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 <u>insulated</u> 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.

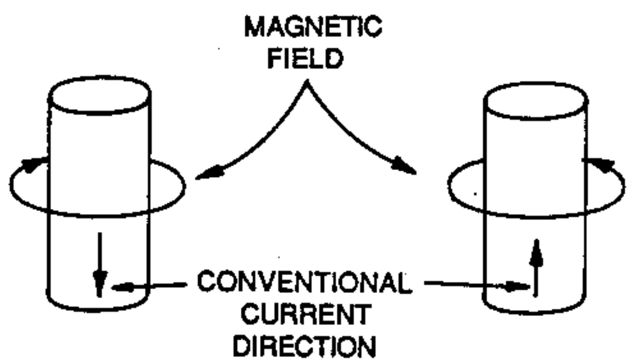


Figure 1: Magnetic Fields Around Conductors Carrying a Current

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).

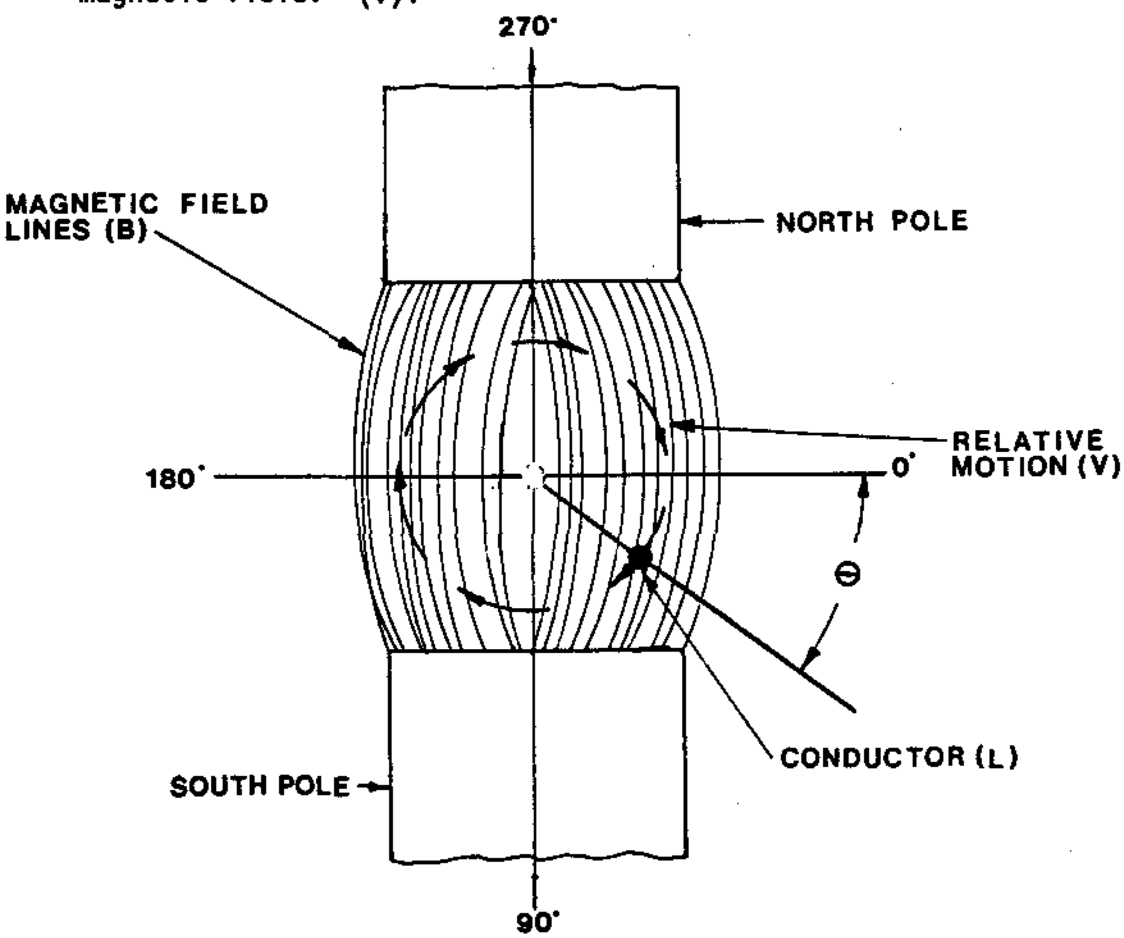


Figure 2: Conditions Required to Induce a Voltage on a Conductor

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.

