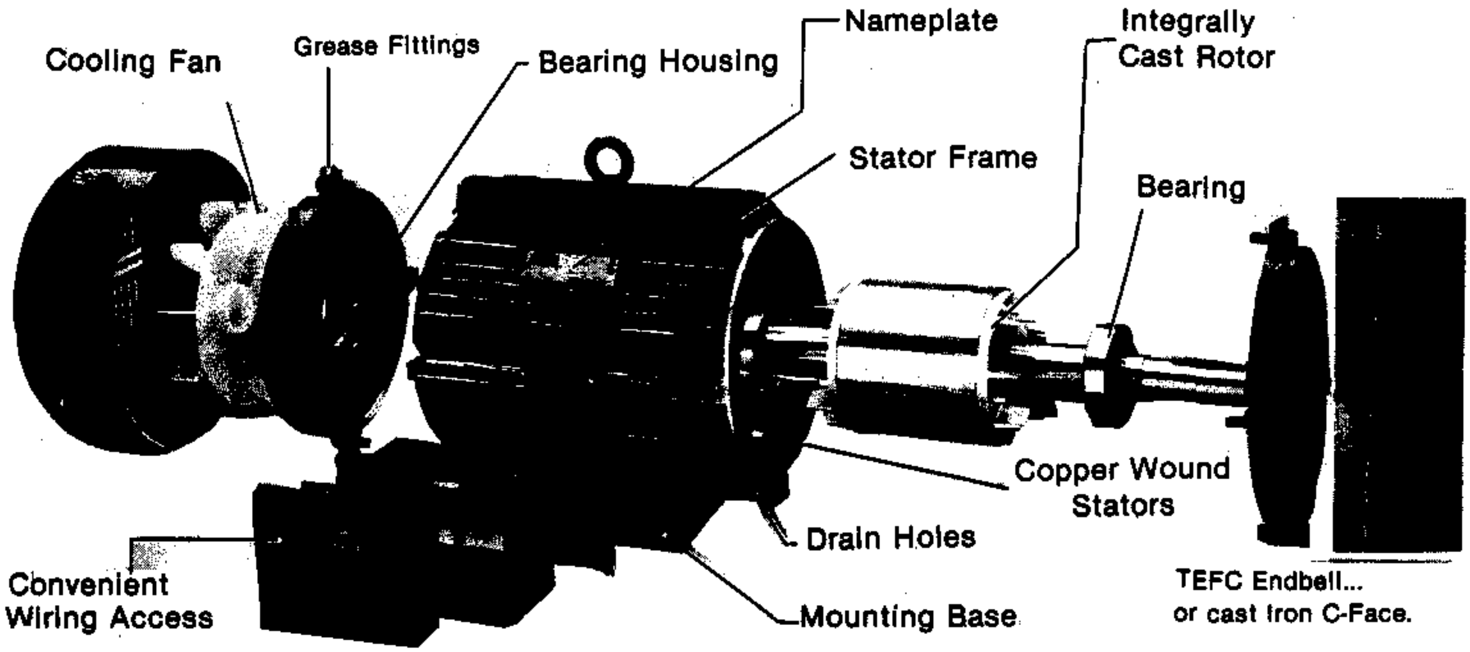


Figure 8: Cutaway View of a SCIM (Squirrel Cage Induction Motor)

4. Motor Torque

The tendency to produce rotation is referred to as **torque.** Figure 9 shows the torque-speed characteristic curves of a motor. The unit of torque is the Newton-meter. The motor running speed and the motor running torque is determined by the characteristics of the load which is coupled to the motor (i.e. a pump). A typical load torque curve is also shown in Figure 9. The motor will always try to deliver the exact amount torque required by the load. This would be where the motor torque and load torque curves intersect.

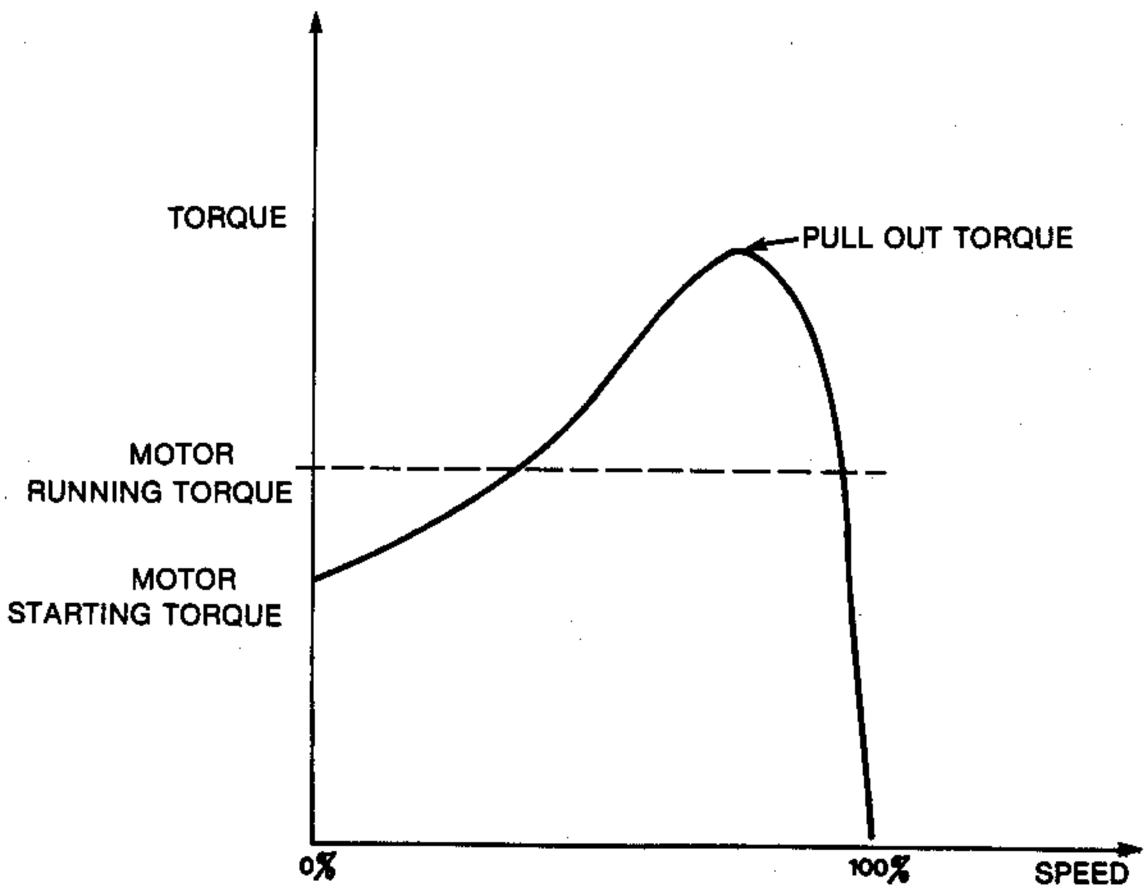


Figure 9: Torque Speed Characteristic Curve of a Motor

4. Motor Torque (continued)

4.1 **Motor Starting Torque:** It is the torque motor delivers when started from standstill position. It is also referred to as **locked rotor torque.**

4.2 **Motor Running Torque:** It is the torque at which the demanded by the mechanical load placed on the motor is equal to the torque produced by the motor. It is the equilibrium point between the mechanical load and the motor.

4.3 **Motor Pull Out Torque;** It is the maximum torque developed by an induction motor at rated voltage and frequency. If the torque demand is increased beyond this point, the motor will stall.

5. Motor Current

Figure 10 shows a chracteristic curve of motor current vs speed. Motor-full load current is the current which the motor draws at the rated voltage, frequency, and torque.

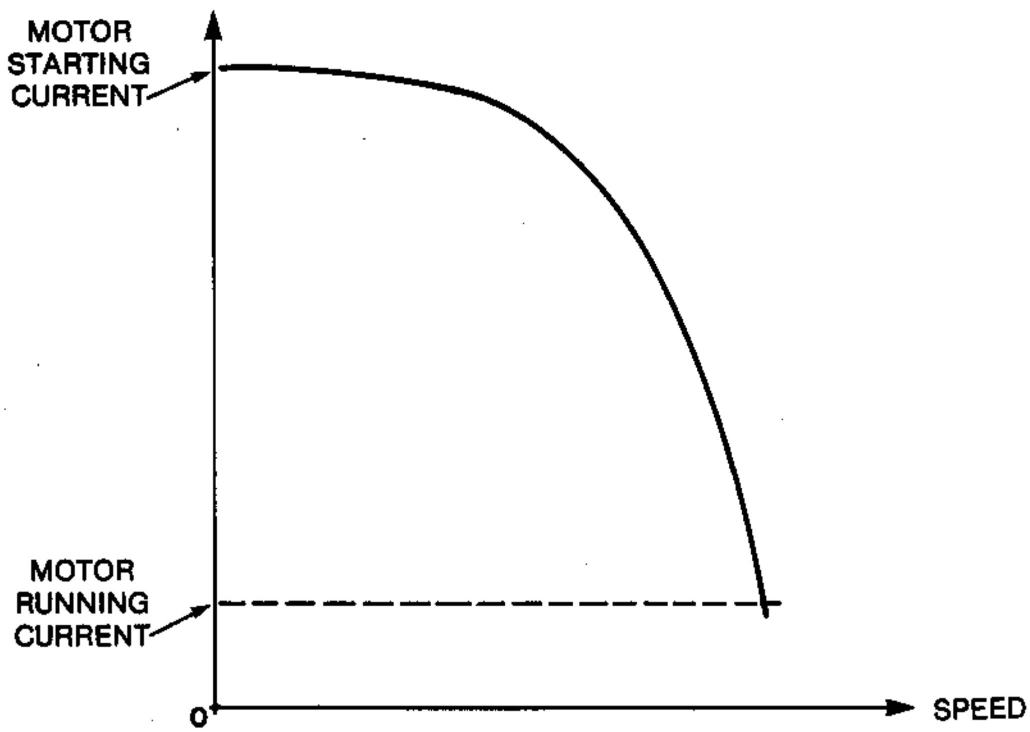


Figure 10: Motor Current vs Speed Characteristics

From the curve shown in Figure 10 it can be seen that the motor draws a large current at starting point. As the motor speed increases, current drawn by the motor decreases.

Motor Starting Current is about six times larger than the motor's full-load current. The exact value depends on the motor design.

6. Synchronous Speed

The speed of rotation of the stator magnetic field is called "**synchronous speed**". Synchronous speed, N_S is calculated by:

$$N_S = \frac{\text{Frequency}}{\text{Number of Pole Pairs}} \text{ revolutions/sec}$$

7. Slip Speed

The rotor of the induction motor follows the rotating magnetic field created in the stator. But, the rotor must always rotate slightly slower than the magnetic field, for the "relative motion" to take place. For idle running, this difference between the synchronous and the actual rotor speed is very small and depends on the friction and windage. The difference between the synchronous speed and the rotor speed is called the **slip speed** or in short **slip** .

Slip is expressed as a % of synchronous speed. Examine the expression below.

$$\%\ \text{Slip} = \frac{\text{Synchronous Speed} - \text{Rotor Speed}}{\text{Synchronous Speed}} \times 100\%$$

If the rotor could rotate at synchronous speed, the slip would be zero. (This, however, does not occur as explained above). If the rotor is blocked from rotating, the slip equals one or 100%.

8. Motor Operation

Figure 10(B) has the previously mentioned motor torque and motor current vs. speed curves superimposed. Let us examine how they are related.

At stand still an induction motor takes standstill or starting current and produces starting torque. Because the torque produced by the motor is greater than the torque required by the load. The motor and load speed will increase and the current falls. Motor torque will continue to increase until it produces its maximum attainable torque or pull out torque, at which time the torque will begin to decrease with increasing motor speed.

The motor running speed, slip speed and normal running current are all determined at steady state operation. This is at the intersection of the motor torque curve and load torque curve.

As an exercise, the reader should be able to follow the chain of events which would occur in a motor if the demanded load torque were to increase. To visualize this, consider the case where a motor was driving a water pump and the pump bearings are now beginning to deteriorate.

Answer:

The motor would eventually burnout due to excessive heat from current overload. Larger motors are protected against this situation. This will be discussed in the Motor Control section of these notes.

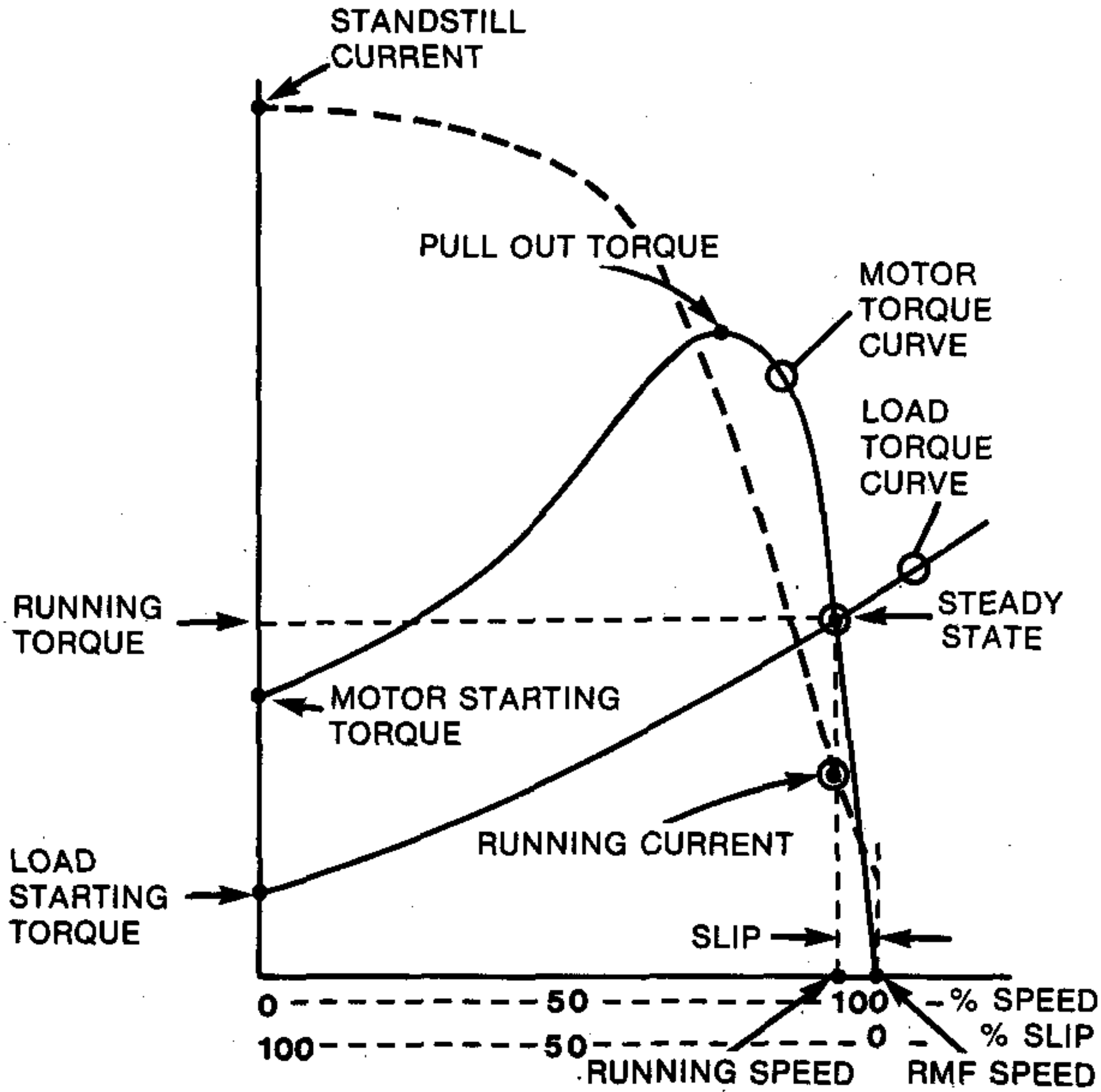


Figure 10(B): Motor Torque and Motor Current Versus Speed For an Induction Motor

6. Motor Nameplate Data

Motor nameplate data provides valuable information about the motor. Some of the most common data that the motor nameplate displays is given below:

