Electrical Insulation for Rotating Machines

KEYVAN FIRUZI

Voltage Level and Connection

- Voltage Level
  - ✓ Peak and RMS value
  - ✓ Line-to-ground Voltage (Phase Voltage)
  - ✓ Line-to-Line Voltage (Line Voltage)
- Three Phase connection
  - ✓ Delta
  - ✓ Star

Neutral Grounding

High impedance grounding scheme

- High resistance – grounding transformer with resistor at secondary
- In large generator distribution transformer used as ground transformer
- Very low ground fault current 3 to 25 A in primary

Low resistance

- Very large and expensive resistor – not used for small generators
- Limit the ground fault current to 200 A or 150% of rated full load current

Reactance grounding

- Fault current will range from 25%-100% of the three-phase current

Neutral Grounding

Direct grounded/zero impedance

- Extremely high fault current – very easy to detect
- Due to high fault current, reaction time must be quick to avoid damage

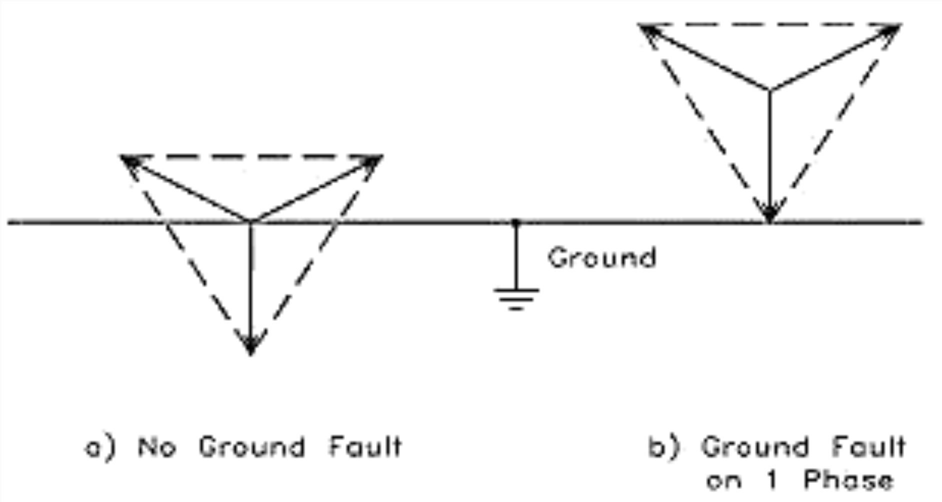
Non-grounded generators

- Popular in marine application
- At the time of a fault, there is no fault current flow so reaction time can be slow
- Voltage elements are typically used to detect such faults

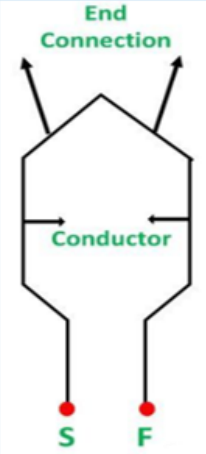
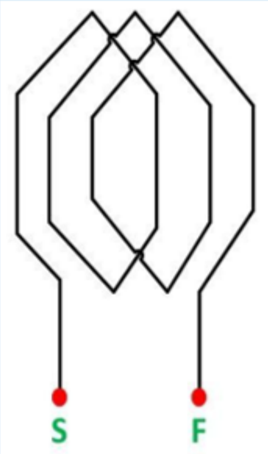
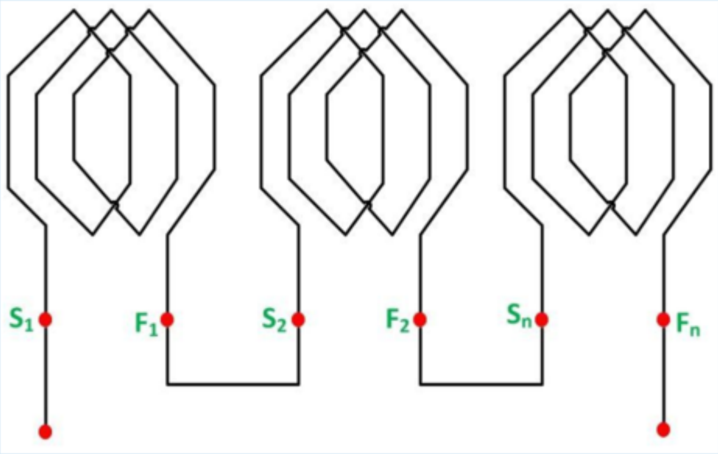
Neutral Grounding

Single Phase to ground fault in isolated neutral system

Transient Voltage can get to twice of line voltage



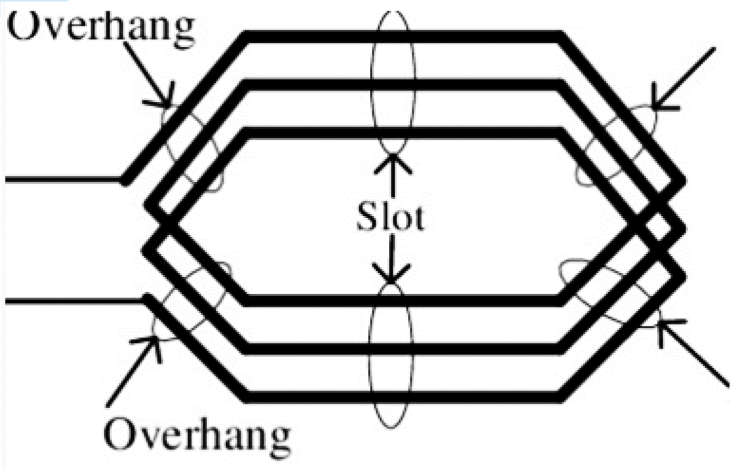
Stator Winding Configuration

Turn	Coil	Winding
		

Each coil can have from 2 to 12 turns

For example, in a 4160-volt stator winding (2400 V line-to-ground), the winding may have 10 coils connected in series, with each coil consisting of 10 turns, yielding 100 turns between the phase terminal and the neutral. The maximum voltage between the adjacent turns is 24 V

In general, the voltage across each turn will be between about **10 V**ac (small form-wound motors) and **250 V**ac (for large generator multi-turn coils).

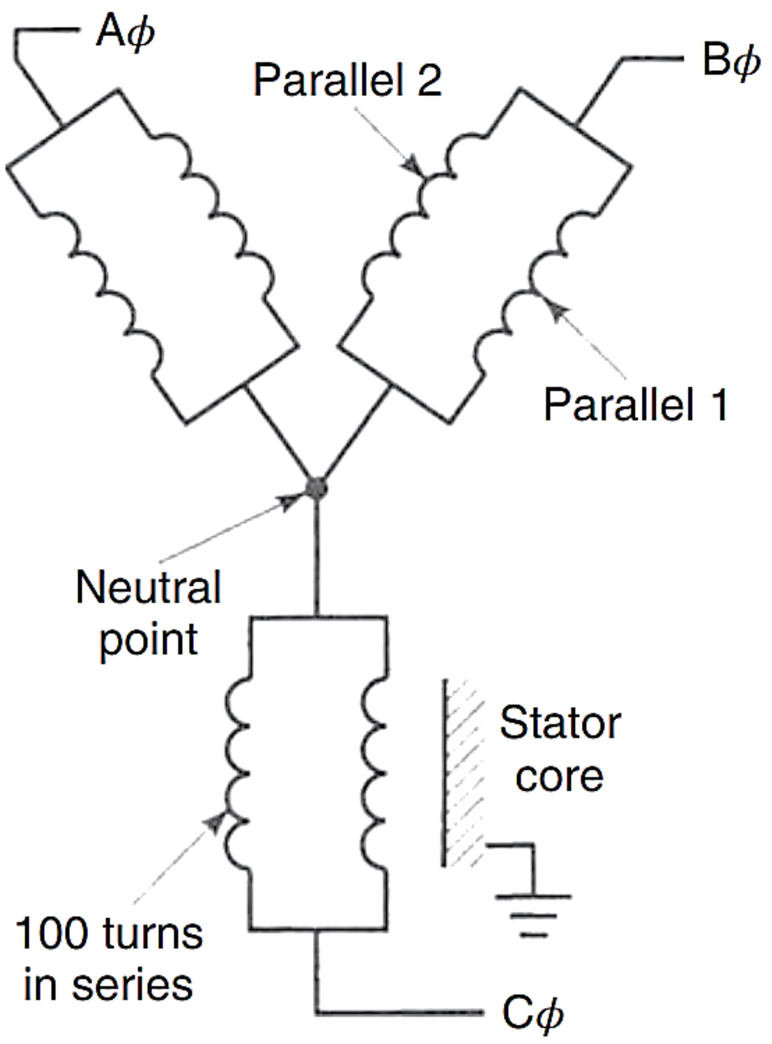


Stator Winding Configuration

The three main components in a stator are

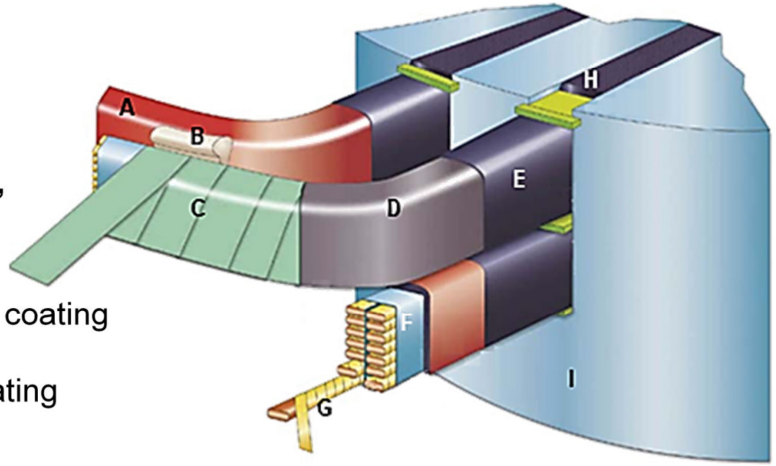
- copper conductors (aluminum is rarely used)
- stator core
- insulation