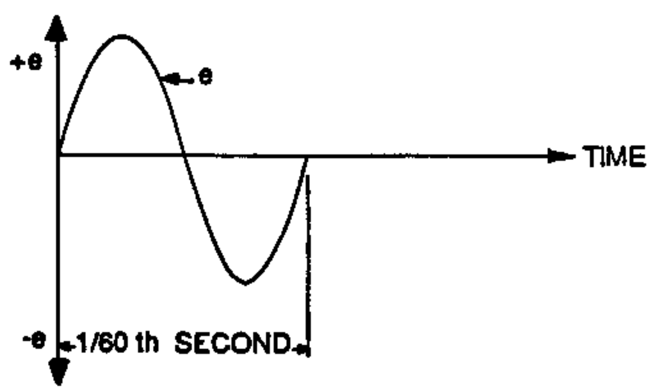


Figure 3: ac Wave Form

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.

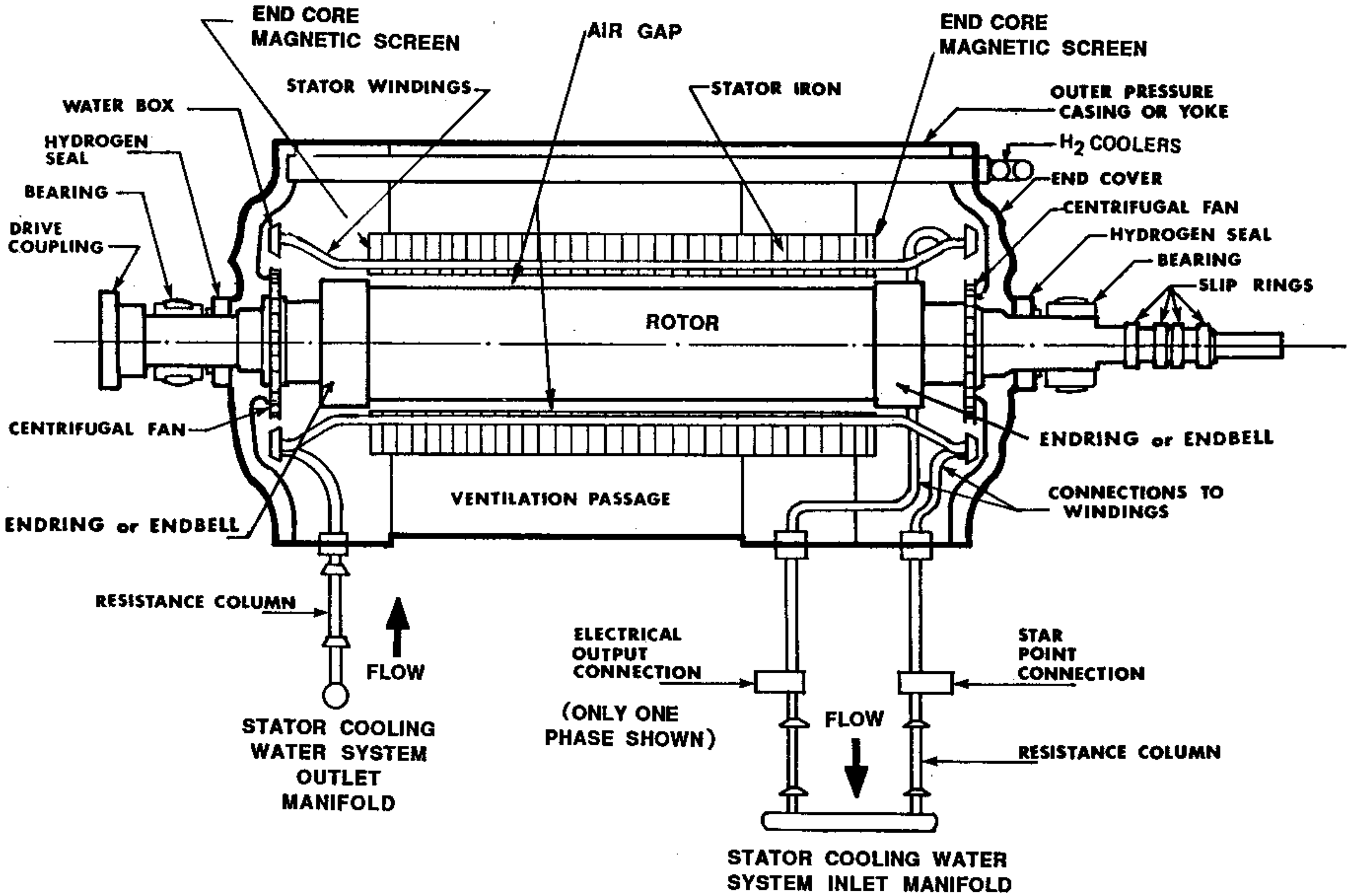


Figure 4: Simplified Sectional Diagram of a Large AC Generator

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.