(a) HP:	Indicates the horsepower rating of the motor.
(b) RPM:	Indicates the normal operating speed of the motor.
(c) Volts:	Indicates the normal operating voltage of the motor.
(d) Amp:	Indicates the normal operating full load current of the motor.
(e) Cycles:	Indicates the normal operating frequency of the power supply connected to the motor.
(f) Phase:	Indicates the type of motor - 3 phase or single phase.
(g) Service Factor:	Indicates how much overload above its nameplate rating the motor can deliver, continuously.
(h) Power Factor:	Indicates the power factor of the motor at rated current, voltage and frequency.
(i) Time Rating:	Indicates the duty cycle, ie, frequency of start and stop permitted for the motor. A motor rated as **continuous** duty cycle is not suited for frequent starts and stops.
(j) Insulation Class:	Letter associated with this rating corresponds to the temperature rating of the insulation used in the motor. For further explanation see the lesson on "Insulation".

(k) Max Ambient Temp: Each motor is rated to operate at a certain maximum working temperature, at rated HP. This temperature rating depends on the class of insulation used. The working temperatures are based on a standard 40°C surrounding temperature, referred to as the ambient temperature. If the ambient temperature is more than the standard 40°C, then the motor would have to be derated, in terms of HP.

(l) CEMA Designation: Letter associated with this designation indicates the motor speed/torque characteristics, % slip, normal voltage, frequency and starting current of the motor as standardized by Canadian Electrical Manufacturers Association (CEMA).

(m) Frame: Number and letters associated with this designation indicate the physical dimensions of the frame, as standardized by CEMA.

(n) Type: The letter designation associated with this information is the manufacturer's own designation for his own recording convenience. It will vary from manufacturer to manufacturer.

(o) Model: Numbers and letters associated with this designation indicate the model number for a particular manufacturer.

(p) Serial Number: Indicates the serial number assigned to a particular motor.

9. Ventilation System

In an induction motor, heat is produced in three main areas:

(a) **Stator Windings** - Heating (I^2R) is produced by the stator current flowing through the stator windings.

(b) **Stator Iron** - Heating is produced by eddy current and hysteresis losses.

(c) **Rotor Windings** - Heating (I^2R) is produced by the rotor current flowing through the rotor windings. Rotor iron core losses are negligable due to low rotor currents.

There are two basic types of enclosures, namely:

(a) Open.
(b) Totally Closed.

In each type, variations exist depending on the motor application. In each case, the heat is removed by air cooling.

Figure 11 shows the ventilation circuits for an induction motor having open ventilation. Outside air is brought in and circulated over the windings. This type of motor is not suitable for use in damp or dusty environments.

Figure 12 shows the ventilation circuits for a totally enclosed fan cooled induction motor. Note that there are two separate air circuits.

The inner circuit is cooled by conduction through the casing.

The outer circuit cools the outer surface of the casing.

This type of motor is suitable for use in damp or dusty environments.

Ventilation of a motor must not be restricted. Any restriction in air flow will result in the motor getting hotter and this may lead to a burn out.

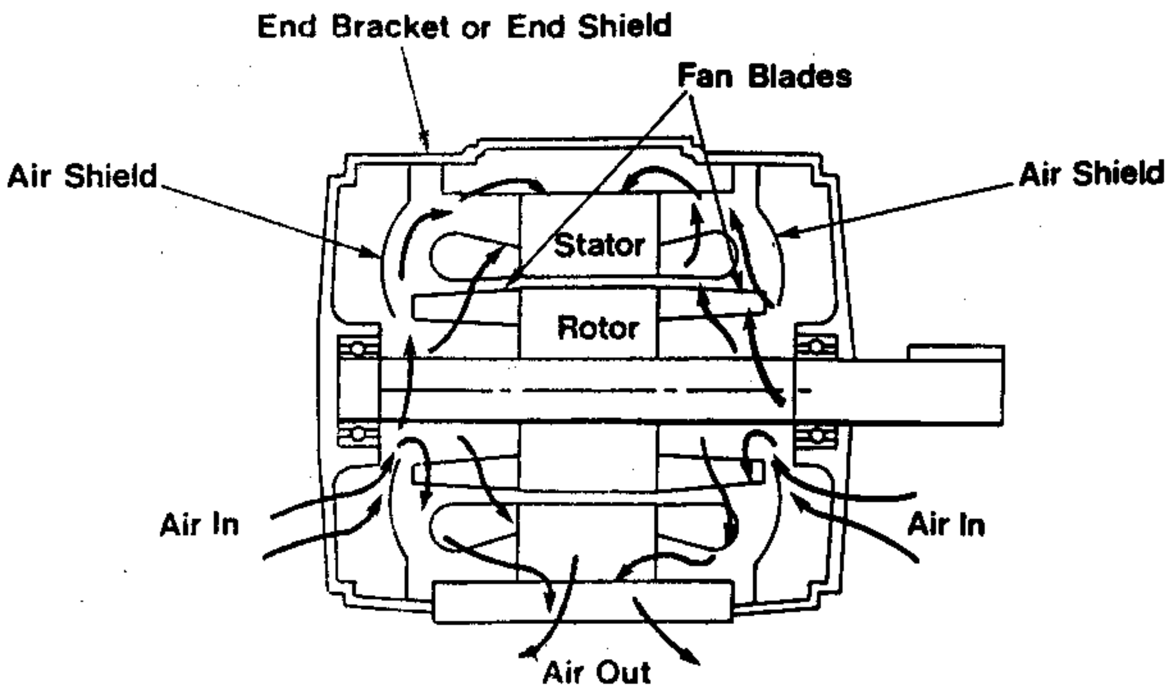


Figure 11: Ventilation Circuits for an Induction Motor Having Open Ventilation

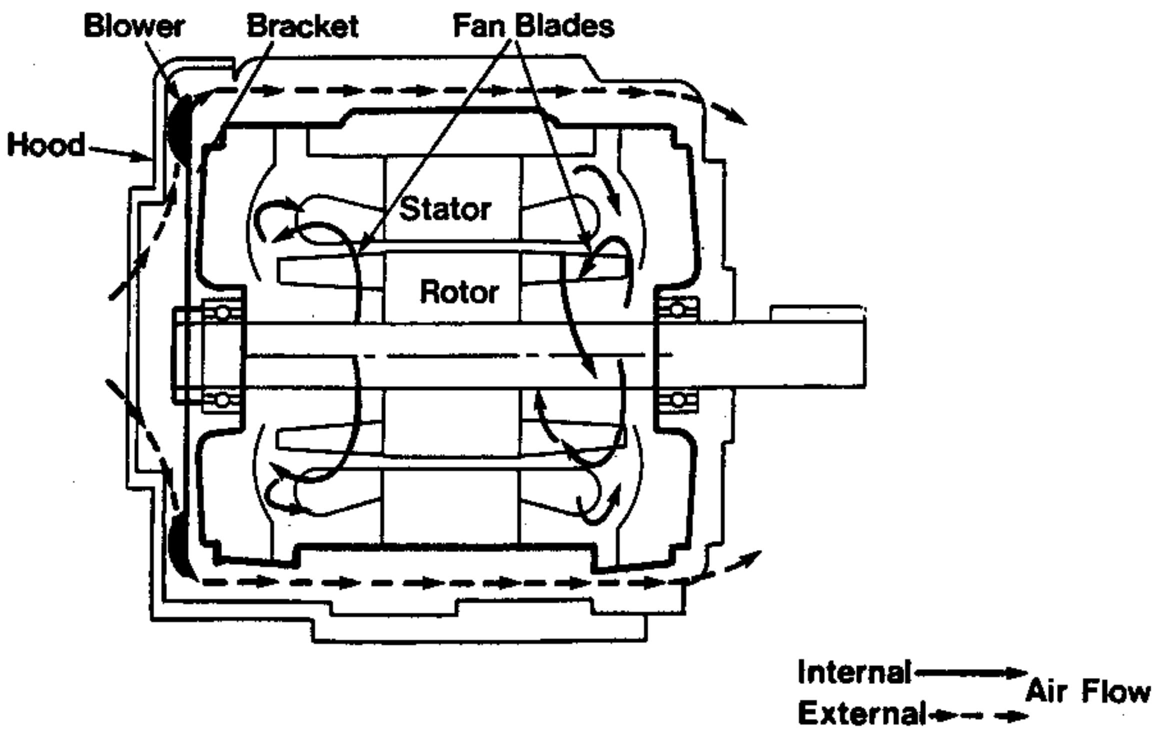


Figure 12: Ventilation Circuits For a Totally Enclosed Fan Cooled Induction Motor

Direction of Rotation and Phase Sequence

10. Three phase power supply connected to the motor must be in the correct phase sequence to provide the correct direction of rotation. If any two leads of the power supply connected to the three phase induction motor are interchanged, phase sequence will be reversed and the motor will rotate in the opposite direction.

Notes

ASSIGNMENT

1. What is a motor. What form of energy is input and output for a motor? (Section 2)

2. Explain how shaft rotation is obtained in a squirrel cage induction motor (SCIM).

3. What is the purpose of the short circuiting rings in the rotor of a squirrel cage induction motor (SCIM)? (Section 3.3)

4. Draw and properly label the following curves for an induction motor.

   (a) Torque vs speed.

   (b) Current vs speed.

5. Define the following terms, as related to squirrel cage induction motors. (Section 4)

   (a) Torque

   (b) Starting Torque

   (c) Running Torque

   (d) Pull Out Torque

6. What is the relationship between the starting current and the full load current in a squirrel cage induction motor (SCIM)?

7. Define the following terms, as related to a squirrel cage induction motor:

   (a) Motor full load current. (Section 5)

   (b) Synchronous speed. (also give the mathematical expression to calculate synchronous speed of a squirrel cage induction motor) (Section 6)

   (c) Slip speed. (also give the mathematical expression to calculate the slip speed) (Section 7)

8. Interpret the following nameplate data for a squirrel cage induction motor. (Section 8)

   (a) HP

   (b) RPM

   (c) Volts

(d) Cycles

(e) Amp

(f) Phase

(g) Service Factor

(h) Power Factor

(i) Time Rating

(j) Insulation Class

(k) Maximum Ambient Temperature

(l) CEMA Designation

(m) Frame

(n) Type

9. What two general types of motor enclosures are available. Give their respective applications. (Section 9)

10. How do the two types of motor enclosures differ from each other, in providng cooling to the motor. (Section 9)

11. What is the consequence of changing the phase sequence, in a three phase induction motor? (Section 10)

S. Rizvi

Three phase current supplied by a generator to a motor establishes three individual magnetic fields within the motor (Figures 1 and 2). The resultant of these individual magnetic fields is the Rotating Magnetic Field (RMF).

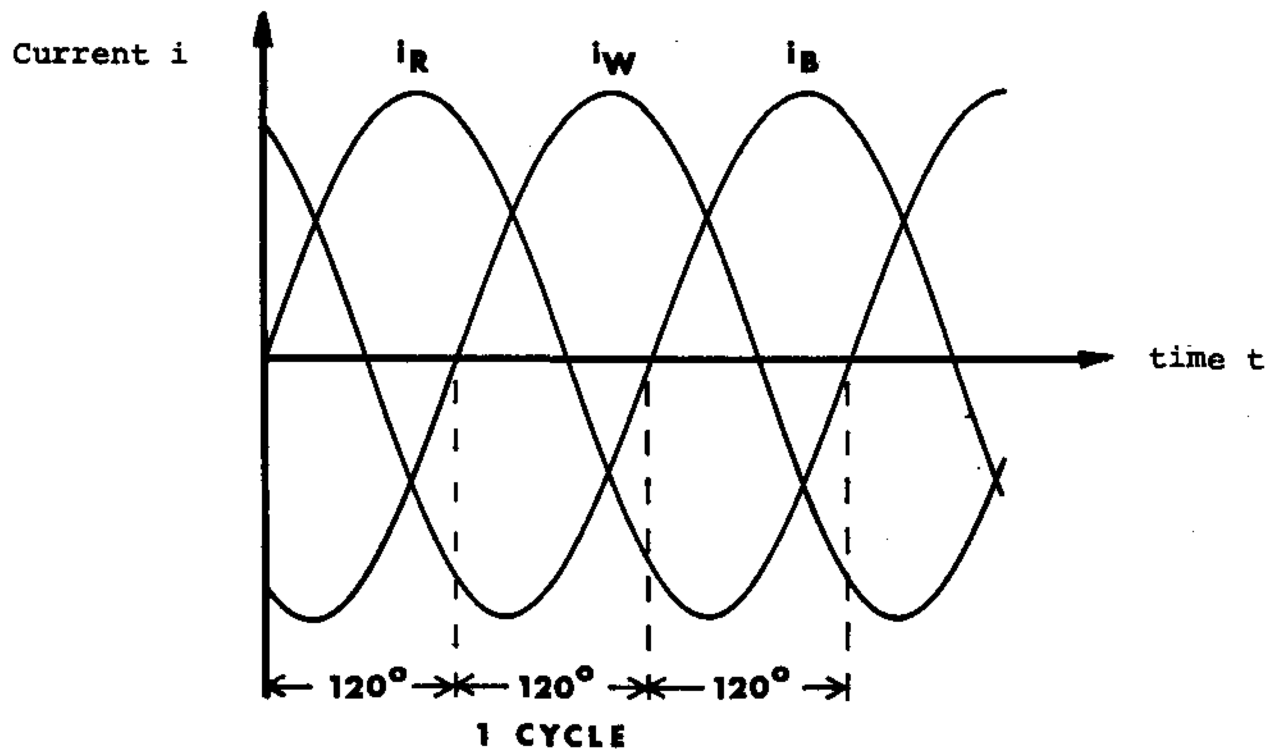


Figure 1: Diagram showing the waveform of currents in the windings of a three phasor motor.