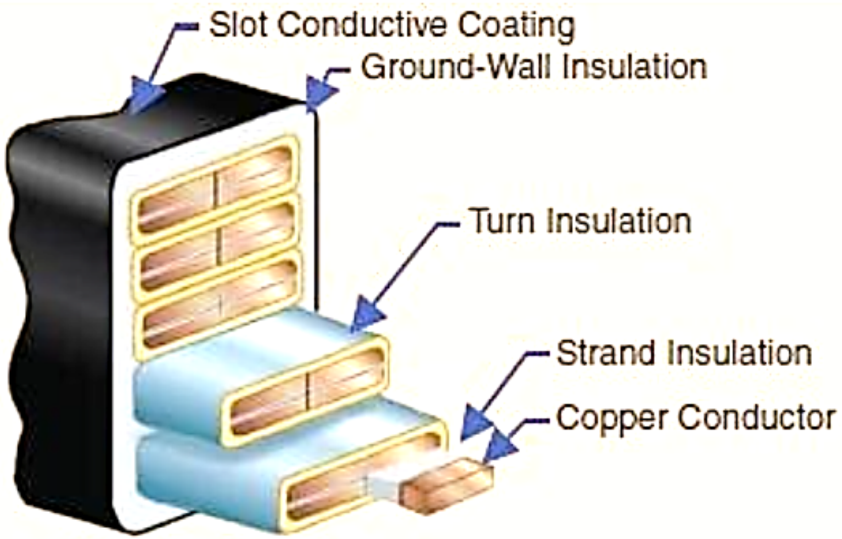
For machines operating at 1 kV and above: **Form-wound stators**

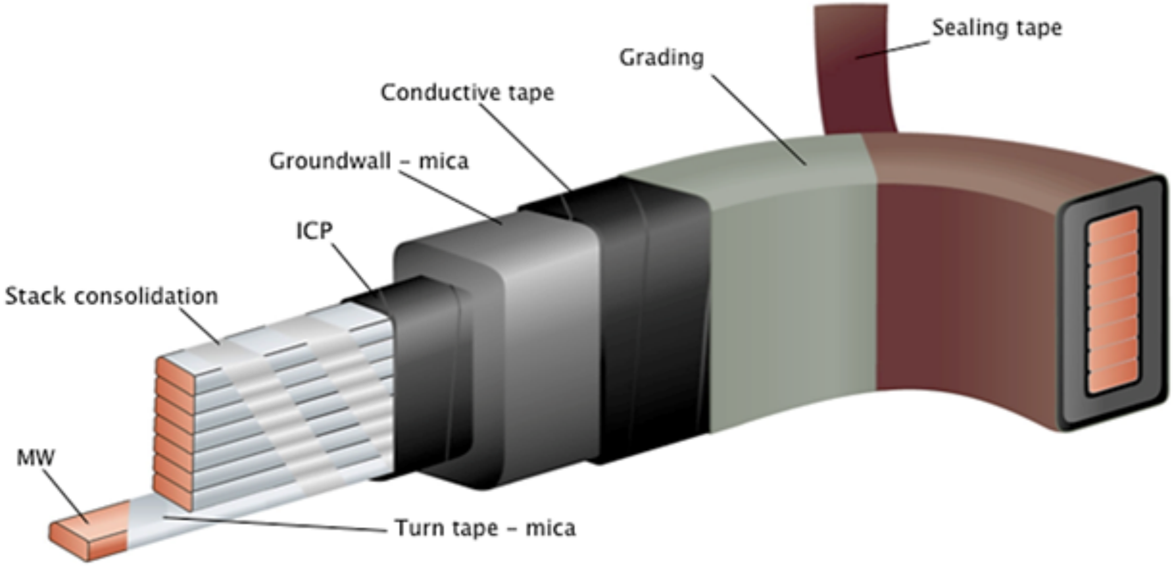


Stator Winding Configuration

A. Covering tape
B. Spacer, coil-end bracin
C. Groundwall insulation, mica tapes
D. Grading/ silicon carbide coating
E. Slot semiconductive coating
F. Inner semicon coating
G. Turn insulation
H. Slot wedge / seal
I. Stator core

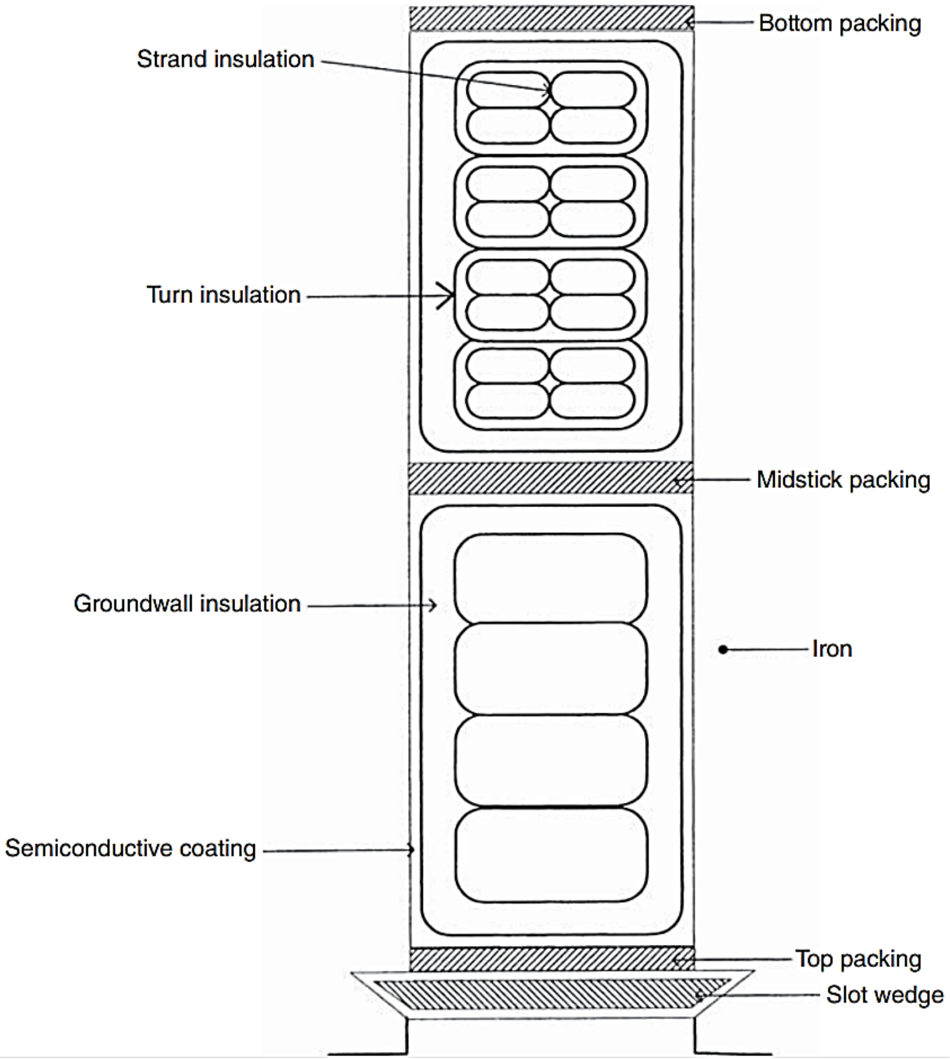






Stator Winding Insulation

- Strand (or subconductor) insulation
- Turn insulation
- Groundwall (or ground or earth or mainwall) insulation



Typically form-wound stator has two coils per slot

Stator Winding Insulation

Strand (or subconductor) insulation

Although manufacturers ensure that strand shorts are not present in a new coil, they may occur during service because of **thermal** or **mechanical** aging

A few strand shorts in form-wound coils/bars will not cause winding failure but will increase the stator winding losses and cause **local temperature increases** because of **circulating currents**.

Stator Winding Insulation

Turn Insulation

If a turn short occurs, the shorted turn will appear as the secondary winding of an autotransformer.

$$n_p I_p = n_s I_s$$

a huge circulating current will flow in the faulted turn, rapidly **overheating** it

Followed quickly by a **ground fault** because of **melted copper** burning through any groundwall insulation

Stator Winding Insulation

Groundwall Insulation - main wall insulation

- **Electrical design**

  A stator rated at 13.8 kV (phase–phase) will have a maximum of 8 kV ($13.8/\sqrt{3}$) between the copper conductors and the grounded stator core.

- **Thermal Design**

  Designed to have the same insulation thickness for both phase- and neutral-end coils the groundwall insulation should have as low a **thermal resistance** as possible

- **Mechanical Design**

  The groundwall insulation must also help to **prevent** the copper conductors from **vibrating** in response to magnetic forces.