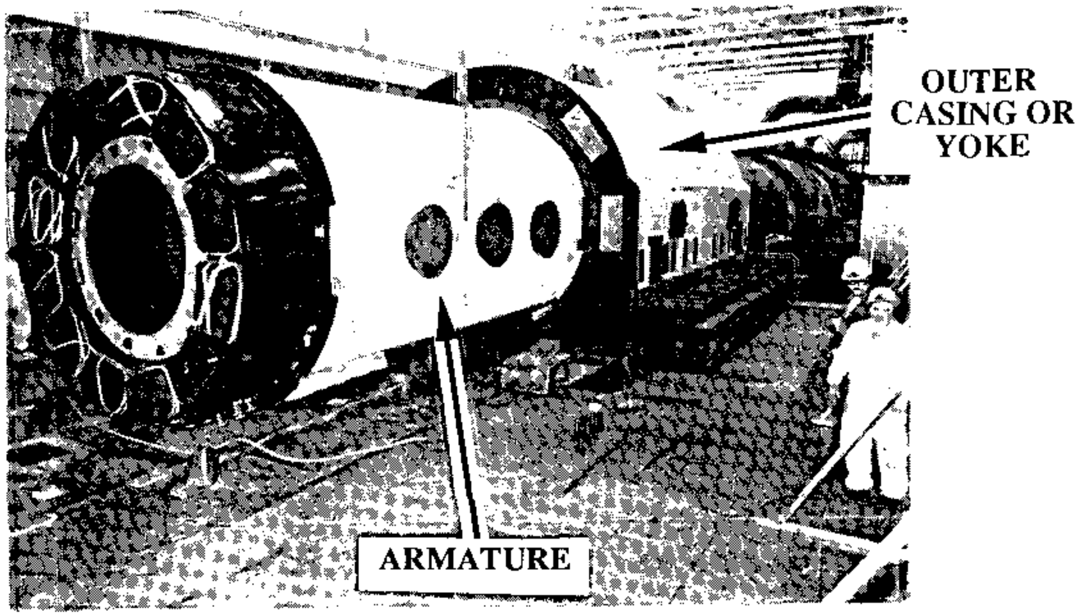


Figure 5: Generator Yoke and Armature

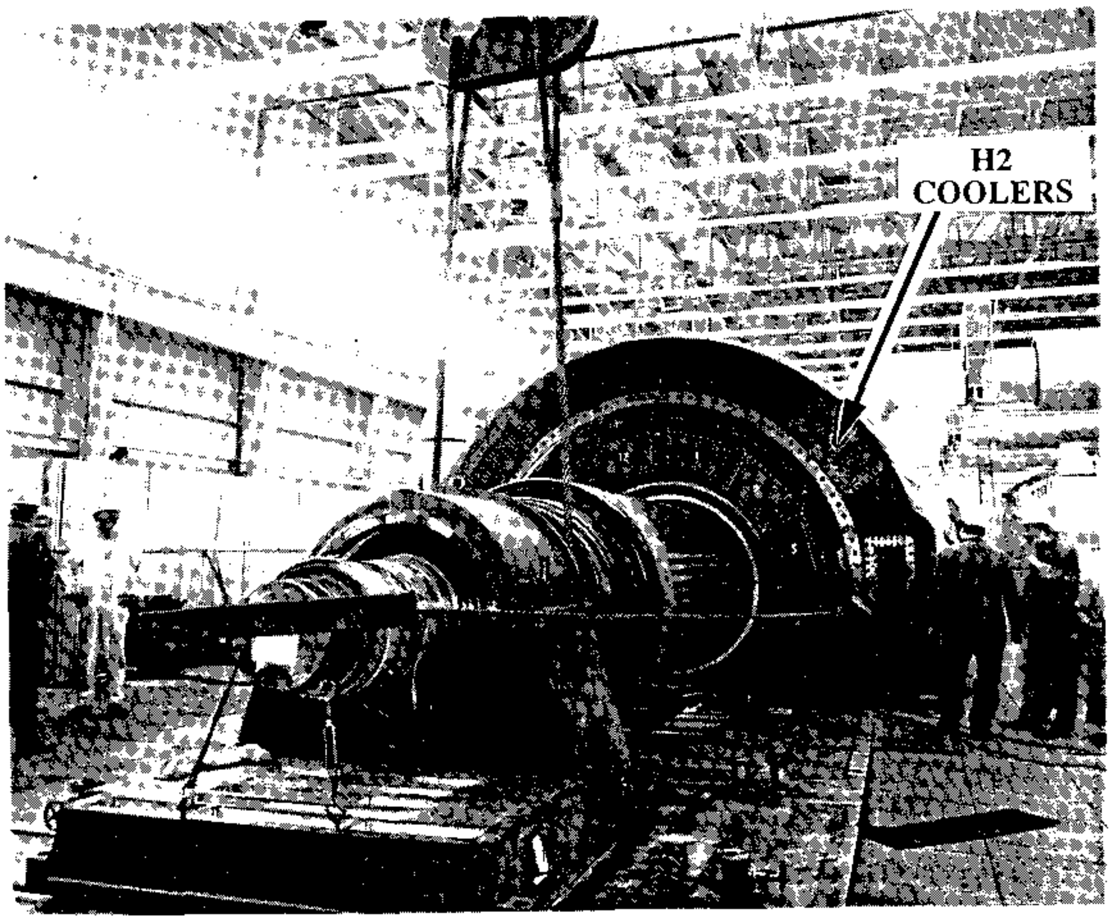


Figure 6: Rotor Being Inserted into Yoke/Armature Assembly

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 ($\approx$ 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.