Each magnetic field is sinusoidal, and is 120° out of phase, with respect to each other. Hence, they can be expressed as follows:

$$\Phi_R = \Phi_{PEAK} \sin(\theta)$$

$$\Phi_W = \Phi_{PEAK} \sin(\theta - 120°)$$

$$\Phi_B = \Phi_{PEAK} \sin(\theta + 120°)$$

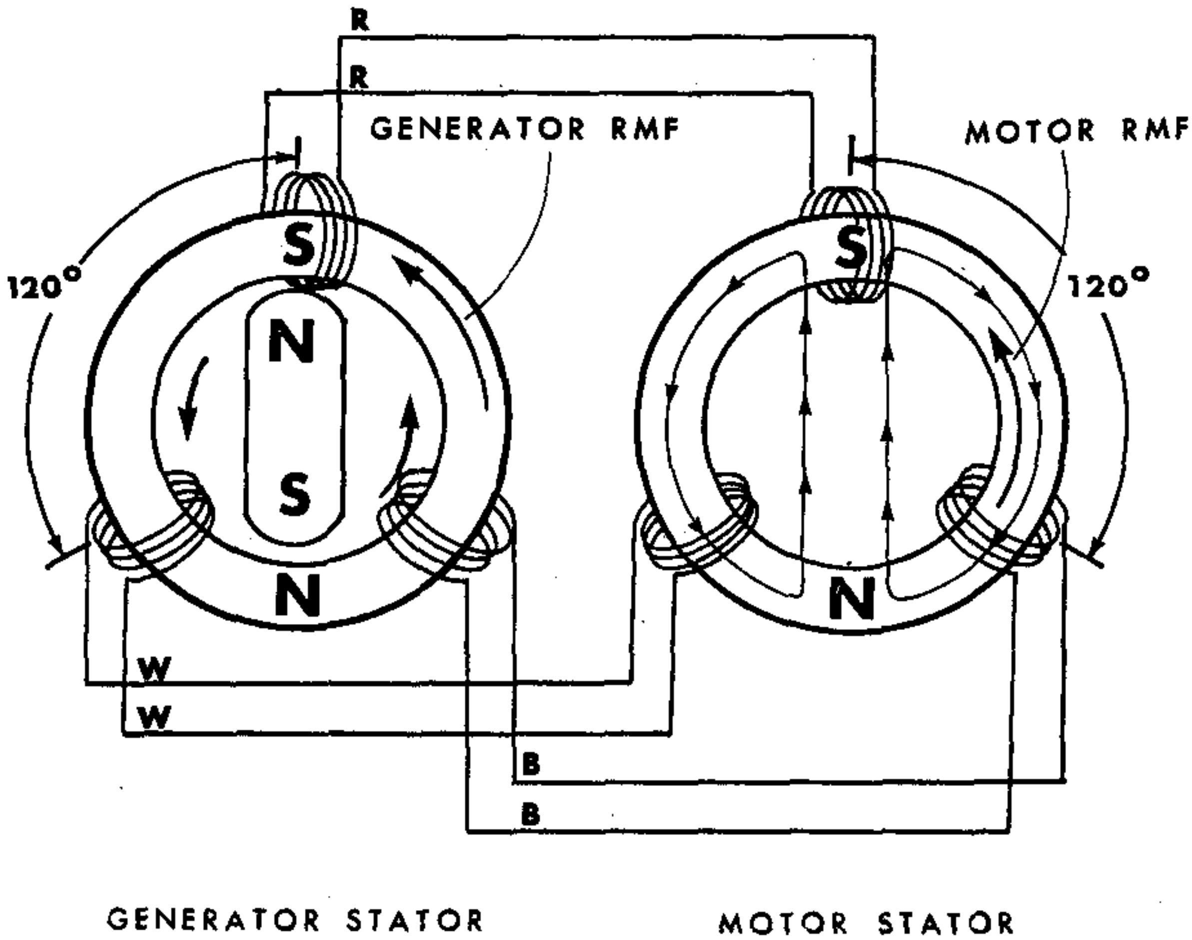


Figure 2: Rotating Magnetic Field in a Motor

These three magnetic fields, Φ_R, Φ_W, and Φ_B can be victorially represented on their respective azes, as shown in Figure 3. The magnetic fields can be victorially added together.

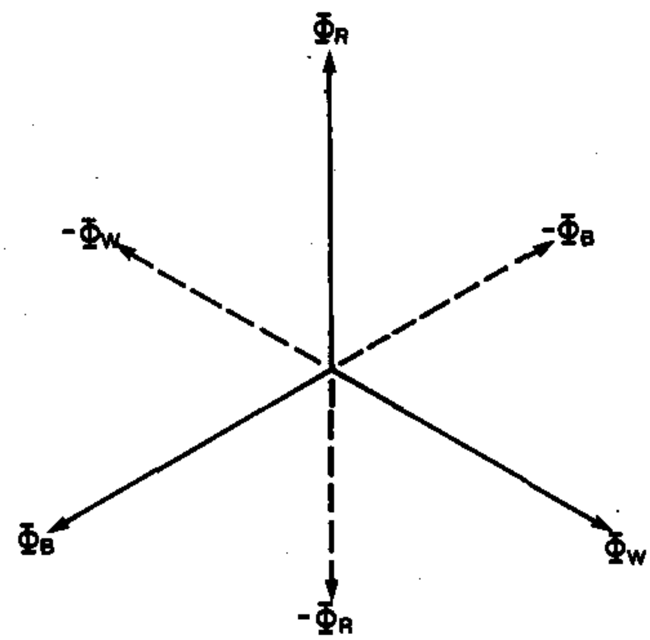


Figure 3: Victorial representation of the Three Magnetic Fields

Notes

Table 1 partially summarizes this phaser addition process and shows the RMF phasor rotation through 360 degrees at 45 degree intervals. Figure 4 displays this phasor rotation.

An obvious advantage of a 3-ϕ motor over a 1-ϕ motor is the constant rotating magnetic field (RMF) which is produced.

TABLE 1 - RMF ROTATION

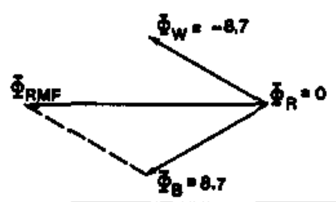
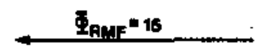
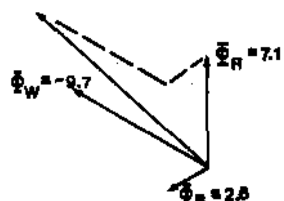
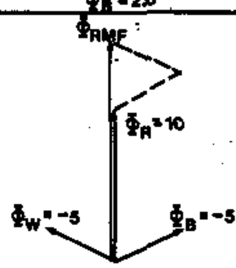
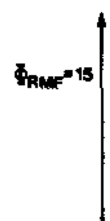
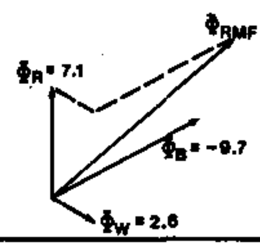
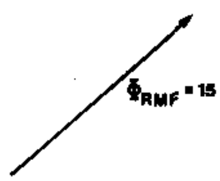
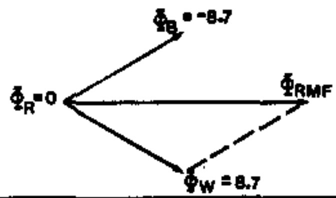
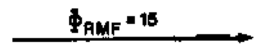
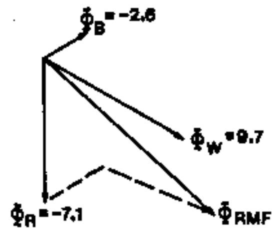
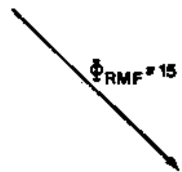
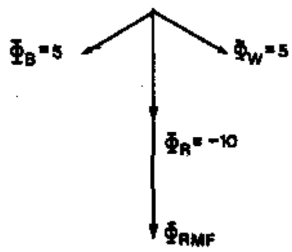
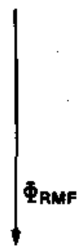
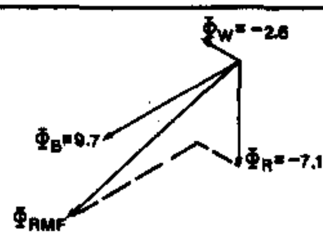
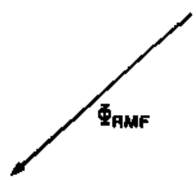
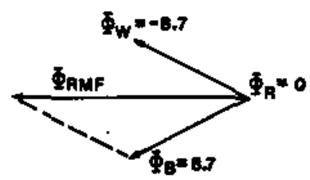
No.	θ	Φ_R	Φ_B	Φ_W	PHASOR ADDITION	RMF
1	0°	0	8.7	-8.6		
2	45°	7.1	2.6	-9.7		
3	90°	10	-5.0	-5.0		
4	135°	7.1	-5.0	-5.0		

Table I - RMF Phasor Rotation (continued)

No.	Θ	Φ_R	Φ_B	Φ_W	PHASOR ADDITION	RMF
5	180°	0	-8.7	8.7		
6	225°	-7.1	-2.6	9.7		
7	270°	-10	5.0	5.0		
8	315°	-71	9.7	-2.6		
9	360°	0	8.7	-8.7		

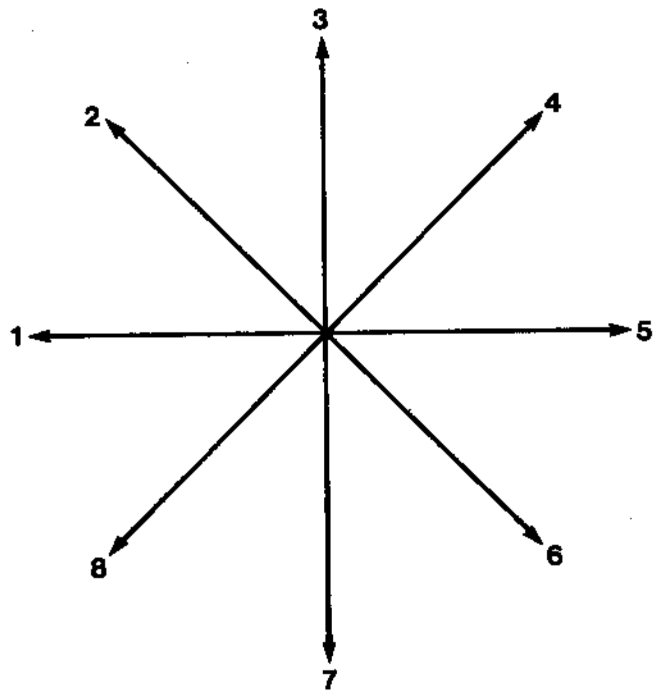


Figure 4: RMF Phasor Rotation

It could easily be shown that, by using this method, the RMF rotation in a motor and the rotor rotation could be made to change direction simply by interchanging any two of the red, white or blue power phases into the motor. That is, in Figure 2, connect the Red generator phase voltage to the White motor winding and vice versa).

It should also be noted that the resultant flux (RMF) always has a magnitude of 150 percent of the individual fluxes for 3-ϕ motors.

Notes

Electrical Equipment - Course PI 30.2

MOTOR CONTROL

OBJECTIVES

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

1. Recall, and list, in writing, four specifications of a contactor.
2. Briefly explain, in writing, the method used to identify contactor components and what normally open/closed contacts are.
3. Recall, and list in writing, five reasons why a motor control circuit is needed.
4. Given a motor control circuit diagram, identify various components and briefly explain their functions and state the sequence of events (i.e. what happens in the circuit) for motor starting and stopping.
5. Briefly explain, in writing, the terms "overload" and "thermal image".
6. Given a list of device numbers, identify the device function.
7. Briefly explain, in writing, when and why the circuit breaker is used for motor control.
8. Recall, that a circuit breaker is a latching type device, and briefly in writing, compare it with a contactor.
9. Given the schematic diagram of a motor control circuit utilizing a circuit breaker, briefly explain, in writing, the operation of the circuit.

1. Introduction

This lesson will introduce the reader to:

(a) The basic principle of operation of electromagnetic devices.

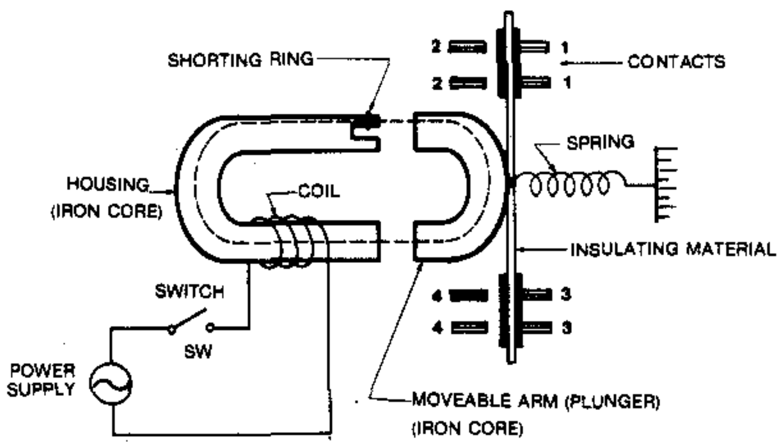
(b) Requirements of motor control.

(c) Operation of a simple motor control circuit.

2. Principle of Operation of an Electromagnetic Device

An electromagnetic device utilizes an electromagnet for its operation. The following discussion explains the operation of such a device (solenoid, relay and contactor).

2.1 Operation of an Electromagnetic Device



Operation of an Electromagnetic Device

Figure 1

In Figure 1, when switch SW is open, no current flows through the coil. As a result:

- The housing is not magnetized.
- The spring will pull the plunger away, to the right.
- Contacts 1-1 and 3-3 are shorted by the conductive plates. Hence, they are referred to, as being "closed".

- contacts 2-2 and 4-4 are open circuited (not shorted). Hence, they are referred to as being "open".

- When no current is flowing through the coil, the device is referred to as being in its "de-energized" state.

- Contacts shown, in the de-energized state, as closed, are called "normally closed" contacts.