Stator Winding Insulation

- **Electrical design**

  the groundwall should be free of voids

  minimize the formation of air pockets

- **Thermal Design**

  As high a **thermal conductivity** as possible, to prevent high

  temperatures in the copper

- **Mechanical Design**

  If the groundwall were full of air pockets, the copper conductors might

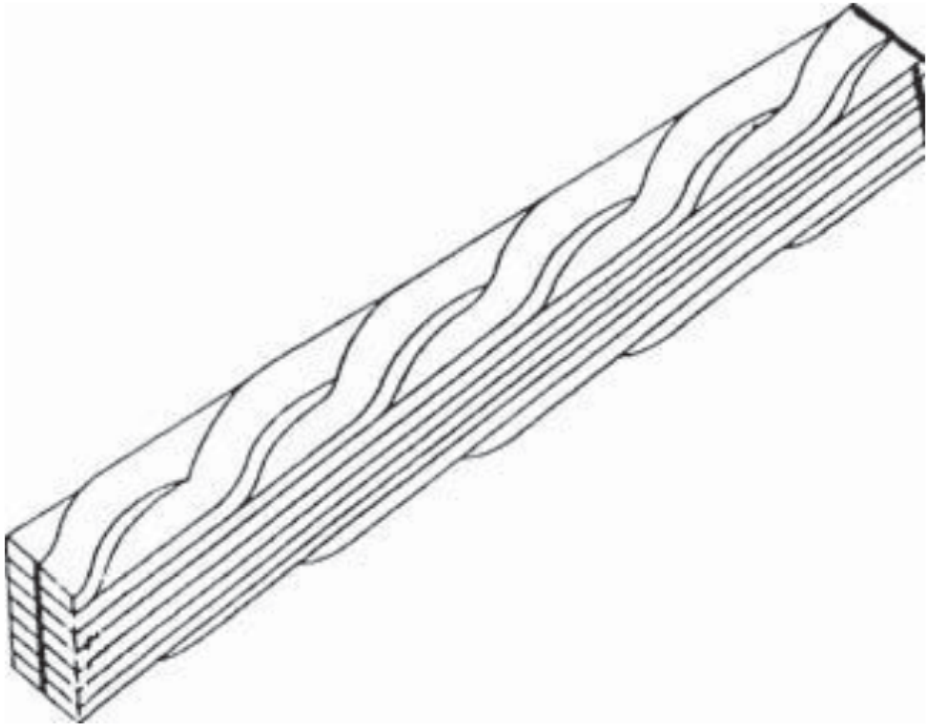
  be free to **vibrate**. Vibrating spark

Stator Winding Insulation

Transposition Insulation

The vicinity where a copper strand is shifted from one position to another, an air pocket can occur.

Extra insulation (**insulation putty**) is needed in these areas to eliminate the air gap and thus any consequent PD



Stator Winding Insulation

Permissible Temperature in Class B Insulation	130°
Ambient Temperature considered in Tropical Country	50°
Margin for Hot Spot Temperature	10°
Permissible Temperature Rise	130° – 50° – 10° = 70°

Thermal Identification and Classification

Old classification: letter designation (A, B, …).

New classification: numerical designation is preferred (105, 130, …)

A Class F or Class 155 material should have an average life of **20,000 h** (about 2.3 years) when operating at 155◦C

Class of Insulation	Permissible Temperature
Y	90°
A	105°
E	120°
B	130°
F	155°
H	180°
C	>180°

TABLE 2.1 Thermal Classification of Rotating Machine Insulation Materials

Numerical Classification	Letter Classification	Temperature (°C)
105	A	105
130	B	130
155	F	155
180	H	180

Source: From IEC 60085

Laminated Core Insulation

C-0	The steel has a natural, ferrous oxide surface
C-2	An inorganic coating of magnesium oxide and silicates that reacts with the surface of the steel during high-temperature annealing. Principally used in distribution transformer cores; not for stamped laminations due to its abrasiveness
C-3	Enamel or varnish coating that enhances punchability and is resistant to normal operating temperatures. Will not withstand stress-relief annealing
C-3A	The same material as C-3, but with a thinner coating thickness to facilitate welding of rotors and stators and minimize welding residue
C-4	An antistick treatment that provides protection against lamination sticking in annealing of semi processed grades
C-5	The insulation is an inorganic coating consisting of aluminum phosphate. C-5 is used when high levels of interlaminar resistance between laminations are required. The coating will withstand stress-relief annealing conditions. C-5 also has a temperature rating in the range of 320–540°C (600–1000°F) which makes it suitable for stator cores used in motors with global VPI stator windings, which usually have to be burned out in an oven to remove the old coils prior to rewinding. This material can withstand steel annealing temperatures up to 815°C (1500°F)
C-5A	The same coating as C-5, but with a thinner coating thickness to facilitate welding of rotors and stators and minimize welding residue
C-6	A combined organic/inorganic coating that can withstand stress-relief annealing

Laminated Core Insulation

ROTOR AND STATOR LAMINATED CORES

Silicon/Aluminum Steels

Required insulation is applied by the steel manufacturer

Small motors use CRML with a C-0 coating

Larger or high-efficiency motors use C-3, C-3A, or C-5 lamination coatings

Large generators typically use C-4 or C-5 coatings, often with a varnish overcoat

C-6 is suitable for large and medium sized motors , H_2 cooled generators . ideal for high frequency application because of its ability to withstand vibrations.

Small- and medium-size motor manufacturers often use pre-insulated core steel to reduce manufacturing costs.

For large and higher efficiency machines, most large OEMs do not rely on the mill-applied insulations alone

Rotor Winding Insulation

The rotor voltage is usually less than 600 Vdc

The turn and ground insulation can be relatively thin

Voltage is DC, there is no need for strand insulation

Thyristor operation, some high spike-type voltages may be superimposed on the DC. This is an additional stress that can cause PD

Voltage transients up to **five times** operating voltage will occasionally be imposed on the rotor winding when power system events occur such as phase-to-ground faults

the steady state current flowing through the rotor winding is usually DC (in synchronous machines), or very low frequency AC (a few hertz) in induction machines. This lower frequency makes the need for a laminated rotor core less critical.

AGING STRESSES

- **Thermal Stress**

  the life of the winding will decrease by **50% for every**

  10°C rise in temperature often approximates this

  equation

- **Electrical Stress**

  Aging by a **PD mechanism**

- **Ambient Stress (Factors)**

  - ✓ Moisture
  - ✓ High humidity
  - ✓ Particles
  - ✓ Dirt

- **Mechanical Stress**

- **Multiple Stresses**

Electric stress

Electric field

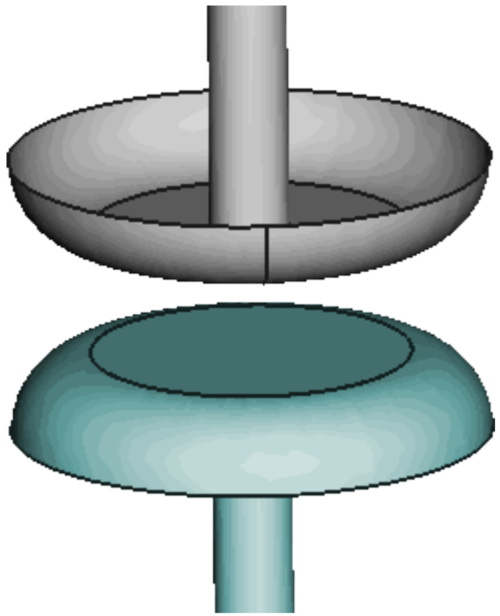
- Voltage
- Geometry

$$E = \frac{V}{d}(\mathrm{kV/mm})$$

$$\text{Poisson's Equation:} \quad \nabla^2 V = -\frac{\rho_V}{\epsilon}$$

$$\text{Laplace's Equation:} \quad \nabla^2 V = 0$$

$$\overline{E} = -\nabla V$$



Electric stress

- Breakdown
- Ionization
- Avalanche

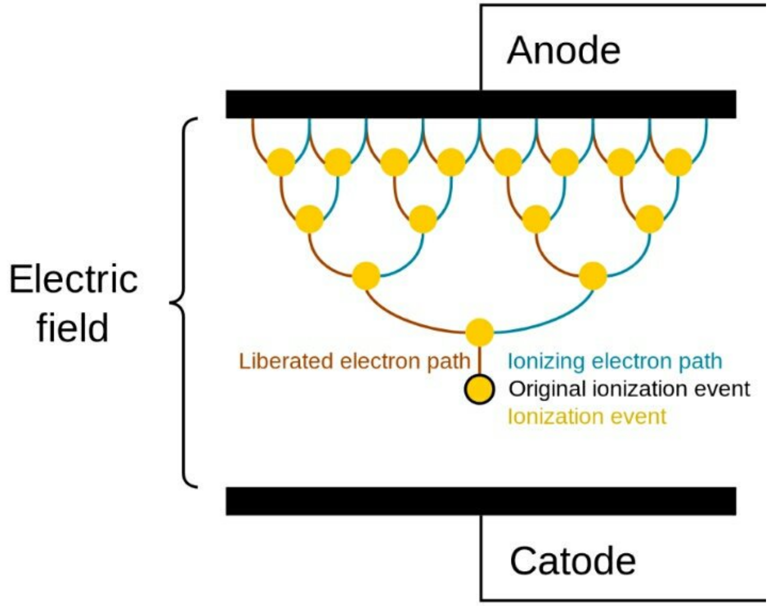
Electric stress in the **air** exceeds **3 kV/mm**

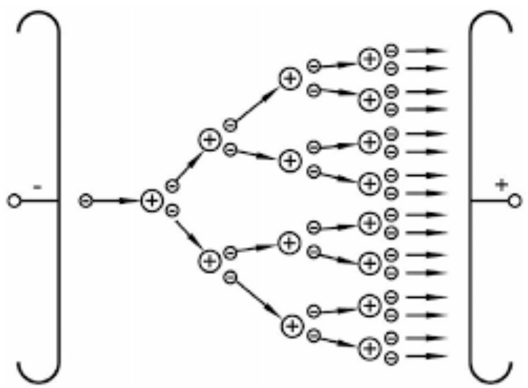
$$E_b = 2.4p + 2.1\sqrt{\frac{p}{d}} \quad kV/mm \quad (p: bar \; - d: mm)$$

The **intrinsic** breakdown strength of mineral **oil** is on the order of **100 kV/mm**.

The **intrinsic** breakdown strength of most **solid** insulating materials such as **epoxy** and **polyester** composites is on the

order of **200 kV/mm**.