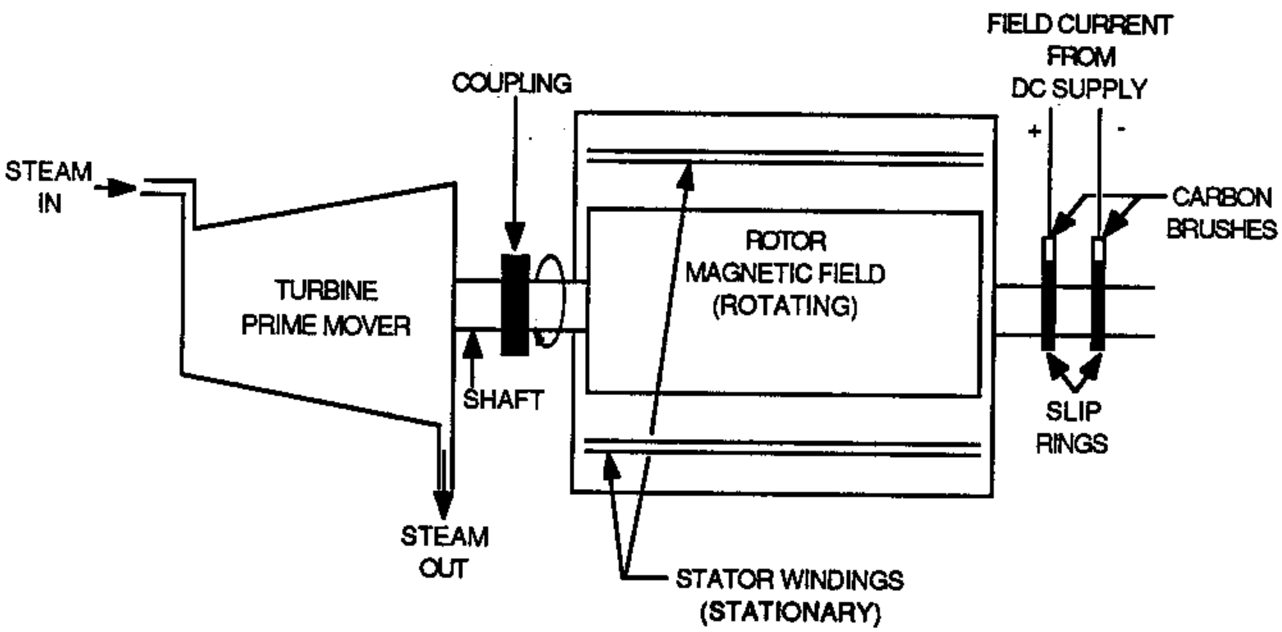


Figure 7: A Simplified Turbo-Generator

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.