Contacts shown, in the de-energized state, as open, are referred to as "normally open" contacts. In the diagram, contacts 1-1, 3-3 are normally closed and contacts 2-2, 4-4 are normally open.

In Figure 1, when switch SW is closed, current flows through the coil. As a result:

- The electric circuit for the coil will be complete and current will flow through the coil.

- Current flowing through the coil will produce a magnetic field.

- The magnetic field of the coil will cause a magnetic flux to be setup in the housing.

- The magnetized housing will draw the plunger, in, against the spring tension and close the gap.

- The arm attached to the plunger will also move with it. Contacts 1-1 and 3-3 will open. Contacts 2-2 and 4-4 will close.

- This condition is referred to as the energized state. Contacts which were closed in the de-energized state become open in the energized state. Contacts which were open in the deenergized state become closed in the energized state. This change of contact status is important and forms the basis for control circuits.

2.2 Contacts

Contacts 1-1, 2-2, 3-3 and 4-4 are independent of each other. While all these contacts are physically operated and located on the same device, they can be electrically connected to operate any equipment in the plant which is in different locations.

These electromagnetic devices are selected to provide the proper number of the contacts for a specific application. Contacts in a schematic diagram are always shown with the coil in its de-energized state.

2.3 Example

In Figure 2, when switch SW is open the red bulb will have a complete electrical circuit to the power supply, via the normally closed contact 1-1. The bulb will light. The green bulb will not have a complete circuit to its power supply because the contact 2-2 is open. This bulb will not be lit. When switch SW is closed, the plunger will operate. Contact 1-1 will open and the red light will turn off. Contact 2-2 will close and the green light will turn on. This condition will remain as long as current is flowing through the coil. If the current through the coil is discontinued, the state of the lights will revert to their previously de-energized states. The two bulbs can be located anywhere in the plant.

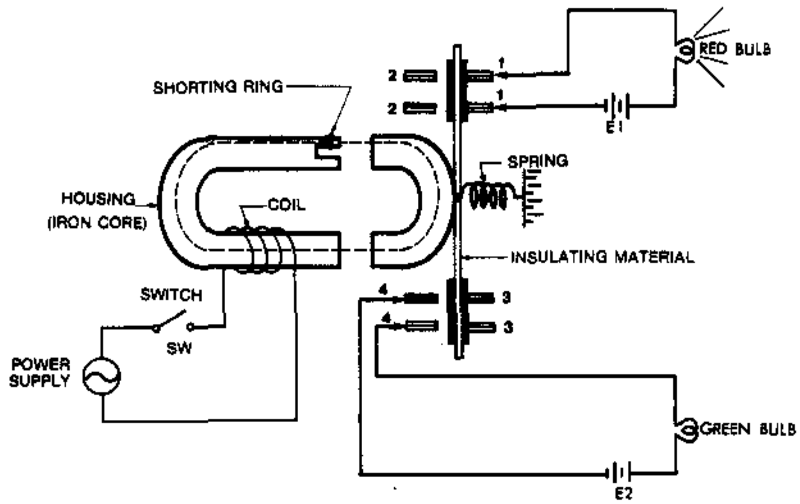


Figure 2(A): De-Energized Circuit

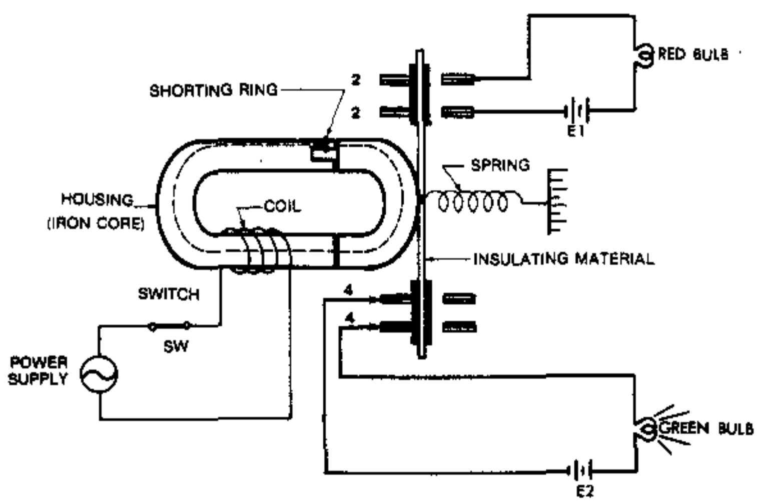


Figure 2(B): Energized Circuit

3. Contactor

A contactor is an electromagnetic device which operates as explained earlier. Refer to Figure 3. A contactor is used for the control of motors up to 40 HP. Motors above 75 HP are controlled by circuit breakers. A contactor remains energized only as long as current is flowing through its operating coil.

3.1 Contactor Specifications

Some important specifications of a contactor are:

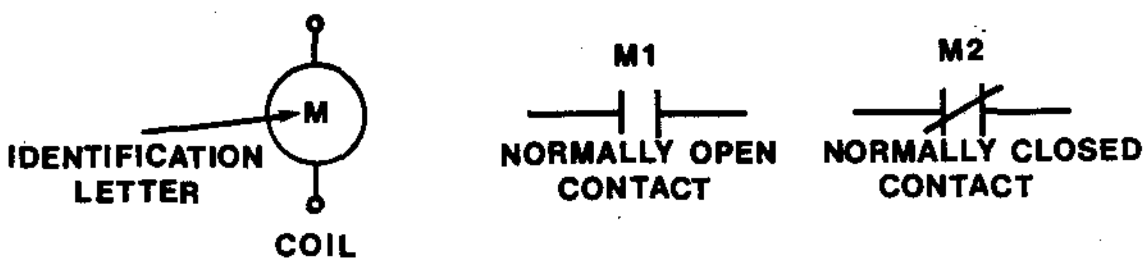
- Operating voltage of the coil.
- Operating frequency of the coil.
- Maximum voltage rating across the open contacts.
- Maximum current rating of the contacts.

3.2 Contact Identification

In a given control circuit, more than one electromagnetic device may be used. To facilitate circuit analysis and to maintain ease of wiring, each device coil is assigned a **letter** for its identification. Each set of contacts is assigned a **number** . Contacts belonging to a particular device are further identified by **prefixing the number with a coil letter designation.** For example, if a coil is identified by the letter M and the device has four sets of contacts, then the individual set of contacts would be marked M1, M2, M3 and M4.

3.3 Schematic Representation of a Coil and Its Contacts

The following is the schematic representation of a coil and it's contacts when the coil is de-energized;



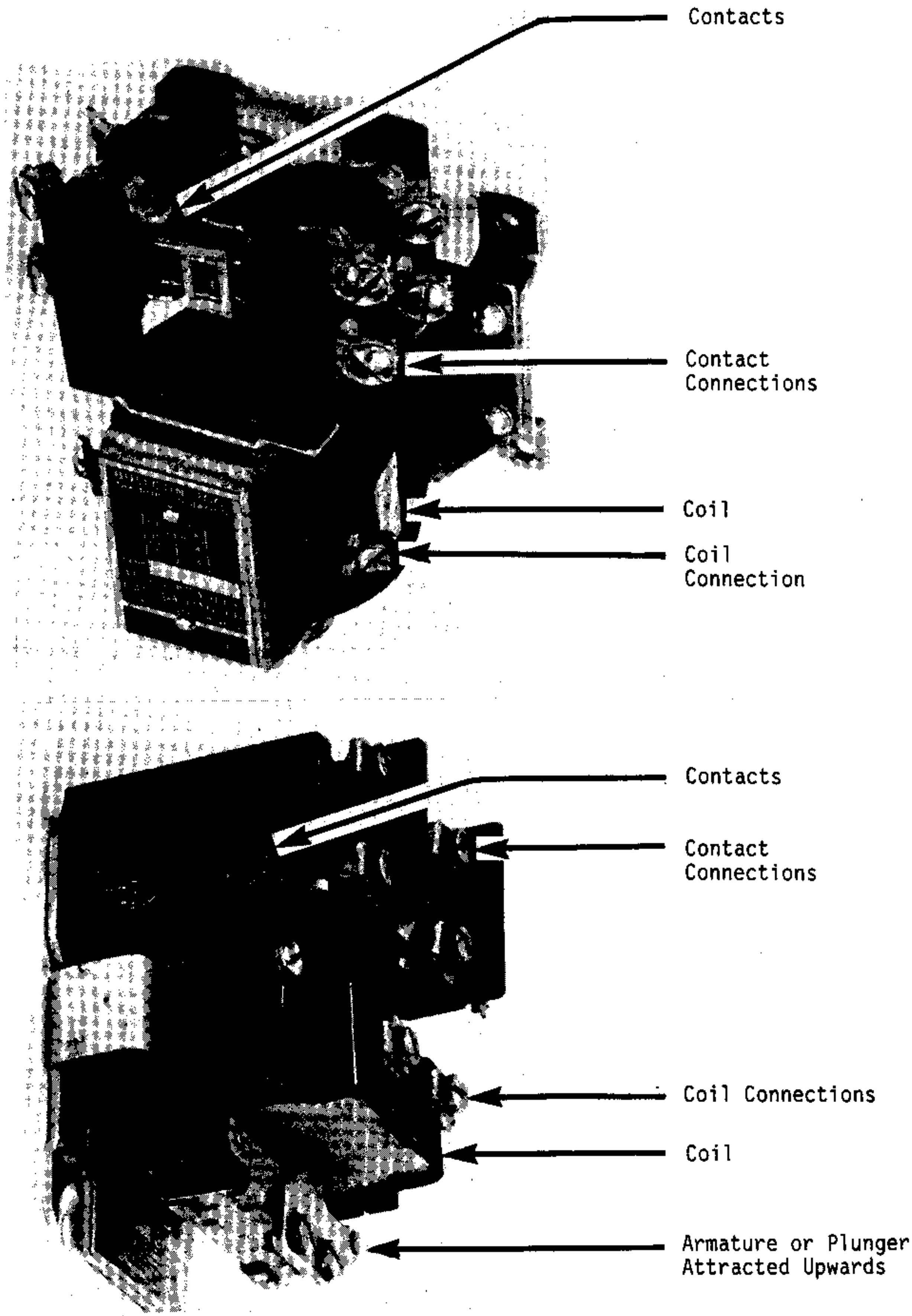


Figure 3: Contactors For 600V, 10 HP Motor

4. Motor Control

4.1 Why Motor Control Is Needed

Motor control is needed to provide for the following:

(a) A means of starting and stopping the motor. The start/stop control can be located far away from the motor. For example, the control of the heat transport pump motor is in the control room and the motor is far away, in the plant. Remote control allows the operator to start or stop the motor from the control room.

(b) Safety: Most of the motors in the plant operate at 600 V or above. For the safety of operating personnel, voltages on the control devices are reduced, via a transformer, to a a much lower voltage, such as 120 V.

(c) Protection of motor under abnormal operating conditions, such as overload.

(d) Fault protection for power and control circuitry.

(e) Means of isolating the motor from the power circuit, for maintenance purposes.

4.2 Development of a Control Circuit

(a) Manual Control: Normally found on household appliances.

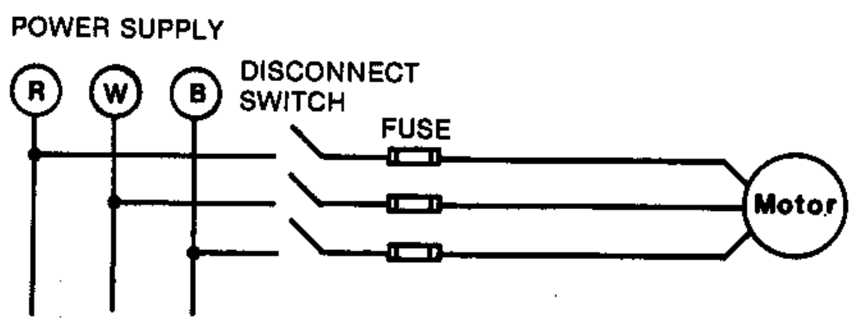


Figure 4(A): A Simple Motor Control

In Figure 4(A) the motor can be started by closing the switch manually and it can be stopped by opening the switch.

Fuses provide protection to the motor, if a fault occurs.

However, this method is manual and it is not safe at voltages of 600 V and greater. To overcome both of these problems, consider the following improvement shown in Figure 4(b).

(b) Contactor Control: The motor can be started or stopped by a local or a remote control station or both.

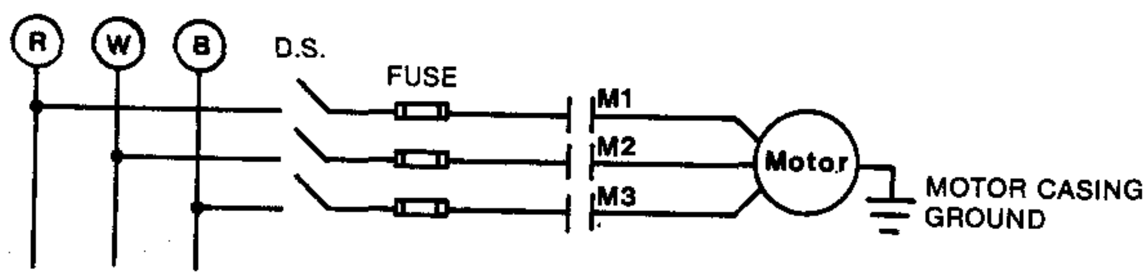


Figure 4(B)

Three normally open contacts of a contactor are placed in series with the motor leads. Now, the only way this motor can be started is, if the disconnect switch is closed, fuses are healthy, and contacts M_1, M_2 and M_3 are closed. To close these contactor contacts, the coil must be energized and this is done as shown in Figure 4(C).

4.2 Development of a Control Circuit

(b) Contactor Control (continued)

In Figure 4(C) two separate circuits can be identified.

- A power circuit, which can be at a high voltage. This circuit involves the power supply, disconnect switches, fuses, normally open contacts M_1, M_2, M_3 and the motor.

- A control circuit, which is powered by a stepdown transformer. This circuit includes the secondary of the control transformer, stop and start push buttons and the coil of the contactor. A fuse is also provided to protect the control circuitry against fault currents.

The operation of this circuit is as follows:

- Press the START push button, and hold this button down. The current path through the control circuit coil, M, will be completed, via the normally closed STOP push button. Coil M will energize. The normally open contacts M_1, M_2 and M_3 will close. This completes the power circuit to the motor, and the motor starts.

- When the spring loaded START push button is released, the electrical circuit to coil, M, is broken and it de-energizes. Contacts M_1, M_2 and M_3 open.

The motor disconnects from the supply and stops running. As can be seen from this discussion, the motor will only run, as long as the START push button is held down. This is not desirable.