Electric stress

Altitude vs pressure

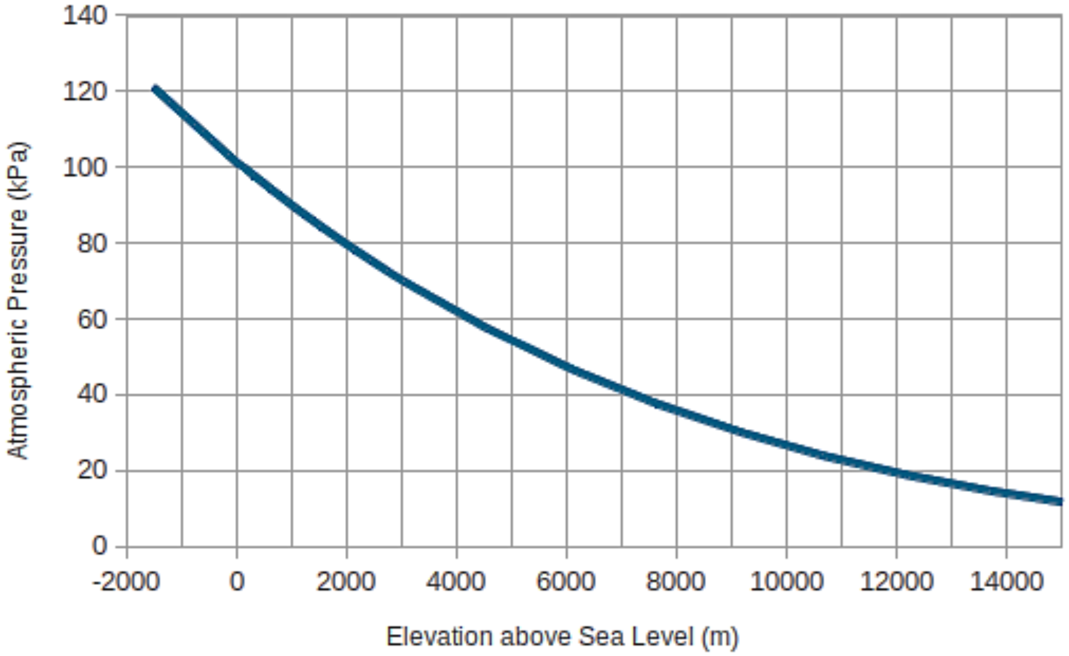
Machines rated 3 kV and above operating above **1000 m** in altitude are especially prone to PD

Pressure drop 5% for each 1 km altitude

Breakdown field drop by almost 5% (2.85 kV/mm)

$H2$ cooled Generator

Pressure is higher and the probability of PD is lower



Insulation

Resin

- Polyester or epoxy resin
- Thermoplastic resin
- Thermosetting resin
- Viscosity

Glass Fibers

- Very high electrical breakdown strength
- Resistant to attack from partial discharges and electrical tracking
- Mechanically strengthen electrical insulation

Laminates

- Thermosetting polymers are widely used to produce laminated electrical insulating materials
- used as wedges, blocking material, filler strips, and slot liners in rotor and stator windings
- made by passing fabric or mat webs through a polyester or epoxy resin dip

Insulation

MICA

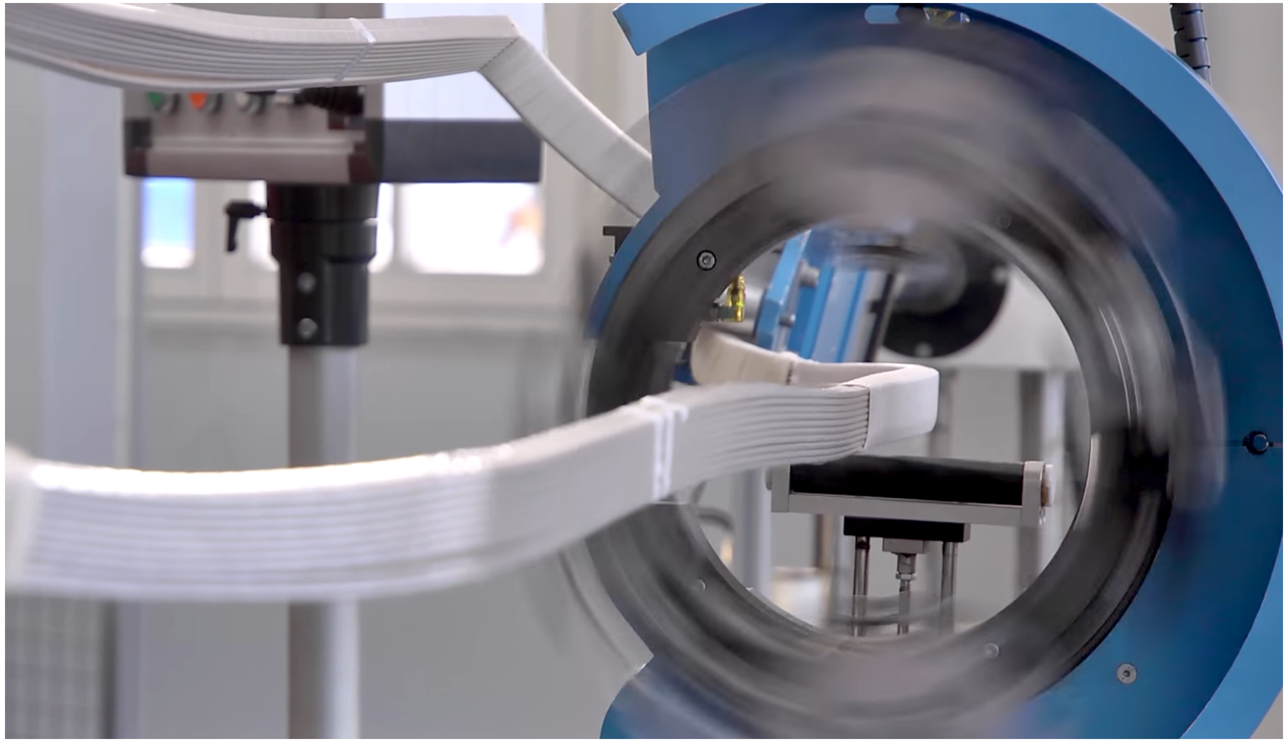
- key materials used in stator windings rated above 1000 V
- High temperature capability
- Excellent resistance to partial discharge
- Weak tensile strength of mica splitting or paper
- Must bonded to a backing material to provide tensile strength
- the backing material by a small amount of epoxy or polyester binder
  - ✓ large generators: epoxy resins
  - ✓ Motors: either polyester or epoxy resin
- Dacron and glass or glass-backed mica paper (large generator)

  Film-backed mica paper tapes (low and medium voltage motors)
- 2–3-cm-wide tapes

Insulation

Manufacturing

- Taping should be as **uniform** as possible
- Taping automation



Fully Automatic Railway Metro Motor Taping Machine Rail transit traction motor insulation - YouTube

Partial Discharge

A localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress

Discharge magnitude

- pC
- Calibration

Measurement

- Offline
- Online

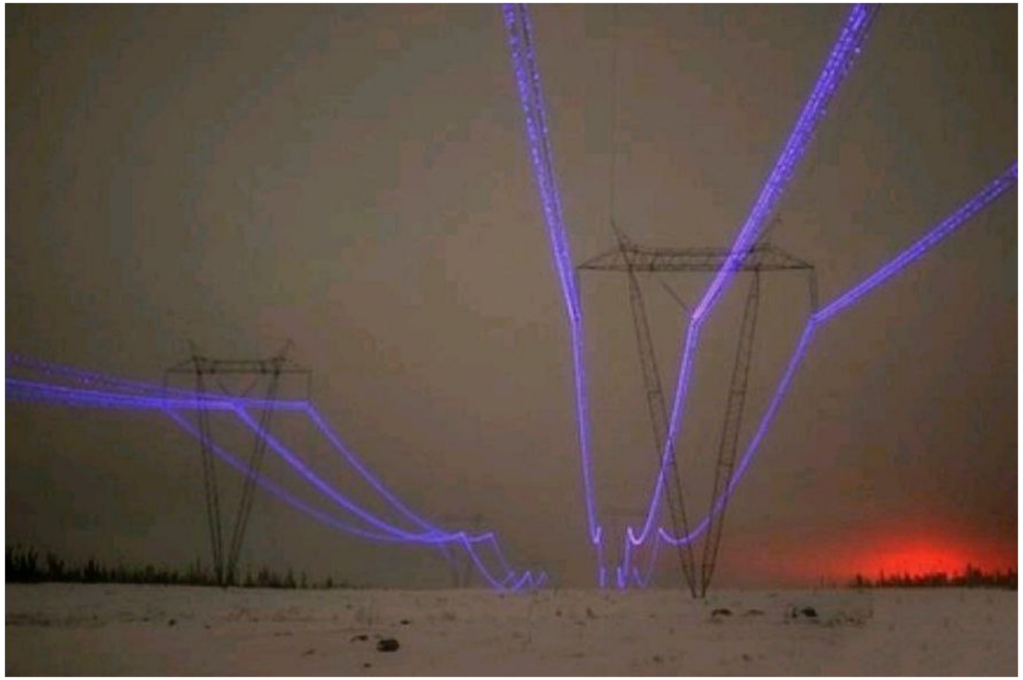
Method

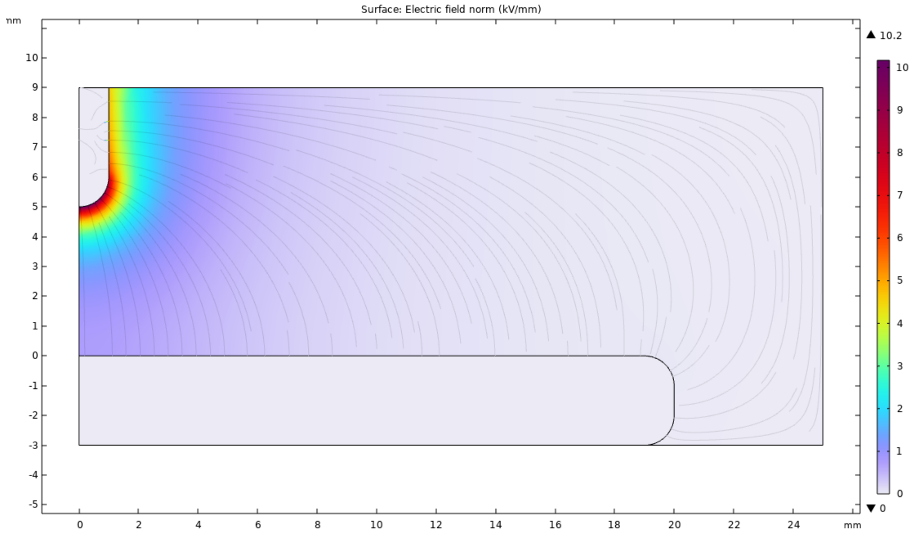
- IEC 60270
- HFCT, VHF, UHF, acoustic, chemical