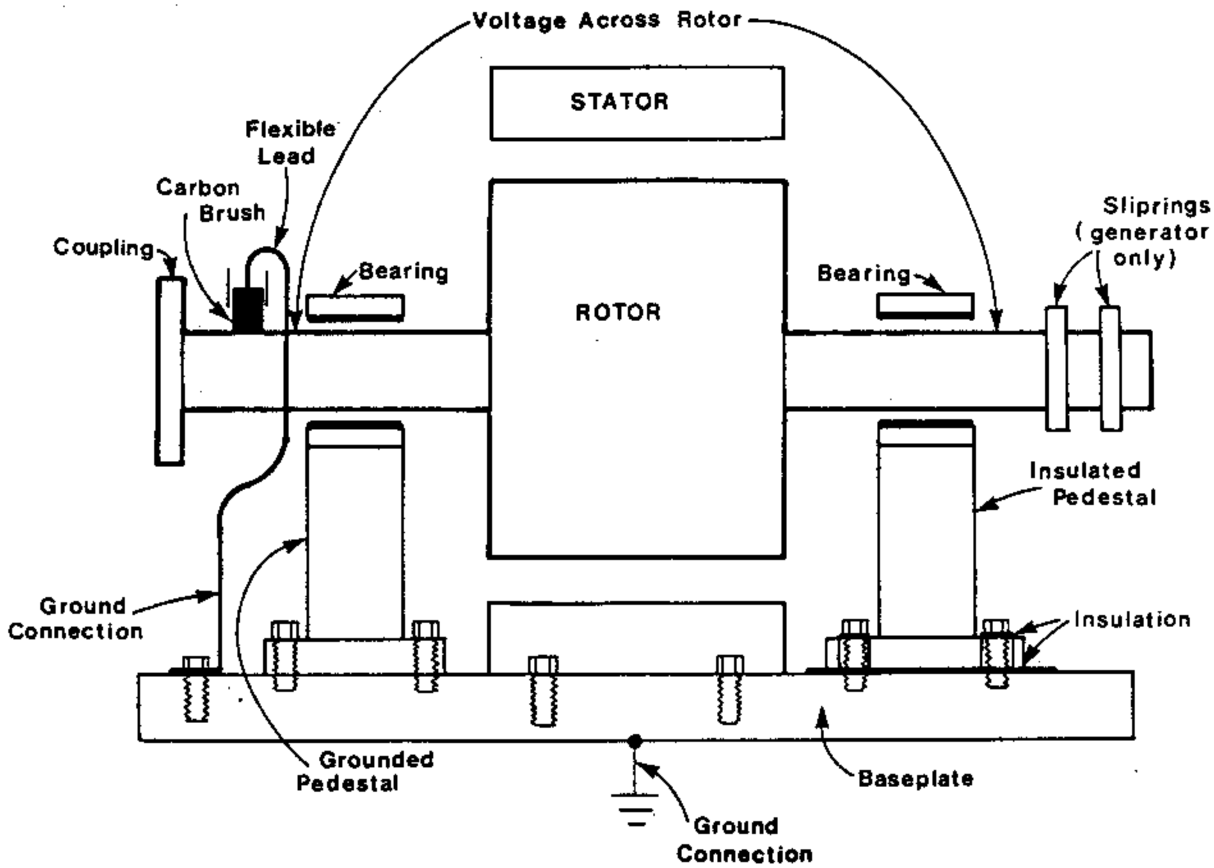


Figure 8: Grounding and Insulation Arrangements for a Large Motor or Generator Rotor

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.