On the following page the circuit is modified as shown in Figure 4(D).

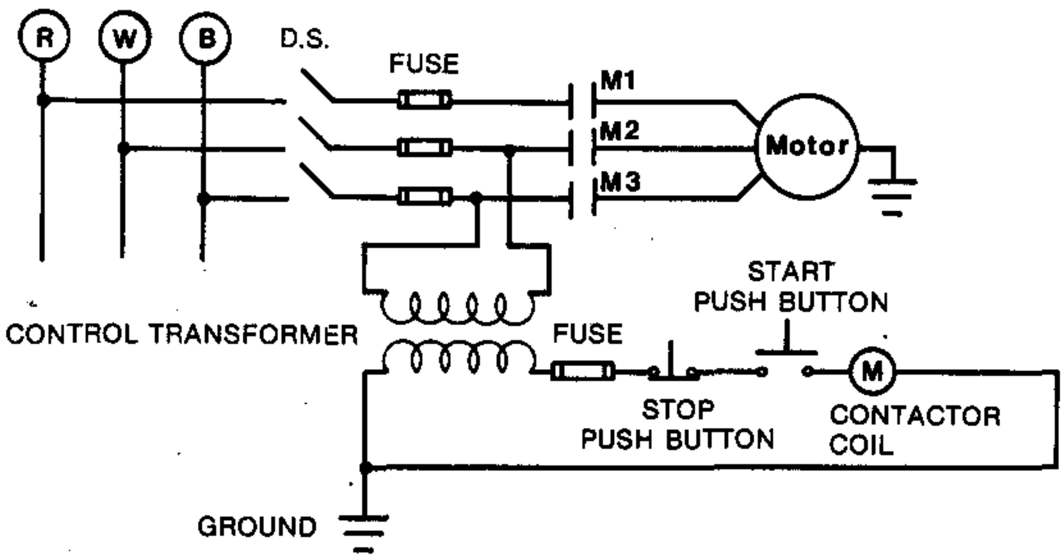

R
W
B
D.S.
FUSE
M1
M2
M3
Motor
CONTROL TRANSFORMER
FUSE
START
PUSH BUTTON
M
STOP
PUSH BUTTON
CONTACTOR
COIL
GROUND

Figure 4(C)

4.2 Development of a Control Circuit

Refer to Figure 4(D).

An additional, normally open contact, operated by M, is placed in parallel to the START push button.

Hence, when the START push button is pressed, coil M energizes and contacts M_1, M_2, M_3 and M_4 close. When the START push button is released, control current continues to flow via the now closed M_4 contact. This keeps coil M_4 energized, and the motor keeps running. Contact M_4 is normally referred to as the "seal in" or "holding" contact.

To stop the motor, the STOP push button is pressed. This breaks the electrical circuit for coil M and the coil de-energizes. Contacts M_1, M_2, M_3, and M_4 open and the motor stops. To restart the motor, the START push button must be pressed again.

So far in this control circuit, we have the following:

- Disconnect switch: which, when opened, provides isolation of the motor, from the power source, for maintenance, etc.

- Fuses: which provide protection for the motor, the main power supply, and the control circuitry in the event of a fault.

- Control Transformer: which provides safety, by reducing the voltage in the control circuit, to a safe, operating level of 120 V.

- START/STOP Buttons: Provide a means for starting and stopping the motor.

- Contactor: Provides for safe, local or remote motor control.

- Ground: Provides safety, by bringing the motor casing to ground potential if the motor casing becomes "live".

The section that follows will discuss OVERLOAD. Figure 4(D) is almost complete, as a contactor control system. However, it lacks motor overload protection.

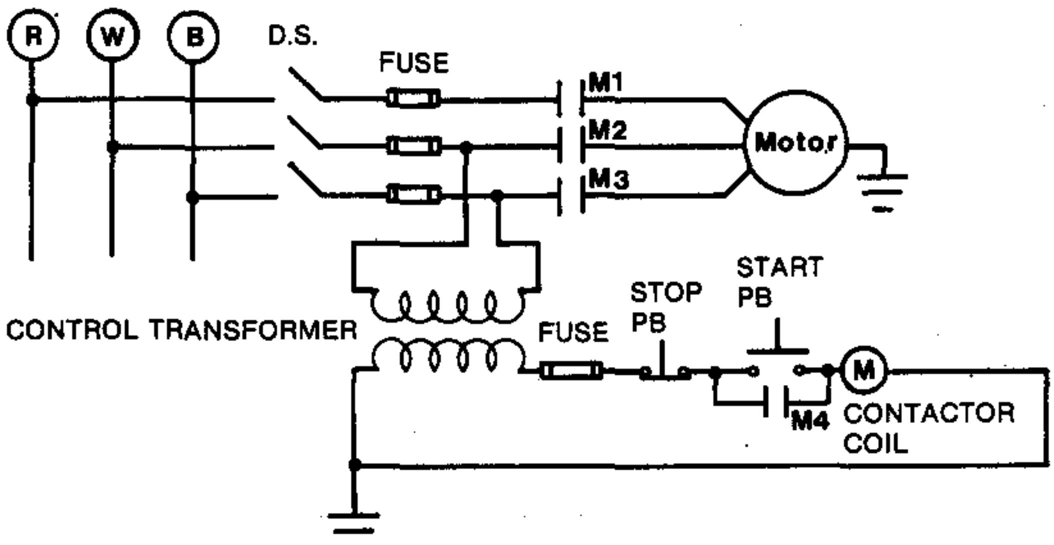

R
W
B
D.S.
FUSE
M1
M2
M3
Motor
CONTROL TRANSFORMER
FUSE
STOP
PB
START
PB
M
M4
CONTACTOR
COIL

Figure 4(D)

4.3 Overload

When a motor is operating normally and it is delivering its rated torque, it is drawing 100% of its rated full-load current.

If the motor is required to deliver more torque than it is capable of delivering, it starts to draw current in excess, of the 100% rated current value. This additional current creates additional heat due to increased I^2R loss, in the motor windings. Excessive heat could damage the windings and permanently damage the motor or reduce motor life. **An increase in the motor current above its rated value is referred to as overload.** Motors can only withstand 115% over-load current, for any extended period of time, without permanently damaging the insulation. It is therefore necessary to provide a means of detecting overloading conditions on the motor and automatically stop motor operations, if this condition exists. **Thermal overload relays are commonly used to detect overload currents in a motor circuit.**

4.4 Thermal Overload Relay

A thermal overload relay contains a bimetal switch, as shown in Figure 5. It has a heater with a resistance R_h, which is connected, in series, with the motor. All the motor current flows through this heater.

A push rod is connected to the bimetal, which can operate a set of contacts. A thermal overload relay works on the **thermal image** principle.

Under normal conditions, the motor current produces a nominal amount of I^2R_m heat in the motor windings. R_m is the motor winding resistance. Also, an I^2R_h heat is produced in the relay heater. Heat produced during this normal operation is not sufficient to bend the bimetal.

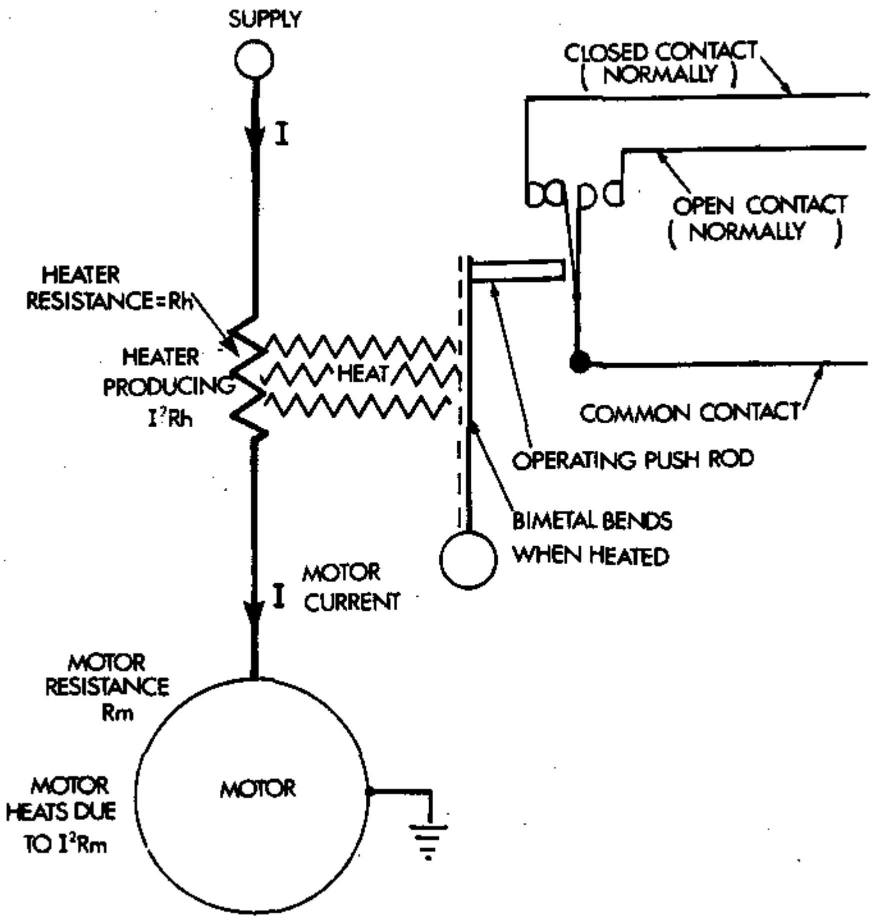


Figure 5: A Thermal Relay

If an overload condition occurs, excessive I^2R_m heat is produced in the motor windings and I^2R_h is also high. This causes the bimetal to bend. The push rod, attached to the bimetal, moves to the right and operates the contacts. Heat produced in the heater of the thermal overload relay is thus a thermal image of the heat produced in the motor.

The heater of the thermal overload relay is shown schematically below.

Contacts of the thermal overload relay can be used to control the motor as illustrated in Figure 6, which follows on the next page.

4.5 Thermal Overload Protection

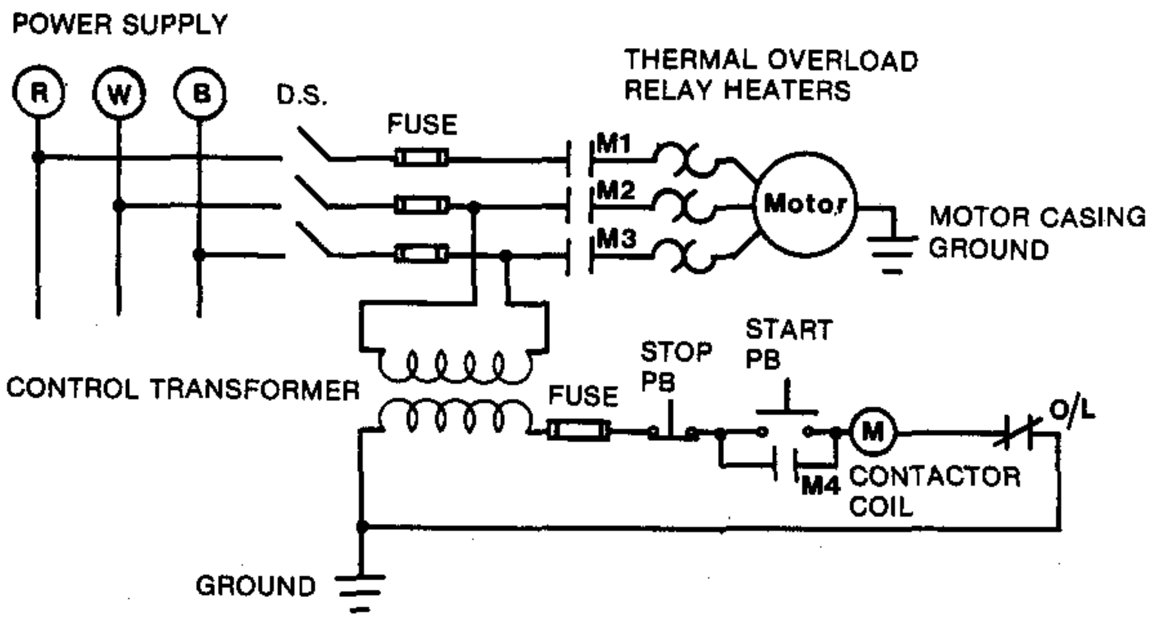


Figure 6: A Simple, but complete Motor Control Circuit

When an overload occurs, the motor current increases. Higher motor current also passes through the heaters of the OL relay and heats the bimetal. The push rod then opens the O/L contacts in the control circuit and de-energizes the contactor coil. This stops the motor.

Important: For large motors, the line current is high. Therefore, the thermal overload relay is connected via current transformers. The turns ratio of these transformers is carefully selected for the specific motor and application. Fuse in the motor circuit is selected to pass the motor starting current which can be as high as 6 times of motor full load current. Fuse therefore will not blow at over currents of 10 to 15%.

4.6 Other Types of Protection

Apart from isolation, short circuit, and overload protection, some other types of protection may also be used. However, their application will be determined by the size and the importance of the motor. All of the electrical control devices are given a standard number. A list of some of these devices and their respective numbers is given in Table 1.

Do not memorize this table.

TABLE 1

IEEE Device Numbers and Functions for Switchgear Apparatus

Device Number	Function
3	Interposing Relay
4	Master Contractor or Relay
27	ac Undervoltage Relay
33	Position Switch
46	Phase Unbalance Relay
49	ac Thermal Relay
50	Short Circuit Selective Relay
51	ac Overcurrent Relay
52	ac Circuit Breaker
63	Fluid - Pressure, Level or Flow Relay
64	Ground Protection Relay
74	Alarm Relay
86	Lock-Out Relay
87	Differential Current Relay
89	Line Switch or Disconnect Switch
94	Tripping Relay

5. Motor Control Using Circuit Breakers

Large motors above 56kW (75HP) draw very high current and are supplied at a high voltage; eg. 600V, 4160V, or 13.8kV. At these high voltages, fault currents can reach very high values. These fault currents must be cleared by the motor controllers. However, contactors are not suitable for handling large fault currents. Hence, the control of the motors, above 56kW (75HP), is achieved by means of circuit breakers.

A circuit breaker simply makes or breaks the current to the motor. In order to start the motor, the circuit breaker must be closed. This can be done either manually or automatically, by energizing the breaker - close coil.

To stop the motor, the circuit breaker must be opened. Again, this can be done manually or automatically, by energizing the breaker-trip coil.

Any type of protection provided to the motor must energize the breaker trip coil, if an abnormal condition exists. It is important to realize that a **circuit breaker is a latching type device.** When the breaker is closed, it latches in the closed state and the current to the close solenoid can be discontinued. Similarly, when the breaker is opened, it latches in the open state, and the current to the breaker trip coil can then be interrupted. A contactor control circuit requires a continuous power supply when the motor is running.