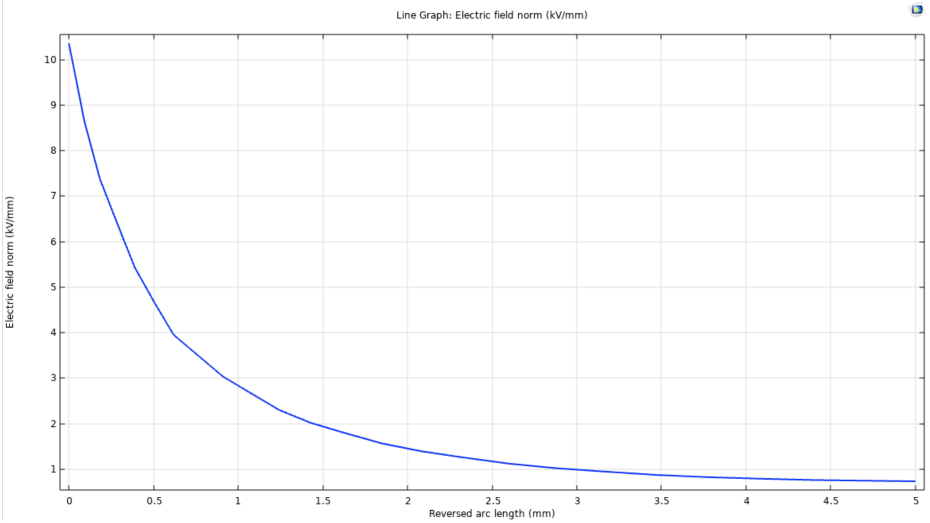
Partial Discharge

Corona

The smaller the radius is the larger will be the electric field



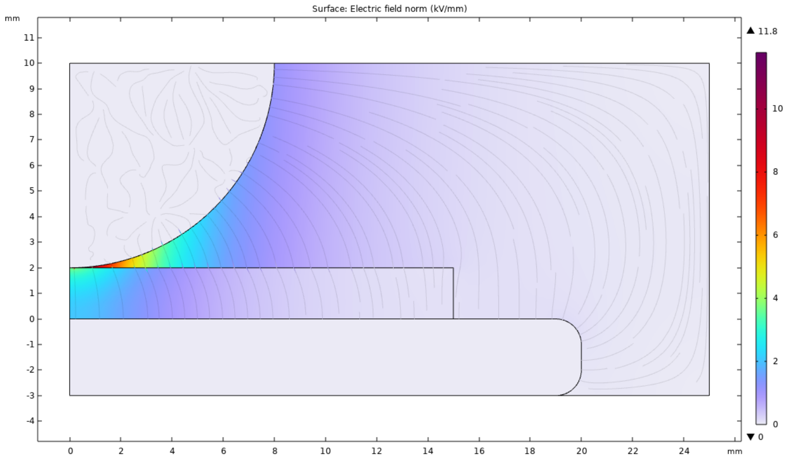




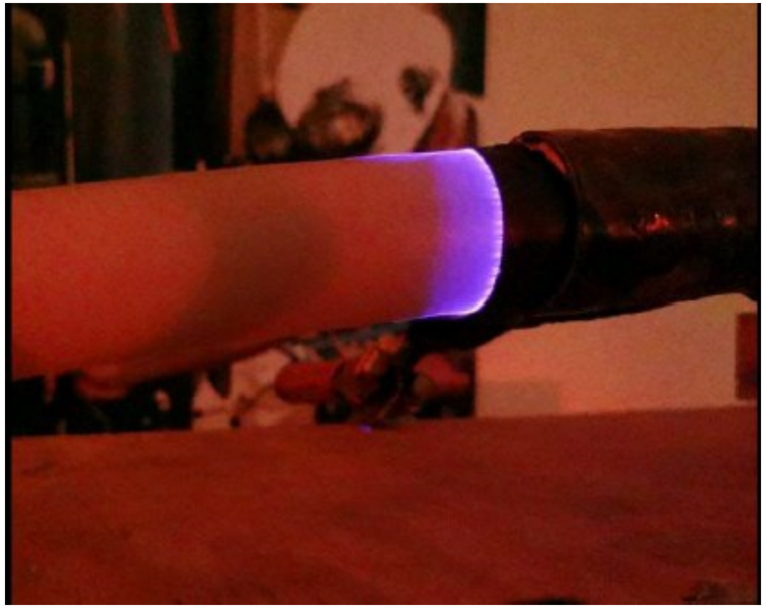
Partial Discharge

Surface Discharge - Tracking

Surface between two insulation is the weakest part because of accumulation of pollution



Surface PD in **air-cooled machines** creates **ozone**. The ozone combines with nitrogen and humid air to create nitric acid (HNO_3) that poses a health hazard, and which can chemically attack organic materials and corrode metal



Partial Discharge

Groundwall Insulation

Example:

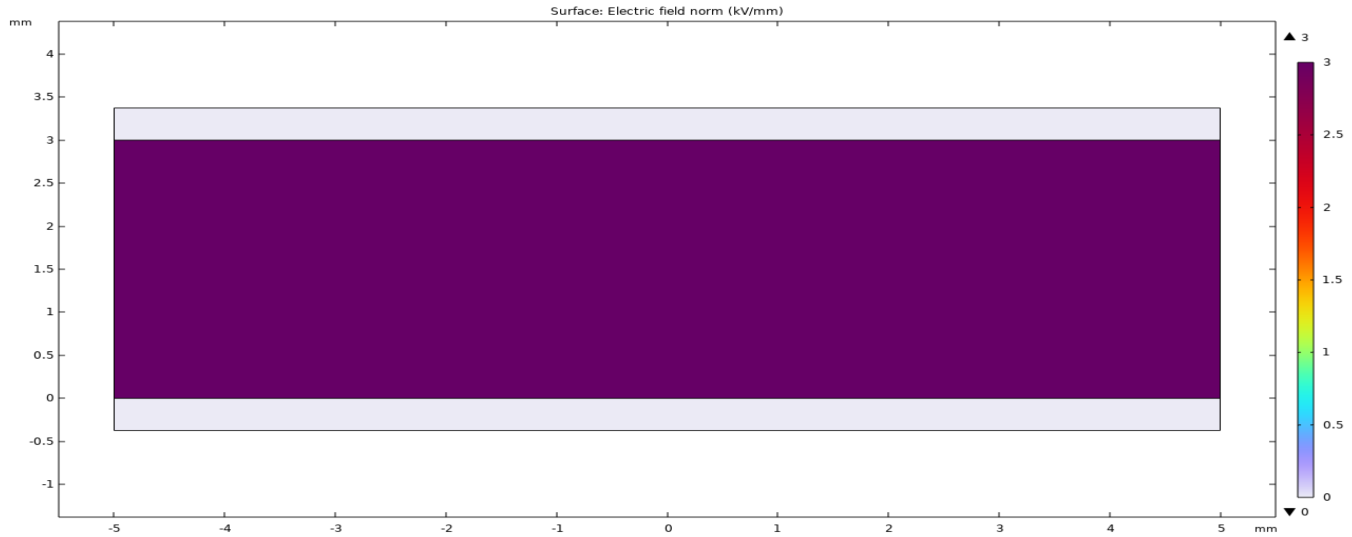
Insulation thickness = 3 mm

Applied Voltage = 9 kV

Electric stress = 3 kV/mm

3 kV/mm << 200 kV/mm

Groundwall insulation thickness has reduced from 15.1 mm in 1911 to only 2.5 mm 100 years later, for the same voltage