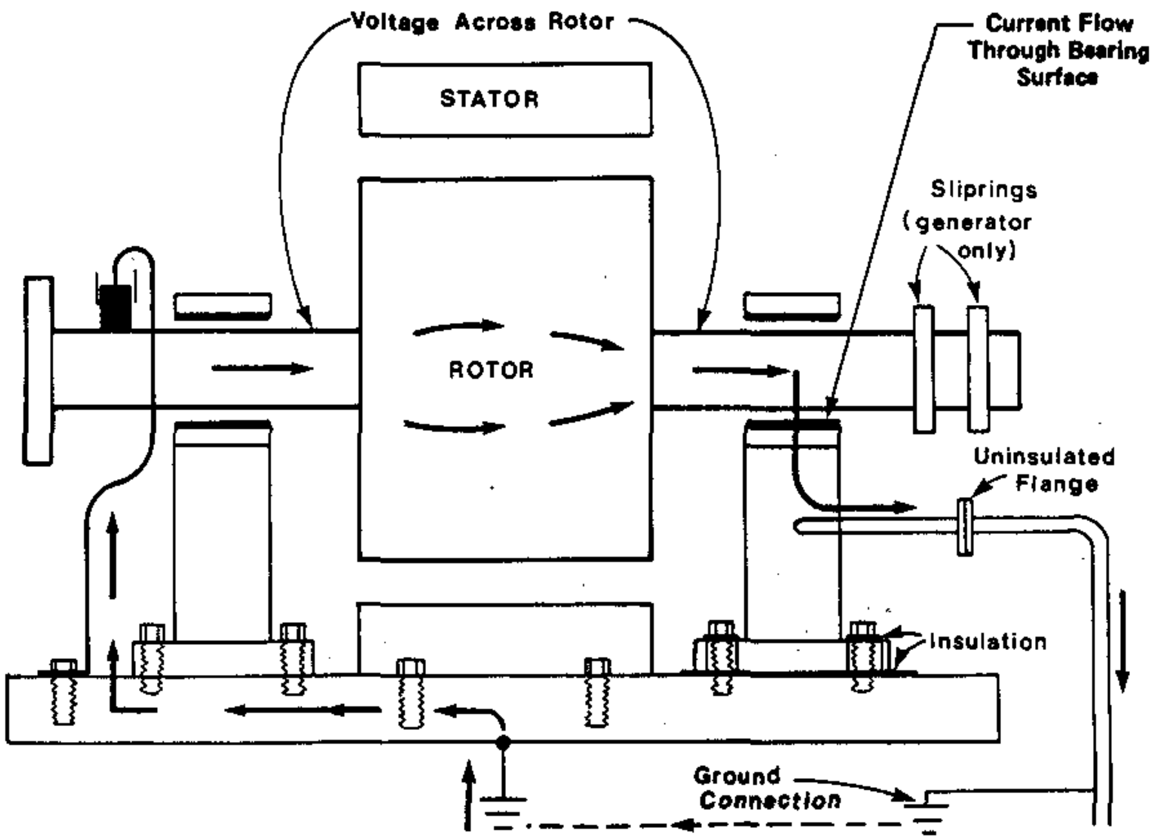


Figure 9: Current Flowing Through Bearings and Uninsulated Flange

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.