Figures 7(a) and 7(b) must be looked at together in order to understand the operation. These figures are located on a pull-out sheet, at the end of this lesson.

The circuits in Figure 7(a) and 7(b) are discussed on the page that follows.

Complete the following table.

Device Number	Device Function
52	
49	
64	

In Figure 7(b):

- 52C is the **"close"** coil of the circuit breaker. When 52C is energized the circuit breaker will close.
- 52T is the trip coil of the circuit breaker. When 52T is energized, the circuit breaker trips.
- Contacts L_a and L_b are mechanically linked and they change their state when the circuit breaker operates.
- The trip circuit and the close circuit are provided with the seperate fuses for reliability.
- 250 V DC class I supply is used in NGD for control of circuit breakers. Classes of power are discussed in the first chapter.

In Figure 7(a):

- Overload protection is provided via the current transformers (CT's). A contact of 49 is located in Figure 7(b) (simplified breaker control circuit). In the event of an overload on the motor, the thermal overload device will actuate and the contact 49-1 in the trip circuit will close and energize the trip coil. The circuit breaker thus will be opened and the motor will stop.
- An ammeter is connected via a CT to indicate the motor current. This ammeter may be located in the control room.
- Ground fault protection also has a contact in the trip circuit. In the event of a ground fault contact 64-1 will close and trip the breaker, thus de-energizing the motor.

ASSIGNMENT

1. In your own words, explain the operating principle for an electromagnetic device. Diagrams may be used for clarity. (Sections 2, 2.1)

2. How are the contacts normally shown in a schematic diagram? Select the right answer.

   (a) Coil Energized.
   (b) Coil De-energized.

3. List four specifications (ratings) of a contactor. (Section 3.1)

   (i)

   (ii)

   (iii)

   (iv)

4. Explain in your own words why and how the contactor contacts are identified. (Section 3.2)

5. Describe contacts as being Normally Open or Normally Closed. (Section 3.3)

6. Give five requirements of a motor control circuit. (Section 4.1)

   (i)

   (ii)

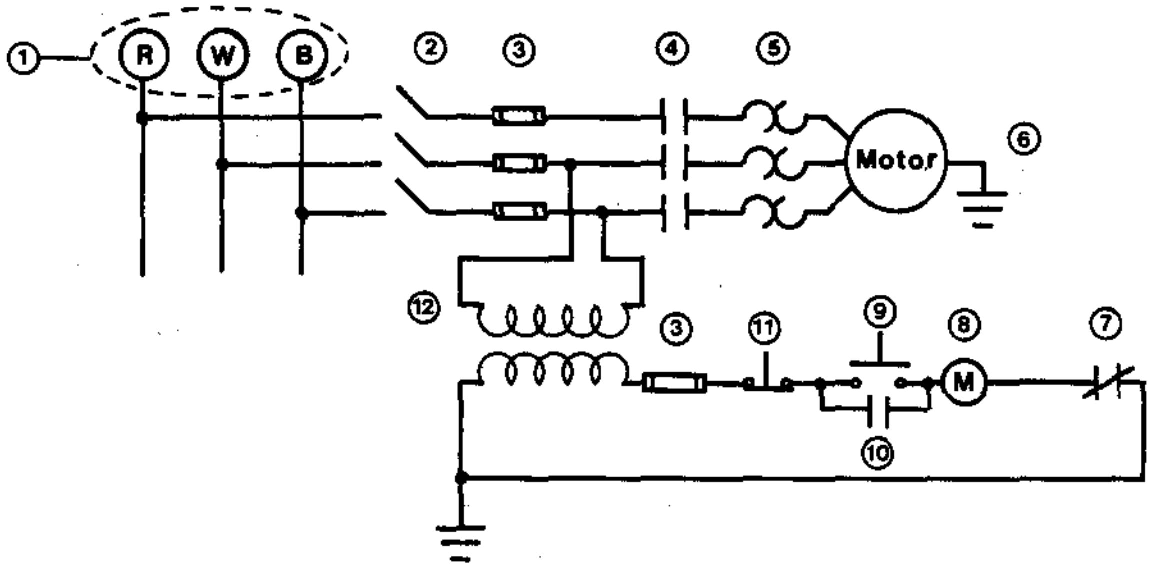
   (iii)

   (iv)

   (v)

7. Explain what is meant by the terms "overload" and "thermal image". (Section 4.3)

8. In the following diagram, identify each component and give its function. (Section 4.2 to 4.5)



Name	Function
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	

9. When are circuit breakers used for motor control and why? (Section 5)

10. Compare a circuit breaker control system and a contactor control system stating their similarities and their differences. (Section 5)

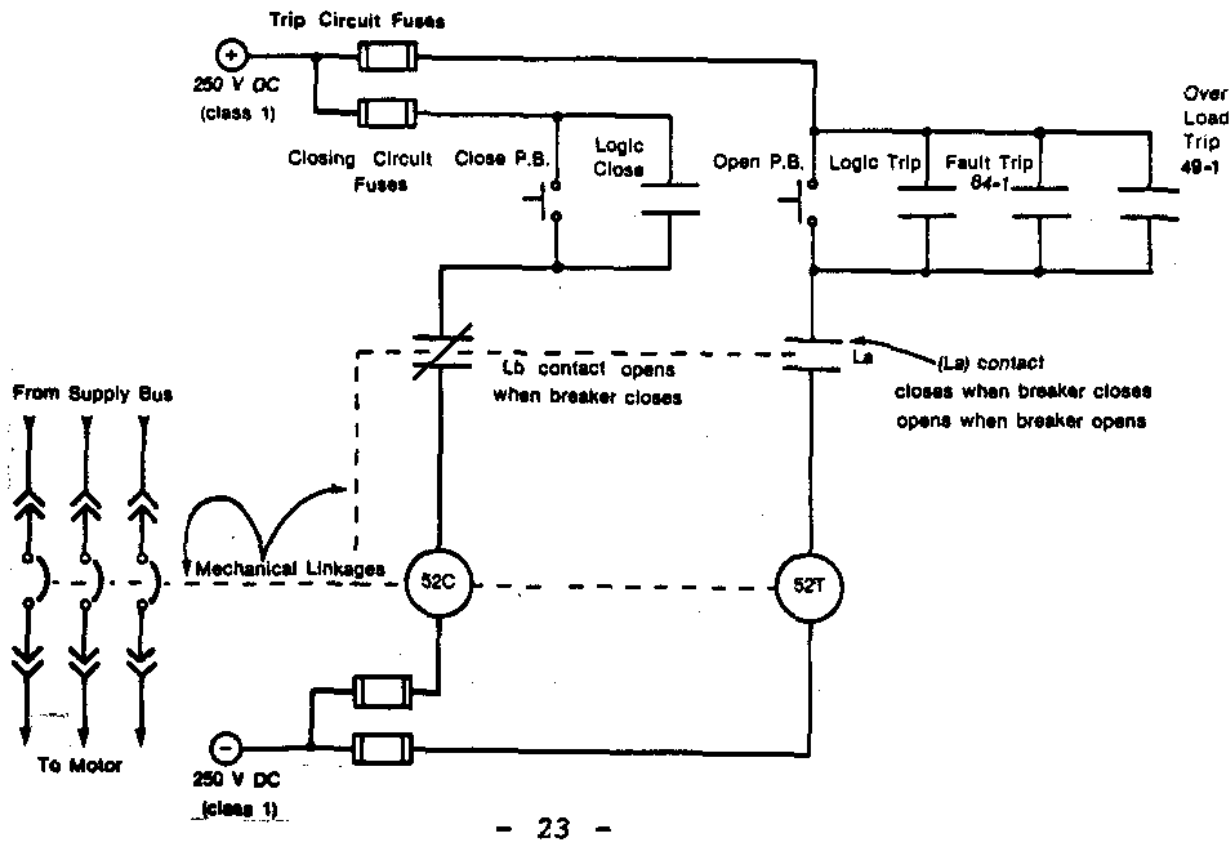
11. (a) In the circuits given below, explain the purpose of: (Section 5.1)

    (i) 52C

    (ii) 52T

    (iii) separate fuses in close and trip circuit.

    (iv) Ammeter.



(b) Using the two given diagrams, explain the operation of the circuit for:

(i) 49

(ii) 64

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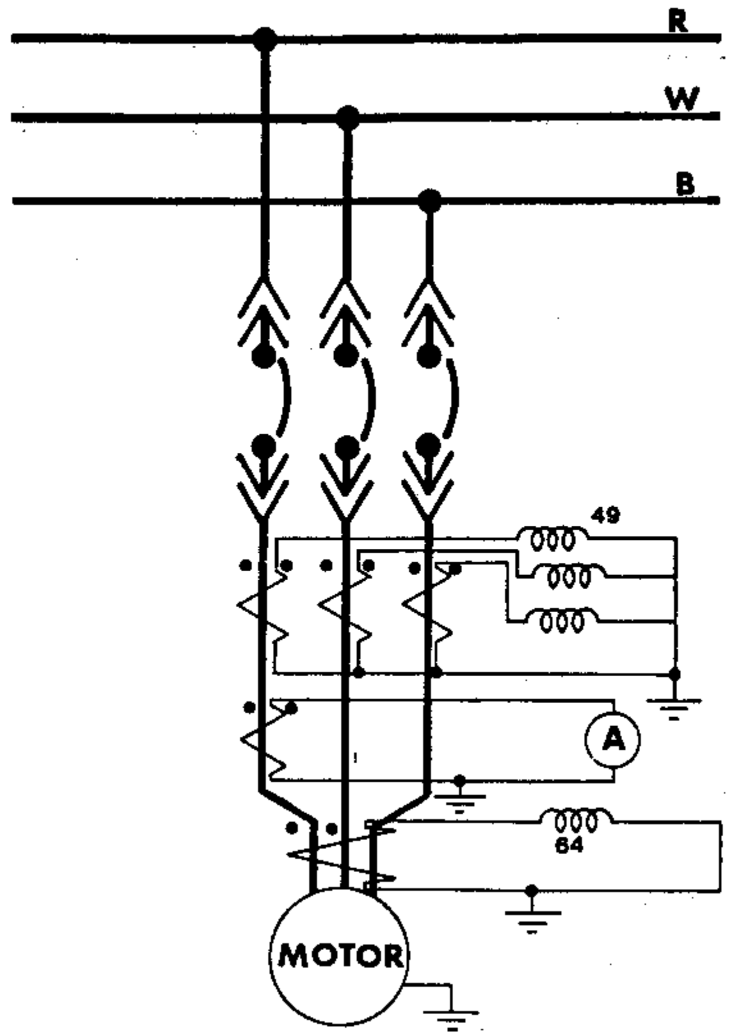

Figure 7(a)

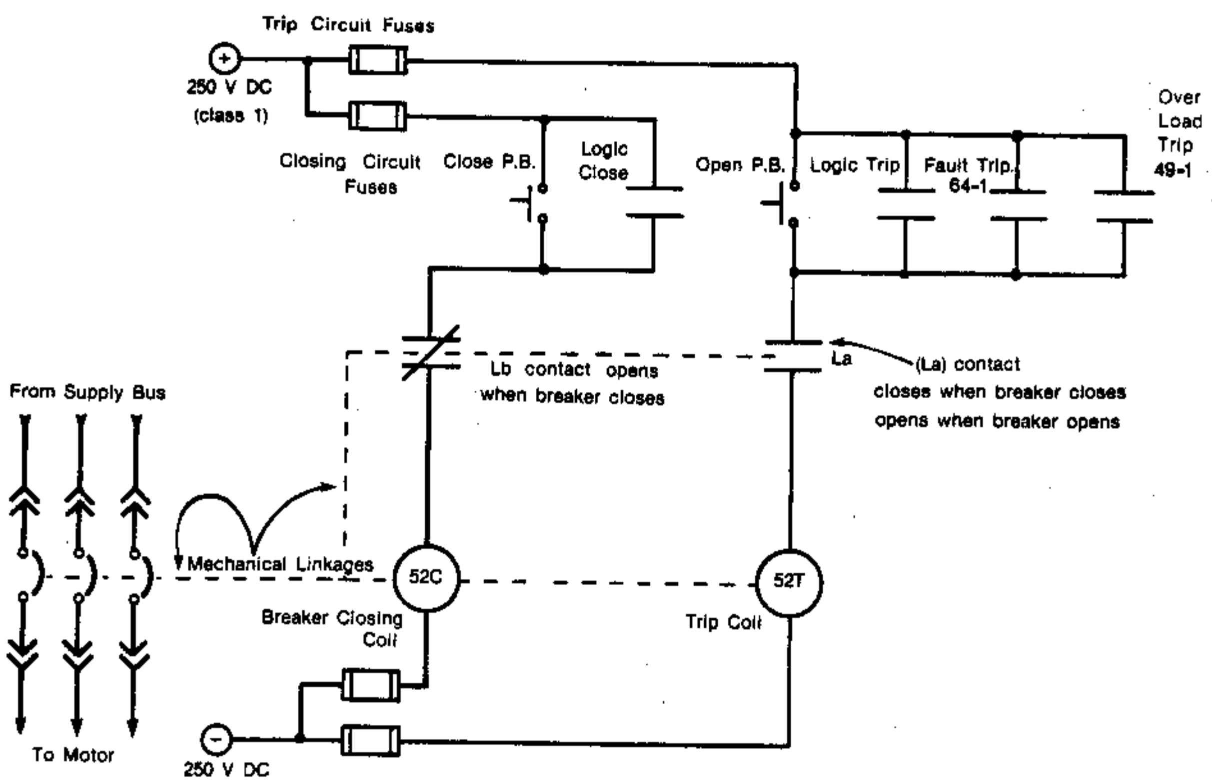

Figure 7(b)

Electrical Equipment - Course PI 30.2

BATTERIES

OBJECTIVES

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

1. Recall, and list in writing, two types of batteries used in NGD.

2. Recall, and note in writing, the type of electrolyte which is used in a lead acid battery. For a lead antimony and lead calcium battery state the voltages and specific gravities when they are fully charged and fully discharged. (Exclude specific gravity for discharged Lead Calcium Battery).

3. Briefly explain, in writing, why antimony or calcium is used in lead acid batteries.

4. Recall, and note in writing, that the specific gravity of battery electrolyte decreases with an increase in temperature.

5. Given a set of readings identify in writing, whether the correction factor for the specific gravity is positive or negative, at various temperatures.

6. Briefly explain, in writing, why a correction to the voltage reading is not normally applied, for a minor change of temperature.

7. In writing, briefly state what constitutes a battery bank.

8. Recall, and list in writing the input voltage of the charger and the output voltage of the battery bank.

   a) Amp hour rating of a battery;
   b) Float charge;
   c) Equalizer charge;
   d) Float voltage;
   e) Pilot cell;
   f) Discharge capacity.