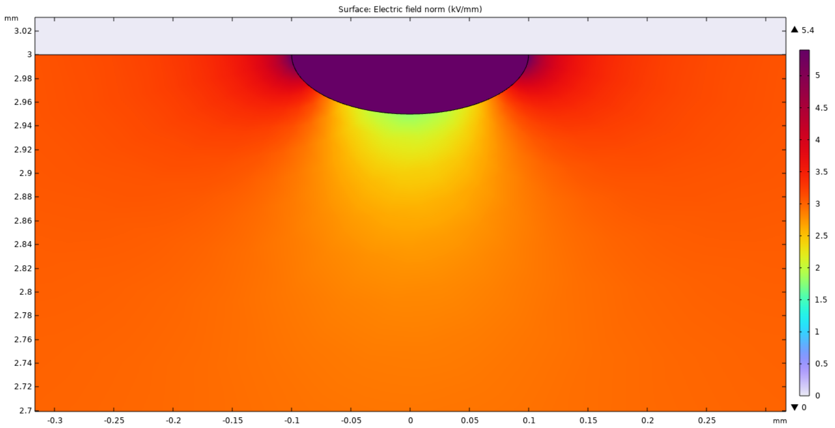
Partial Discharge

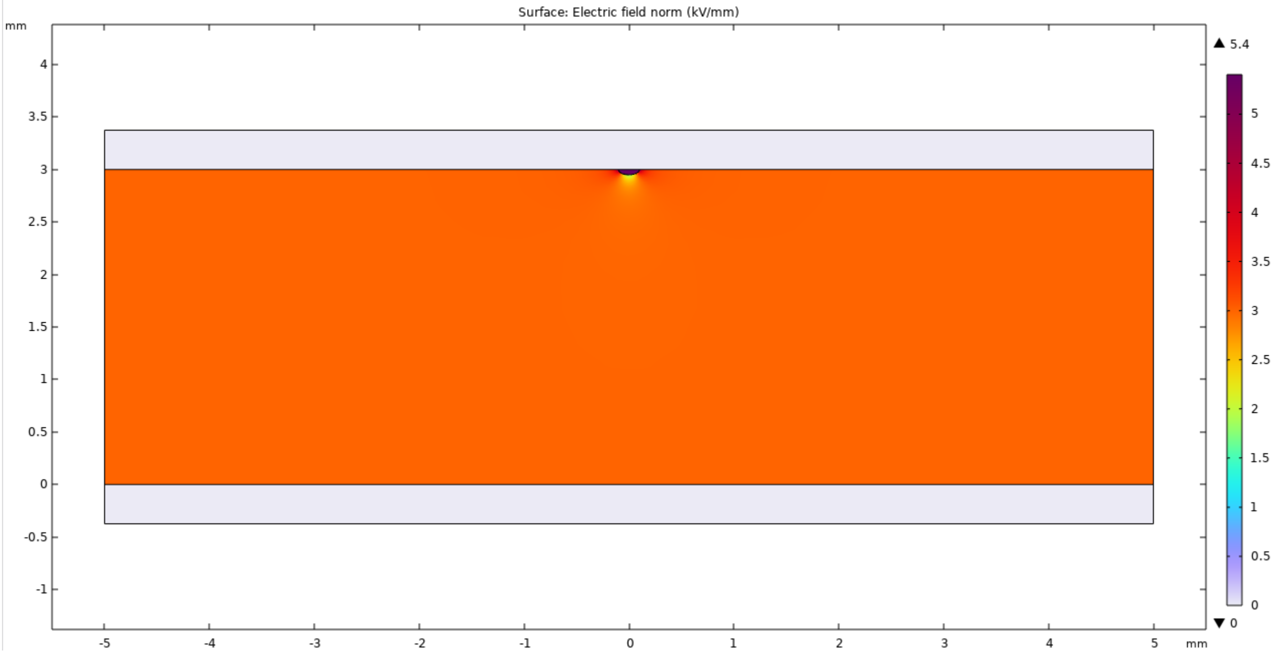
Debonding Discharge

Air gap between insulation and HV conductor

Electric stress inside air gap = 5.4 kV/mm > 3 kV/mm

Partial Discharge inside the gap





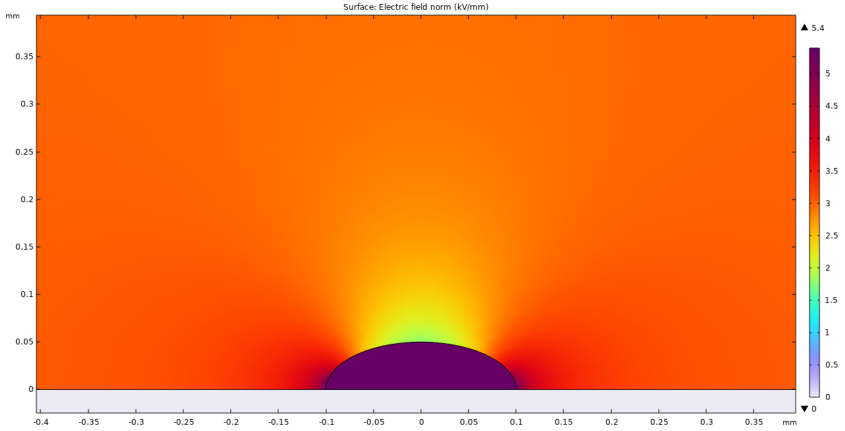
Partial Discharge

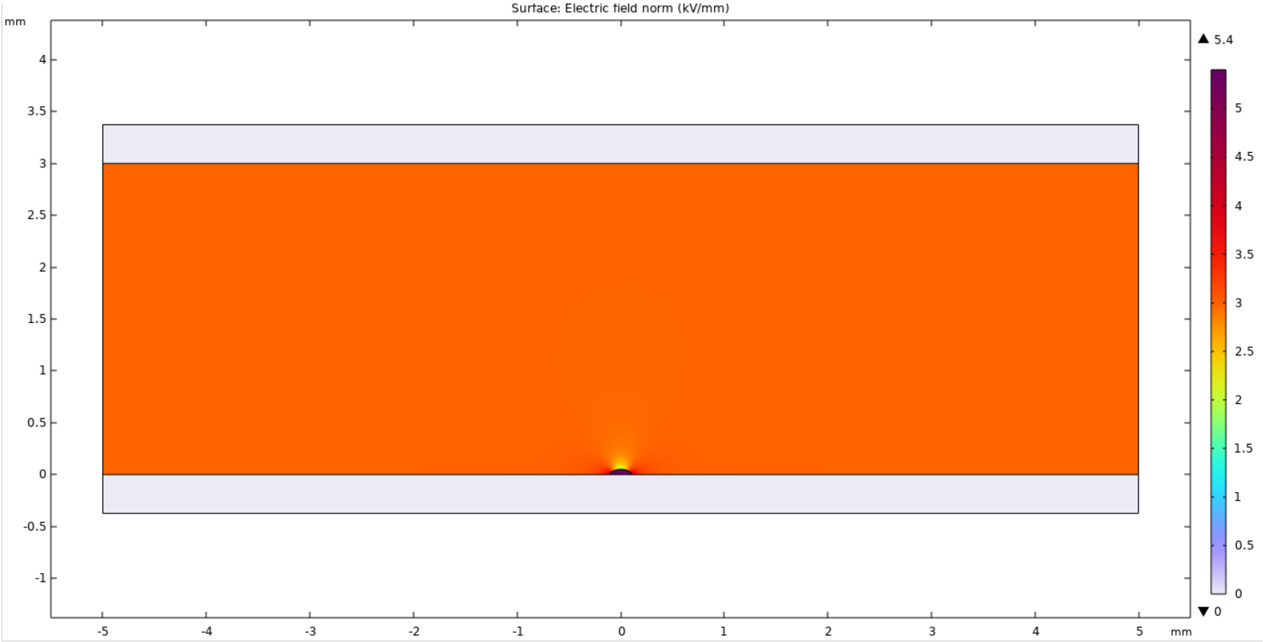
Slot Discharge

Air gap between insulation and ground conductor

Electric stress inside air gap = 5.4 kV/mm > 3 kV/mm

Partial Discharge inside the gap





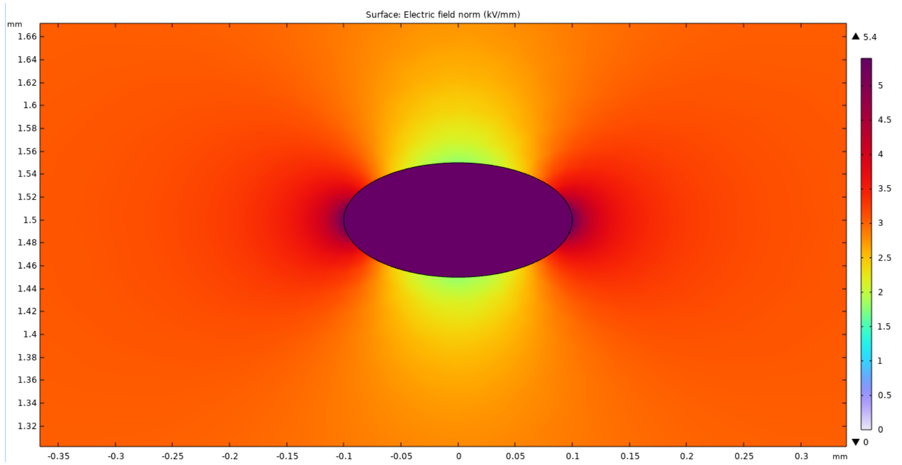
Partial Discharge

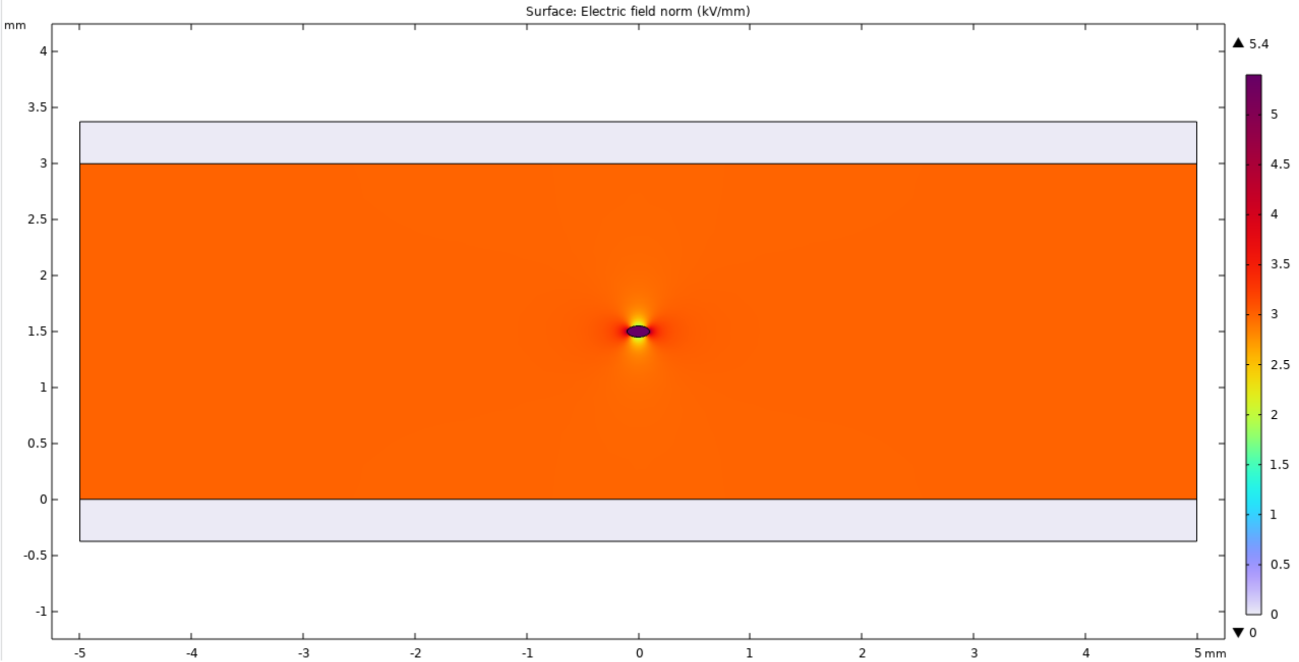
Internal/delamination Discharge

Air gap inside insulation

Electric stress inside air gap = 5.4 kV/mm > 3 kV/mm

Partial Discharge inside the gap





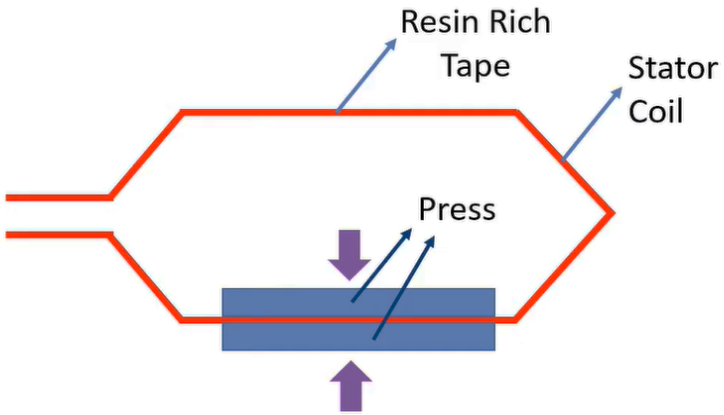
Impregnation

The winding must be impregnated to eliminate voids which would lead to PD, even on windings rated as low as 400 V

Roll Dip impregnation

Rich Resin System

The straight portion of the stator coils is wrapped with rich resin tape which is in B stage (semi cured)



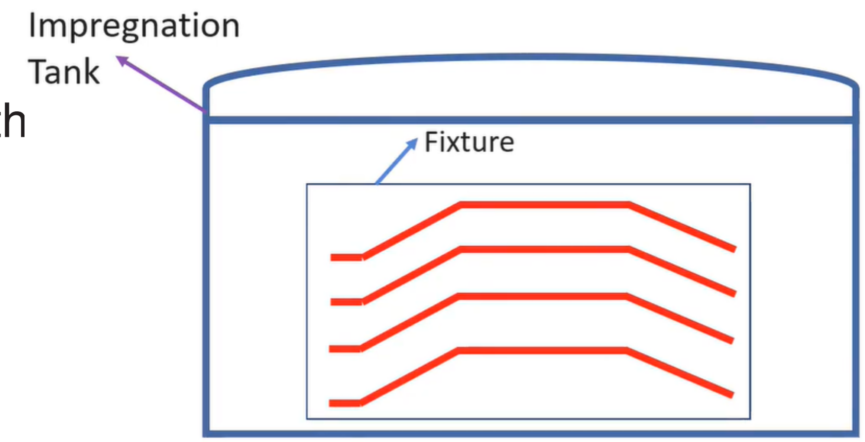
Both the sides of coil are pressed under heat and pressure

Resin flows and the resin is cured by heating

Impregnation

Vacuum Pressure Impregnation (VPI)

- Vacuum is created in the impregnation tank to remove air/ moisture
- Resin is inserted till the bars is completely submerged in the resin
- Nitrogen pressure is applied so that the resin impregnates th coils fully and fill the voids