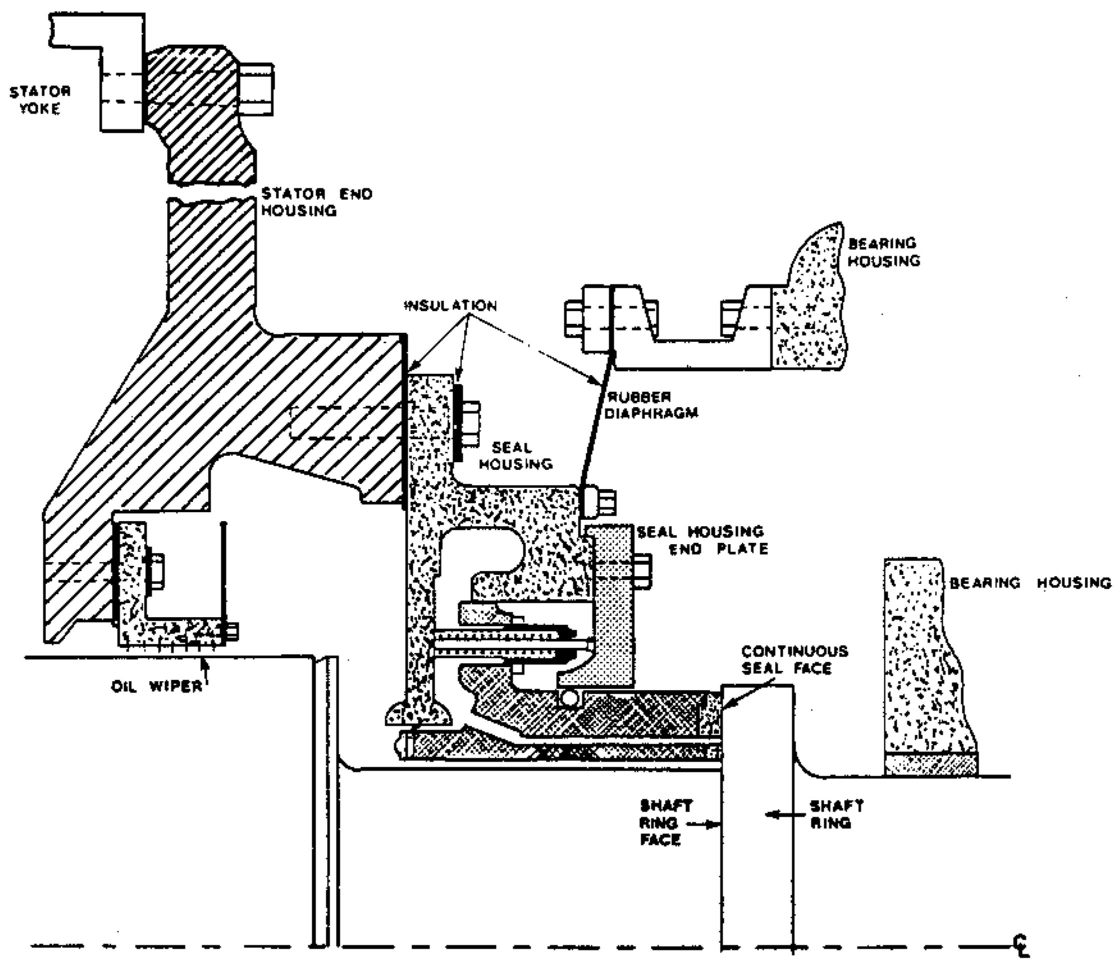


Figure 10: Section of a Generator Hydrogen Seal Showing Insulation

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)