9. Recall, and list in writing, three conditions which dictate when the equalizer charge is to be stopped.

10. Briefly explain, in writing, how battery capacity is affected by:
    a) Discharge rate;
    b) Temperature.

11. Briefly explain, in writing, what is meant by a "capacity test".

12. Recall, and list in writing, the factors which affect battery life.

13. Recall, and list in writing, three hazards associated with batteries and give two precautions for each hazard.

14. In writing do a five point comparison of lead calcium versus lead antimony batteries.

1. Introduction

This lesson will introduce the reader to:

(a) The purpose of batteries in CANDU power plants.
(b) Types of batteries used in NGD.
(c) Battery characteristics.
(d) Charging of a battery.
(e) Float charge and equalizer charge.
(f) A comparison of the two types of batteries used in NGD.

2. Lead Acid Batteries

2.1 What Is a Battery

A lead acid battery is an electrochemical device that produces direct current (dc).

2.2 Purpose of the Batteries in the CANDU System

In the CANDU system, safety of the plant and the personnel is the utmost priority. **In the event of a power failure, a battery bank ensures an uninterrupted supply of power** to equipment which is essential for safe operation or shutdown. A typical load on the battery bank, in a CANDU system, is as follows:

(a) Emergency lighting
(b) Reactor shutdown system
(c) Safety mechanism
(d) Circuit breaker control

2.3 Type of Batteries

In the Nuclear Generation Division, two types of batteries are used.

(a) Lead Acid Antimony is used in nuclear generating stations.

(b) Lead Acid Calcium is used in the heavy water plants and is frequently the replacement battery specified in nuclear generating stations.

2.4 Lead Acid Battery Construction

Each cell of a lead acid battery consists of many positive and negative plates, which are insulated from each other, with porous plastic spacers. This whole assembly is inserted in a transparent plastic case. The case is filled with a dilute solution of sulphuric acid.

Figure 1 shows a section of a lead acid cell. For simplicity, only one positive and one negative plate is shown.

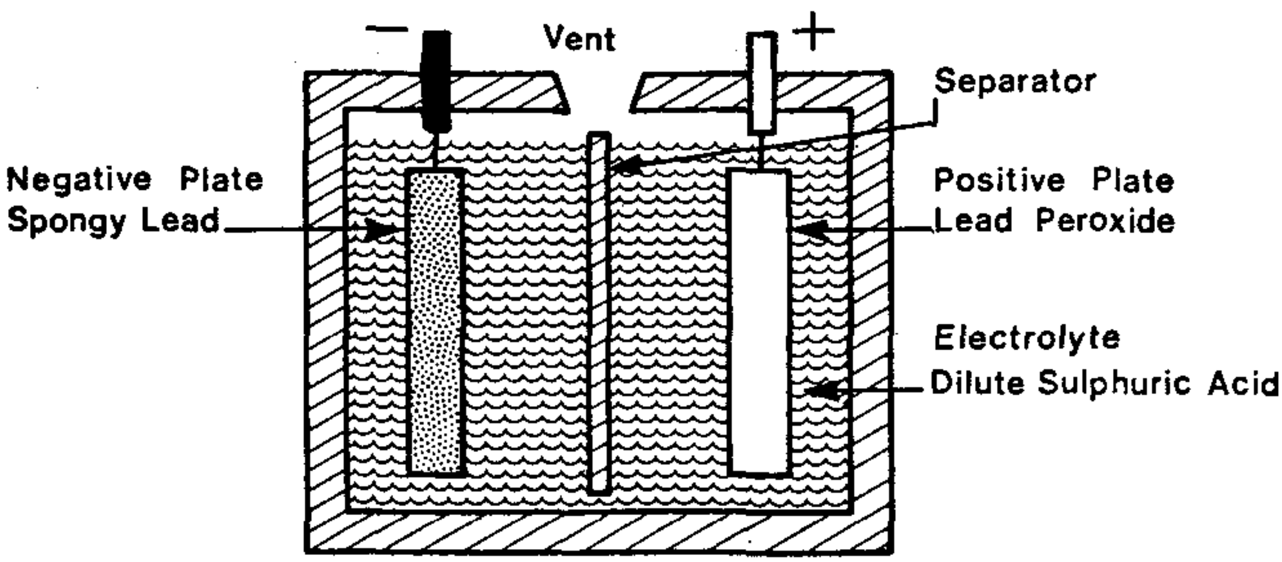

Figure 1: Sectional Diagram of a Lead Acid Battery With Two Plates

The plates are made from a cast lead grid which is covered with a paste. The positive plate is covered with a brown, lead peroxide (PbO_2) paste. The negative plate is covered with a spongy lead (Pb) paste. The plates are immersed in a dilute (50% concentration) sulphuric acid solution, which is called the **electrolyte.** The ratio of acid to water is measured as specific gravity. The following reversible chemical reaction takes place.

$$\underbrace{PbO_2 + Pb + 2H_2SO_4}_{\text{Battery charged}} \rightleftharpoons \underbrace{2PbSO_4 + 2H_2O}_{\text{Battery discharged}}$$

From the above, it can be seen that a charged battery has an electrolyte consisting of H_2SO_4, while a discharged battery has an electrolyte consisting of water. In practice, when discharged, the plates do not convert all the sulphuric acid to water and the electrolyte still contains a significant quantity of sulphuric acid.

Since lead is a soft, dense material, it can not maintain its dimensional integrity against forces produced by corrosion products or in some cases, even by its own weight. Antimony or calcium is provided in the alloy with lead to harden the grid. This makes the lead more workable, provides mechanical strength, and reduces buckling.

2.5 Cell Characteristics

For a lead acid antimony cell, Figure 2 shows the relationship between voltage/specific gravity and percent charge on the cell.

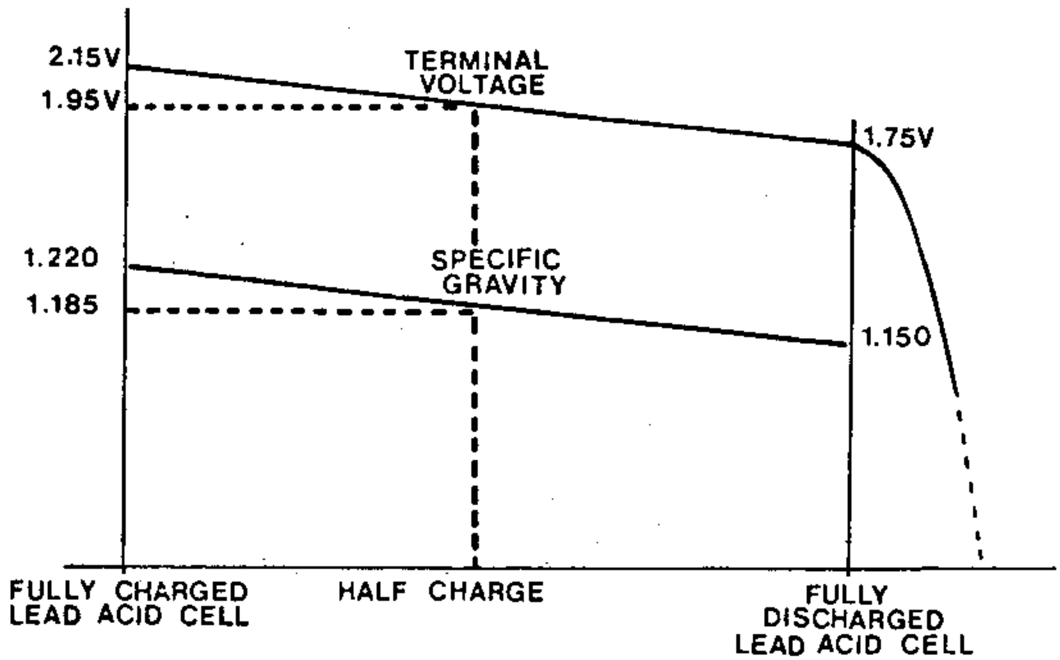

Figure 2: Curves of Terminal Voltage and Specific Gravity Versus Charge For a Lead Acid Cell (Antimony)

From Figure 2, note the following:

- Cell voltage at (100%) full charge state is 2.15 volts.
- Electrolyte specific gravity at full charge state is 1.220.
- Cell voltage in fully discharged state is 1.75 volts.
- Electrolyte specific gravity in fully discharged state is 1.150.

Because it uses chemical interactions, a lead acid cell is affected by changes in temperature. Performance ratings of lead-acid stationary batteries are based on a standard temperature of 25°C (77°F). Any deviation from that temperature affects battery performance and life expectancy.

Table 1, below, lists the specific gravity of the two types of batteries, at four different temperatures.

Table 1

Variation of Specific Gravity With Temperature in Fully Charged Lead Acid Cells

Temperature	Specific Gravity Per Cell	
	Antimony Type	Calcium Type
15°C	1.226	1.256
20°C	1.223	1.253
25°C	1.220	1.250
30°C	1.217	1.247

When taking readings of specific gravity at temperatures, which are significantly different from 25°C, a specific gravity correction must be applied. Such temperature corrections are usually not applied to voltage measurements, because voltage variations are very small, for each degree change in temperature. Also, the battery room is maintained at 25°C ±5°. Very low temperatures, will seriously affect the amount of electrical energy that can be taken out of the battery. Appendix A provides various correction factors. The ramp (slanted) characteristics of the battery's specific gravity and the cell voltage curves are used to predict the state of charge, of the battery.

3. Battery Bank.

The battery bank is a group of identically-sized cells, of the same construction, connected in series. The number of cells connected in series determines the voltage rating of the battery bank.

Each lead acid antimony cell, at full charge, has a voltage of 2.15 V. A battery bank in the CANDU system must provide 250 V. This is achieved by connecting 116 (lead calcium) or 120 cells (lead antimony) in series. See Figure 3.

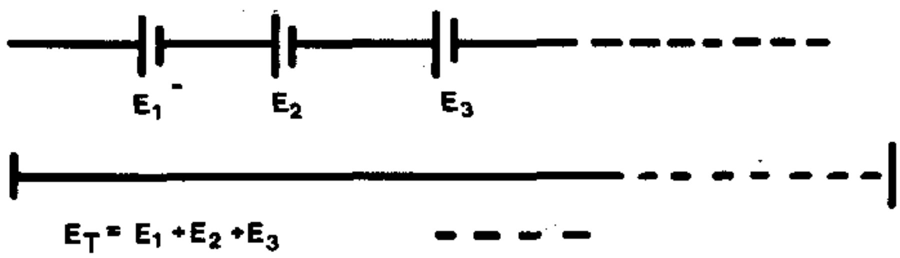

Figure 3: A Battery Bank

Ampere-hour rating of a battery = (current in amperes) x (time in hours).

If a battery is rated for 200 A-H then it can produce 200 A for one hour, 100 A for two hours, 50 A for four hours, etc. However, in practice, a battery can not deliver its full rated capacity, if it is discharged too rapidly.

4. Charging of a Battery Bank

4.1 Battery Charger

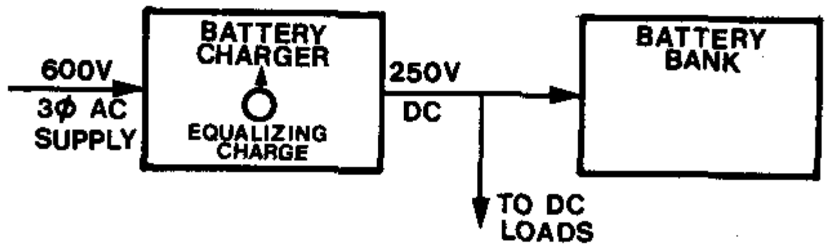

Figure 4: A Block Diagram of Battery Bank *and* Associated Charger

A battery bank is charged by a battery charger. Input to the charger is a 600 V, 3 AC supply and the output is 250 V DC. The charger also has a control to adjust its output voltage, to provide equalizing charge to the battery.

4.2 Pilot Cell

At the time of installation of a new battery, and **before the charger** is turned on, the specific gravity and voltage readings of each cell are recorded in the permanent logbook. The battery is then given an "initial charge", which is in essence, an extended *equalize charge, the duration of which is indicated in* the Installation and Operating Manual.

After the initial charge has been completed, the battery is placed on float, and at the end of one week, specific gravity, voltage per cell and battery float current readings are recorded in the permanent log. All future specific gravity readings and voltage per cell readings will be compared to these initial values.

The cell, with the lowest specific gravity at this time, is labelled the pilot cell and its readings are used as an indicator of the battery's state of charge. Regular comparison is made of the specific gravity and float current, where possible, with previous readings.

4.3 Float Charge

Normally, station lead-acid batteries are "floated" across the dc busbars, and the load is supplied by the charger. If the charger fails, the battery carries the load until the charger is restored to service.

While the battery bank is being recharged, the charger has to supply the load current, as well as the battery charging current. Battery charging current is called float charge. It has two purposes.

(a) Charge the battery, while in use.

(b) Supply the makeup charge to maintain the battery at its charged state. Makeup charge is required because internal leakage, in the battery, occurs at all times.

4.4 Equalizer Charge

The voltage across the battery bank is the algebraic sum of all the individual cells connected in series (120 cells for a 250 V lead antimony system, 116 cells for a 250 V lead calcium system).

However, no two cells are exactly alike due to the manufacturing, material, temperature and specific gravity variations. Therefore, one cell voltage may be higher than another cell. This means that the normal terminal voltage of a battery bank does not guarantee that each individual cell voltage is also normal. Some cells with higher than normal voltage will mask those cells with a lower than normal voltage. If a cell does not have a full charge voltage, it is not fully charged and the battery bank cannot deliver its rated output. Refer to the battery cell terminal voltage and charge curve, Figure 5.