- Bars is shifted to the curing Owen where resin is cured by heating
- Siemens in 1965, introduced a VPI process for individual bars



Impregnation

Global Vacuum Pressure Impregnation (GVPI)

Repeating the same process as VPI except for entire stator

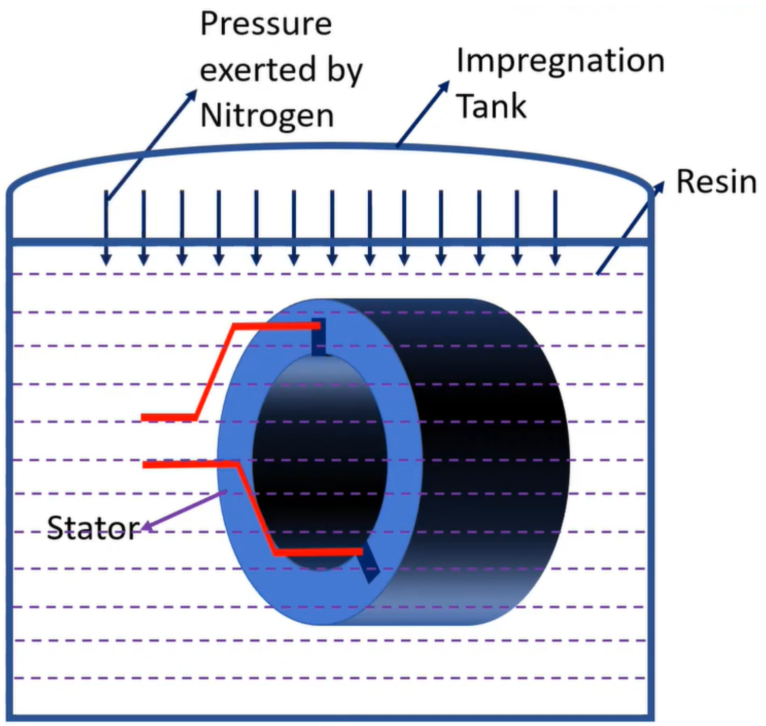
Motors and smaller generators shifted to the GVPI method in the early 1970s

For motors, almost all manufacturers use the GVPI process with **either** epoxy or polyester resin.

Large generator stator use epoxy in preference to polyester.

Some manufacturers also use the GVPI process for turbine generators up to about **300 MVA**

Low viscosity resin impregnator



Impregnation

Advantages of VPI Process are

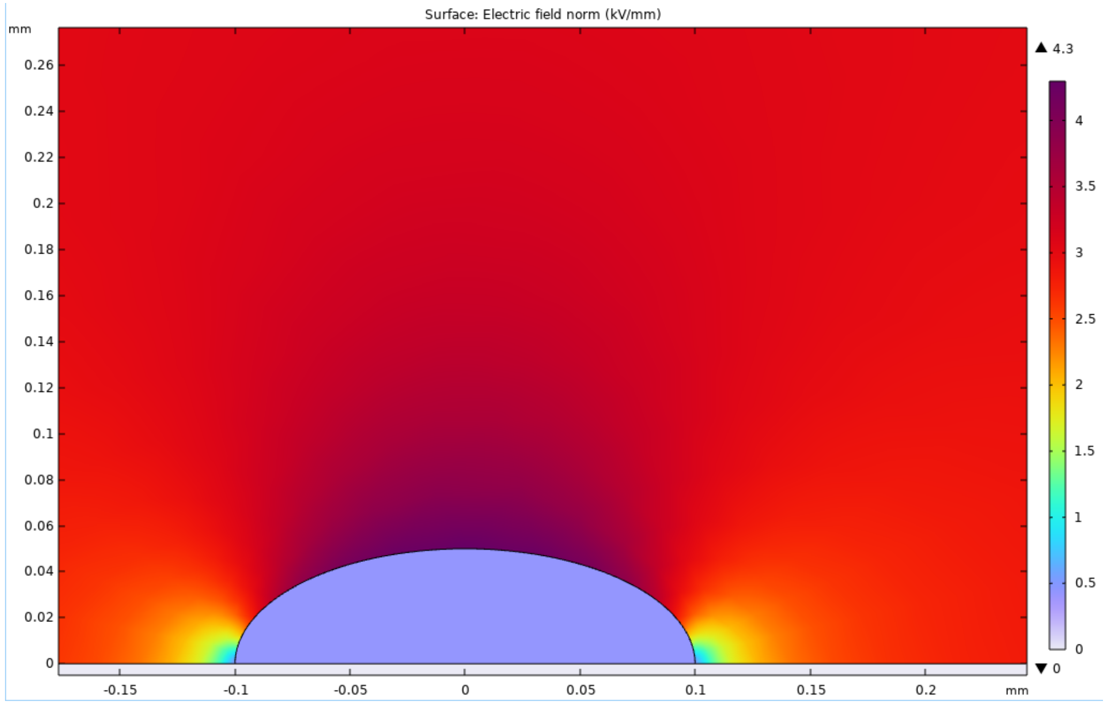
- It produces void free Insulation
- Higher Dielectric Strength
- It reduces Coil Vibrations
- Protection against the ingress of Water, Dust, Chemicals and Contaminations
- Improves Heat Transfer

Semiconductive Coating

Slot Semiconductive (Semicon) Coating

- A graphite-loaded paint or tape
- Surface resistance from 0.3 to 10 kΩ per square prevent surface discharges in the slot
- The coating cannot be too conductive (i.e., a metalized coating), as this will short out the stator core laminations and/or lead to **vibration sparking**
- Not normally needed for stators rated less than **6 kV**
- At high altitudes -> lower pressure – it may neccary to do a coating in voltage level as low as **3.3 kv**