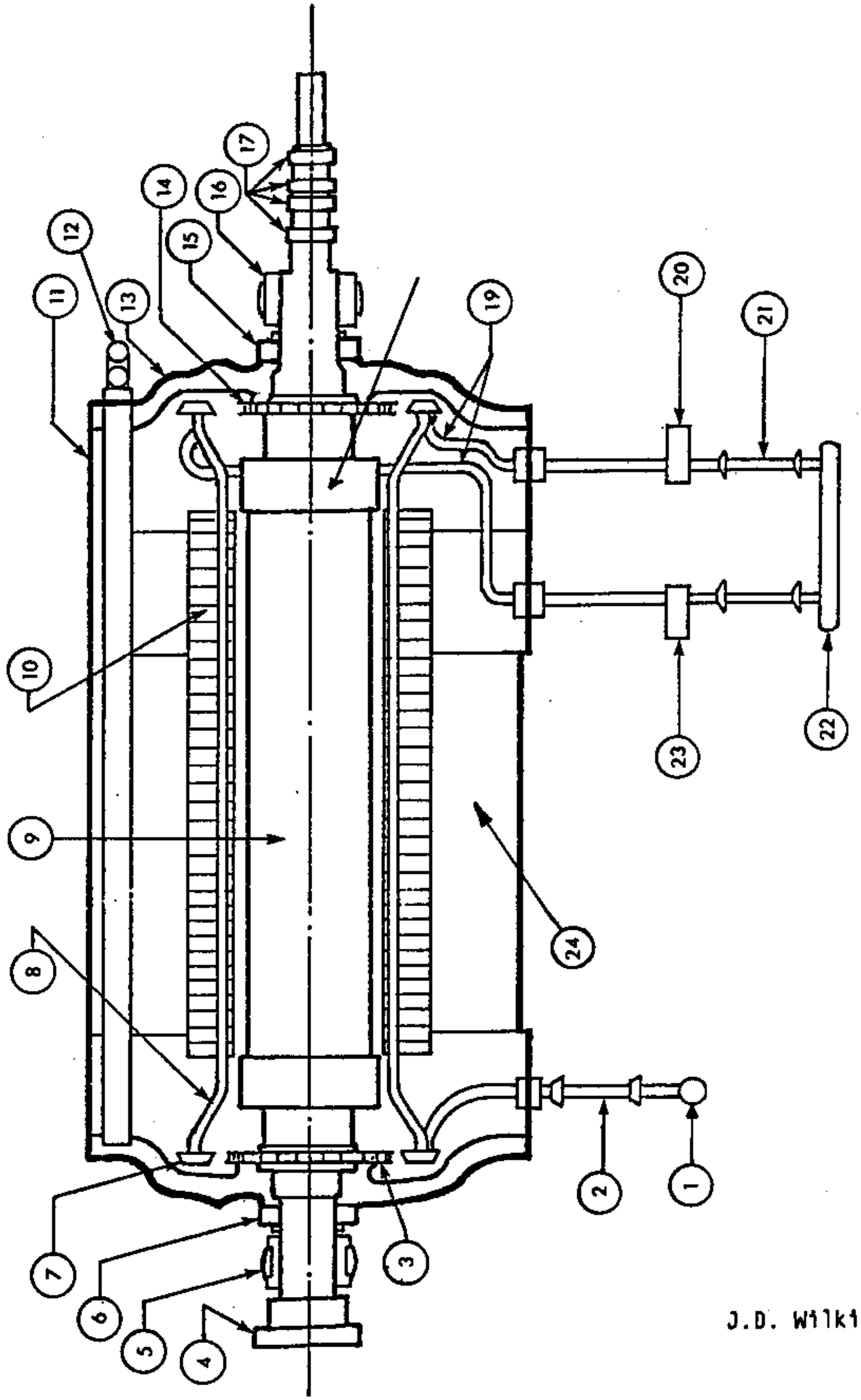
(10) Briefly explain the need for:

(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