To overcome this inconsistency of state of charge, in the individual cells, the **whole battery bank is intentionally overcharged periodically, under controlled conditions. This brings the weak cells to the required charge level and over charges the normal cells to some degree. This charge is called an equalizer charge.**

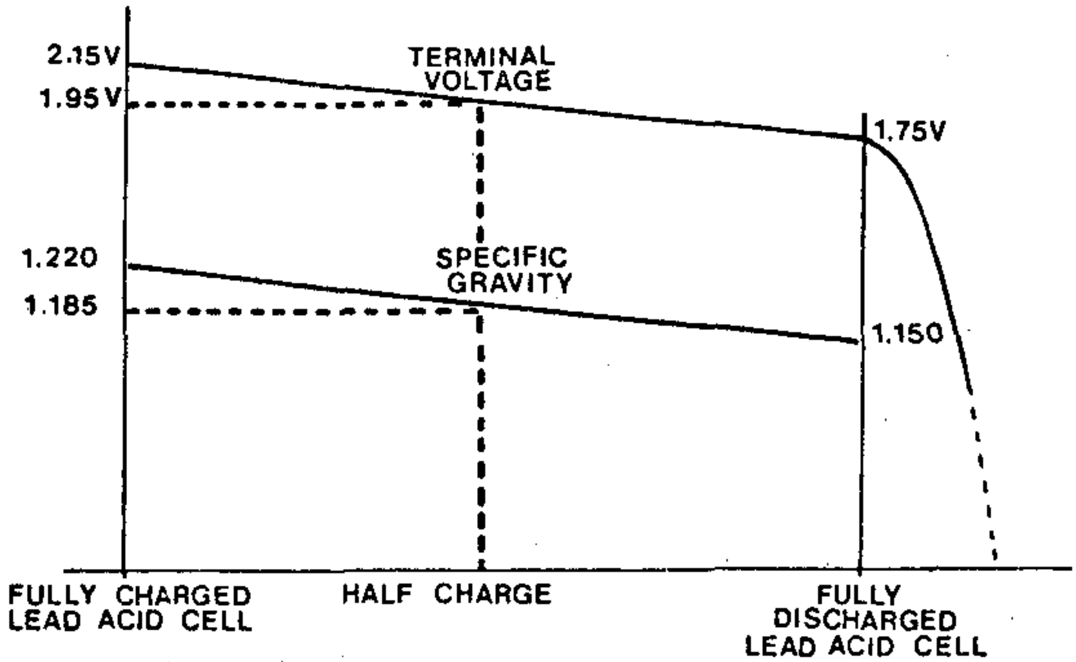

Figure 5: Curves of a Terminal Voltage and Specific Gravity For a Lead Acid Cell (Antimony)

During the equalizing charge, the battery and bus voltage is above the rated value. Care must be taken to ensure that other equipment connected to the battery bank is not damaged, due to this excess voltage.

An equalizing charge should be stopped if **any** of the following are exceeded:

Condition	Lead Antimony Type	Lead Calcium Type
(a) the voltage per cell exceeds	2.33 V	2.41 V
(b) the specific gravity of any cell exceeds	1.240	1.275
(c) the temperature of any cell exceeds	43°C	43°C

CAUTION: Batteries must not be left on equalizing charge for an extended period of time. Failure to observe this precaution will seriously reduce the life of the battery.

4.5 Float Voltage

The float voltage is the normal operating voltage of the battery, necessary to maintain the battery in a fully charged condition. The maximum recommended float voltage is 2.17 volts per cell for lead-antimony cells and 2.25 volts per cell for lead-calcium.

A minimum float voltage of 2.15 volts per cell for lead antimony and 2.17 volts per cell for lead-calcium will maintain the cells fully charged and provide optimum life. Any lower float voltage will result in less than fully charged cells.

5. Battery Capacity

5.1 Discharge Capacity

Discharge capacity of the battery is basically its ability to supply a given current for a given period of time, at a given initial cell temperature, while maintaining voltage above a given minimum value. This capacity is stated in amperes, at a given discharge rate. Most battery cells are rated for 8 h or 5 h.

For example, the ampere-hour capacity is the product of 8 times (or 5 times) the discharge rate in amperes, at a temperature of 25°C (77°F), when discharged to an average voltage of 1.75 volts per cell.

When discharged at higher than 8h (or 5h) rate, the expected output, in ampere-hours, is less than the rated capacity. At lower rates or intermittent loads, it is more.

The initial capacity may be slightly less than the rated capacity and will normally reach 100% within two years of service. The capacities of older batteries, particularly on charge-discharge routines, may be reduced due to loss of active material.

The ability of a fully-charged cell to deliver a certain number of ampere-hours, at a given discharge rate is determined, primarily by the size and/or number of positive and negative plates in the cell.

5.2 Capacity Variation With Temperature

Battery capacity increases with an increase in electrolyte operating temperature, but the life of the battery is reduced. Table 2 gives some idea as to the extent of this change, in terms of the capacity.

Table 2

Electrolyte Temperature (Degrees F)	Electrolyte Temperature (Degrees C)	Capacity (At 8 h Rate In Percent)
110	43	114
90	32	106
77	25	100
70	21	97
60	15.5	92
40	4	80
20	-6.7	65
0	-18	45

5.3 Capacity Test

To guarantee the Ampere-Hour rating of a battery, it is discharged, at its current rating, over an eight hour period. This discharge test is called a **capacity test.** The battery is then re-charged. The battery is not available for use while being capacity tested or re-charged.

A capacity test is performed routinely every two to three years, or whenever there is a doubt about a battery's performance.

Table 3 shows the size and type of batteries used in various generation stations and Heavy Water Plants, in NGD.

Table 3

Location	Battery Size/Bank	Battery Type
Bruce NGS B	975 AH	Lead Calcium
Bruce NGS A Unit Batteries	1350 AH	Lead Antimony
Pickering NGS B	825 AH	Lead Calcium
Pickering NGS A	912 AH	Changed to Lead Calcium Originally Lead-Antimony
NPD NGS	320 AH	Lead Antimony
Douglas Point NGS	600 AH	Lead Antimony
Heavy Water Plants	360 AH	Lead Calcium

Notes

6. Aging of Lead Acid Batteries

Lead acid batteries, as any other piece of electrical apparatus, have an economic life. In Hydro's experience, this is about 15 years, for lead antimony and 20 years, for lead calcium batteries. This useful service life will be shortened by poor maintenance and/or poor operation. The main factors which shorten the life of a battery are:

(a) Overcharging

This can occur if the charge rate is too high; that is, too high a charging current or too high a charge voltage. In both cases, the manufacturer's or the station's recommendations must be adhered to.

(b) Discharging at Too High a Rate

Too high a discharge rate will shorten the life of a battery. Again, the recommended values should not be exceeded.

(c) Excess Temperature

During charging and discharging, a battery's temperature will increase. It must not be allowed to exceed 43°C.

All of the above will shorten the life of a battery, causing the paste to become detached from the plates, and fall to the bottom of the cells. Figure 6 shows a cell where the paste has fallen to the bottom of the case. This paste forms a sediment which builds up until it touches both plates. When this occurs, the sediment forms a short-circuiting path and the battery no longer holds a charge.

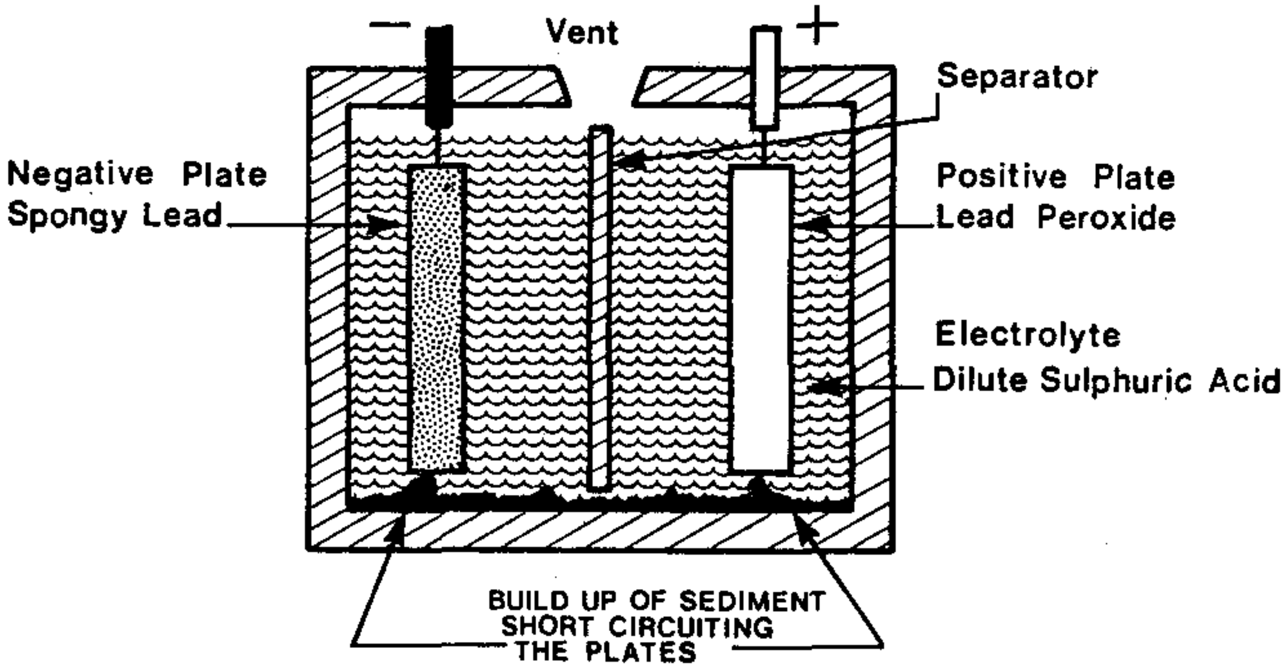

Figure 6: Plates Being Short-Circuited by Sediment

The lead plates may break if a battery is charged at too high a rate, or if the internal, cell temperature exceeds 43°C.

Battery cases are made of transparent material. This allows a visual inspection of the plate condition, electrolyte level, gassing state, and sediment level. Frequent inspections will prevent cell or battery failure.

7. Hazards and Precautions With Lead Acid Batteries

There are three safety hazards associated with lead acid batteries. The hazards are:

(a) Gases

Oxygen and hydrogen are given off from the electrolyte during charging and discharging. If these gases are allowed to accumulate, an explosion can result. **No smoking** or **naked lights** or **flames are permitted in a battery room.** It is essential that the ventilation systems in these areas are continuously operating. This should be checked by personnel prior to entry into a battery room.

(b) Acid

To avoid **acid burns,** before any work is done with acid, including taking specific gravity readings, **proper protective clothing** must be worn. A facemask to protect the eyes, and an **apron** and **gloves** to protect the body, are required. In addition,there must be a **supply of water available** to wash off any acid that may come into contact with eyes or skin.

(c) Electricity

It **is** often forgotten that a **battery contains** a **large amount of stored electrical energy.** It should be noted, that **station batteries have bare exposed terminals** and intercell connectors. **Short circuiting** battery terminals will produce large currents, which can **damage the battery, cut off the class 1 supply,** and **burn or electrocute** the person involved. Therefore, insulated tools must be used in a battery room. Aluminum ladders cannot be taken into a battery room.

8. Comparison of Lead Antimony and Lead Calcium Batteries

The lead calcium battery is a new development and it is just gaining acceptance in the Nuclear Generation Division, (as noted in Table 3).

A brief comparison of the two battery types is given below.

(a) The lead calcium battery has a longer life (20 years), as compared to lead antimony (15 years). Actual life may be affected by the application and maintenance.

(b) Lead calcium batteries require less makeup distilled water.

(c) Lead calcium batteries have a higher cell potential, 2.17 volts, as compared to 2.15 V, for lead antimony cells. Hence, fewer lead calcium cells need to be connected in series to give the desired output voltage.

(d) Lead calcium batteries produce less gas.

(e) Lead calcium batteries require less frequent equalizer charge. This also results in an increased life, since over-charging reduces battery life.

Notes

APPENDIX A

Specific Gravity Temperature Correction Chart

°C	SG Correction	°C	SG Correction	°C	SG Correction
6.7	-0.011	18.9	-0.003	31.7	+0.004
		19.4	-0.003	32.2	+0.004
7.2	-0.010	20	-0.003	32.8	+0.004
7.8	-0.010				
8.3	-0.010	20.6	-0.002	33.3	+0.005
		21.1	-0.002	33.9	+0.005
8.9	-0.009	21.7	-0.002	34.4	+0.005
9.4	-0.009				
10	-0.009	22.2	-0.001	35	+0.006
		22.8	-0.001	35.6	+0.006
10.6	-0.008	23.3	-0.001	36.1	+0.006
11.1	-0.008				
11.7	-0.008	23.9	0.000	36.7	+0.007
		24.4	0.000	37.2	+0.007
12.2	-0.007	25	0.000	37.8	+0.007
12.8	-0.007	25.6	0.000		
13.3	-0.007	26.1	0.000	38.3	+0.008
				38.9	+0.008
13.9	-0.006	26.7	+0.001	39.4	+0.008
14.4	-0.006	27.2	+0.001		
15	-0.006	27.8	+0.001	40	+0.009
				40.6	+0.009
15.6	-0.005	28.3	+0.002	41.1	+0.009
16.1	-0.005	28.9	+0.002		
16.7	-0.005	29.4	+0.002	41.7	+0.010
				42.2	+0.010
17.2	-0.004	30	+0.003	42.8	+0.010
17.8	-0.004	30.6	+0.003		
18.3	-0.004	31.1	+0.003	43.3	+0.011

These numbers are compiled from the following rule used by Exide and Gould. For every 1.67°C above 25°C add 0.001. For every 1.67°C below 25°C subtract 0.001 in SG readings.

Electrolyte Level Correction

1. Gould Cells - Add 0.006 to the Specific Gravity reading for each 0.64 cm below the high level mark.

2. Exide and C and D Cells - Add 0.015 to the Specific Gravity reading for each 1.27 cm below the high level mark.

Notes

ASSIGNMENT

1. Describe the principle used in a battery. (Section 2.1)

2. What is the purpose of a battery bank in the CANDU system. List three typical loads on the battery bank. (Section 2.2)

3. Which two types of batteries are used in NGD? (Section 2.3)

4. Why is antimony or calcium added to the lead? (Section 2.4)

5. What is the voltage and specific gravity of the lead antimony battery used in NGD at: (Section 2.5)

   (a) Full Charge

   (b) Full Discharge

6. How is specific gravity affected by temperature? When is the specific gravity correction factor positive/negative? (Section 2.5)

7. Why is a correction factor not applied to the voltage, for minor changes in temperature? (Section 2.5)

8. What is a battery bank? Give the expression for total terminal voltage of the battery bank. (Section 3)

9. What is the input voltage, output voltage, and voltage type (AC or DC) for a battery charger? (Section 4.1)

10. Define what is meant by:

(a) Ampere-Hour rating of a battery. (Section 3)

(b) Pilot cell. (Section 4.2)

(c) Float charge. (Section 4.3)

(d) Equalizer charge. (Section 4.4)

(e) Float voltage. (Section 4.5)

(f) Discharge capacity. (Section 5.1)

11. List the three conditions which dictate when an equalizer charge must be stopped. (Section 4.4)

12. How is battery capacity affected by:

(a) Discharge rate. (Section 5.1)

(b) Temperature. (Section 5.2)

13. What is a capacity test and how often is it performed? (Section 5.3)

14. List three hazards associated with batteries and two precautions for each hazard. (Section 7).

15. Compare lead antimony and lead calcium batteries. (Section 8).

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