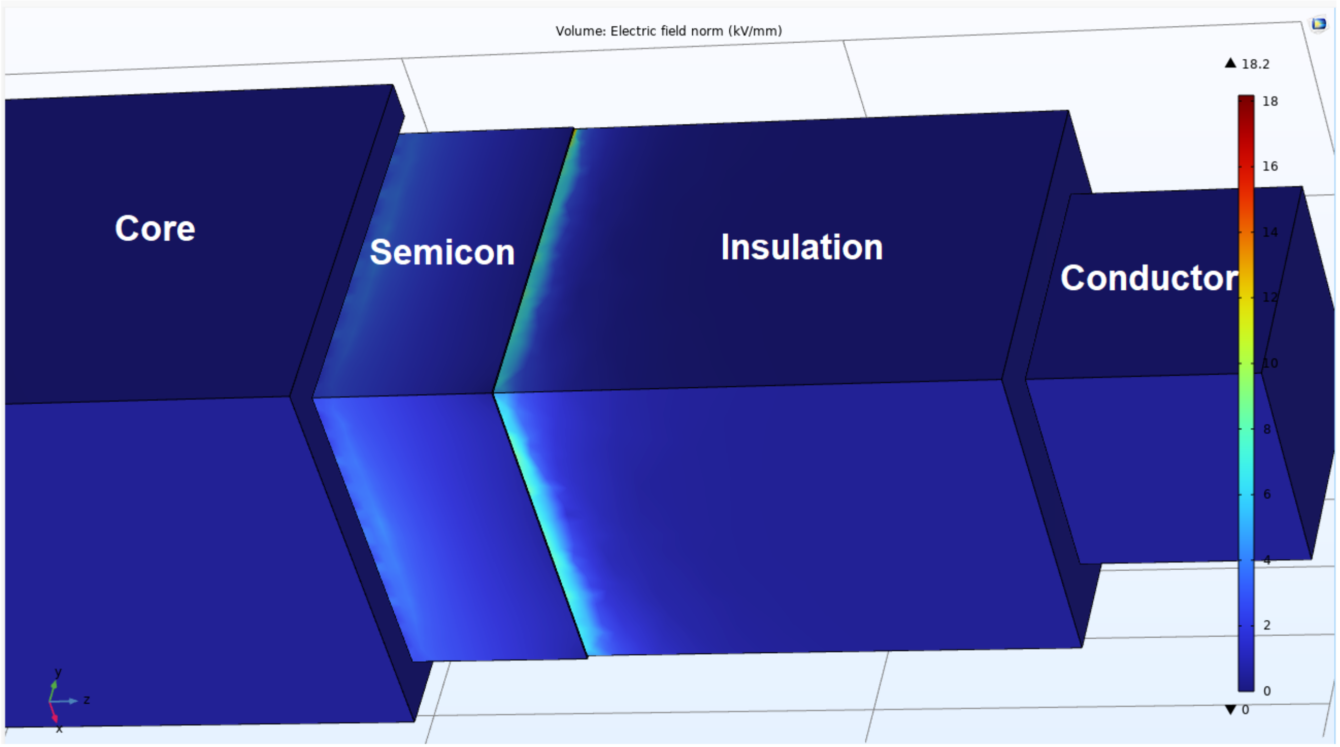
Groundwall Partial Discharge Suppression
Groundwall Stress Relief Coatings



Semiconductive Coating

Slot Semiconductive (Semicon) Coating

- Extends only **a few centimeters** beyond each end of the slot (to the end of the pressure fingers clamping the stator core together)
- The slot semiconductive coating cannot end abruptly a few centimeters outside the slot thin coating would give rise to a **high, localized electric field**
- This field would exceed 3 kV/mm, and **PD** would occur at the end of the coating



Silicon Carbide Coating

Silicon Carbide Coating

Gradient coating or the OCP (outer corona protection coating)

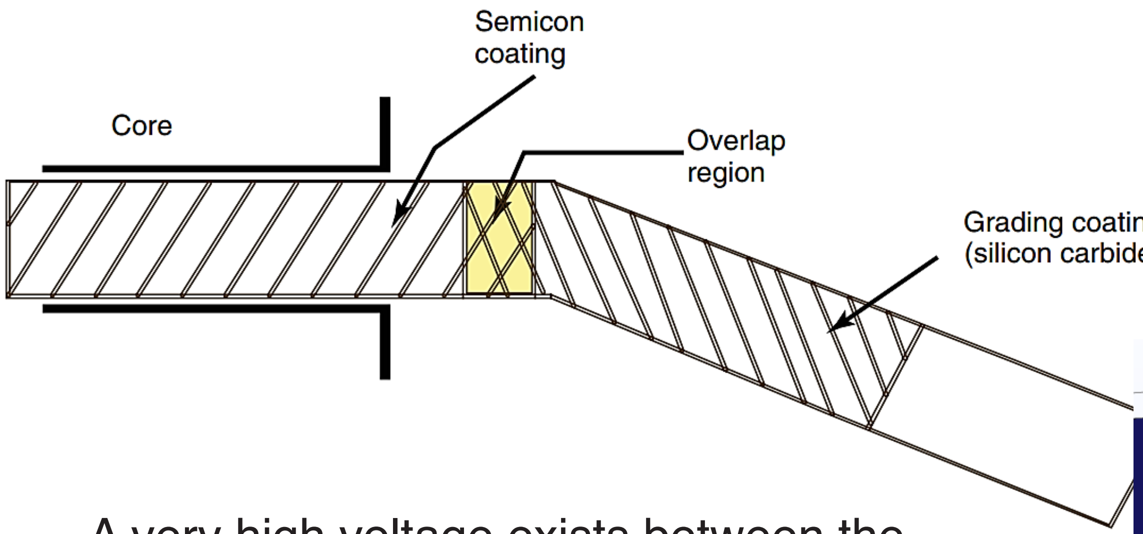
High resistance coating

Silicon carbide was used in high-voltage surge arrestors to divert high-voltage surges due to lightning strikes to ground

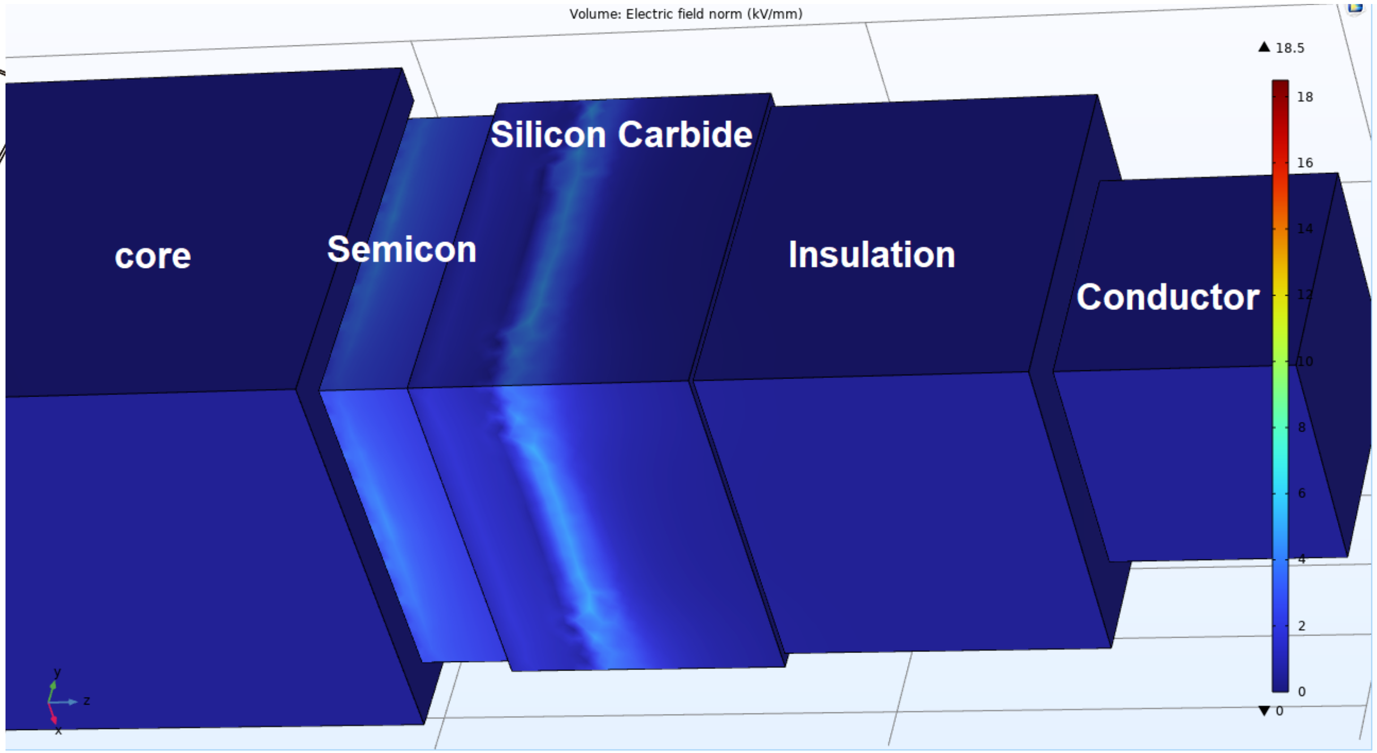
Silicon carbide particles are usually mixed into a **paint base** or incorporated into a **tape** that is applied to the coil/bar surface.

Length of the silicon carbide surface coating depends on the voltage rating and the silicone carbide particle size, but **10–20 cm** is usual.

Silicon Carbide Coating



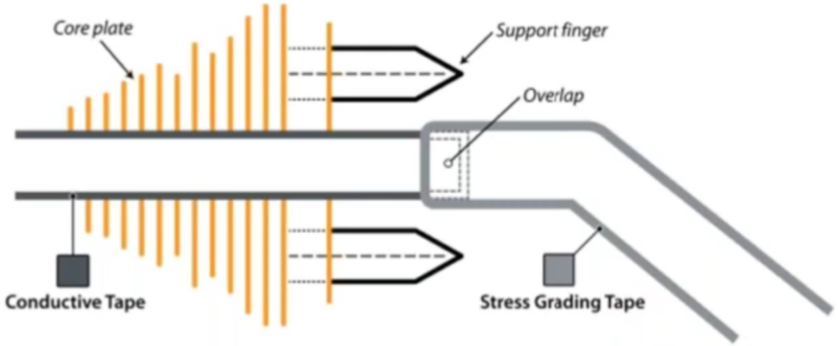
Overlap is typically about **1 cm** wide



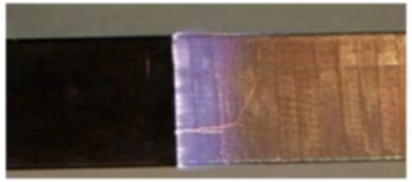
A very high voltage exists between the semicon coating and the silicon-carbide coating, separated by a small air gap (the overlap region)

on a 13.8 kV winding, the floating silicon carbide coating on the phase-end coil will tend to attain a voltage of about **8 kV**

Silicon Carbide Coating

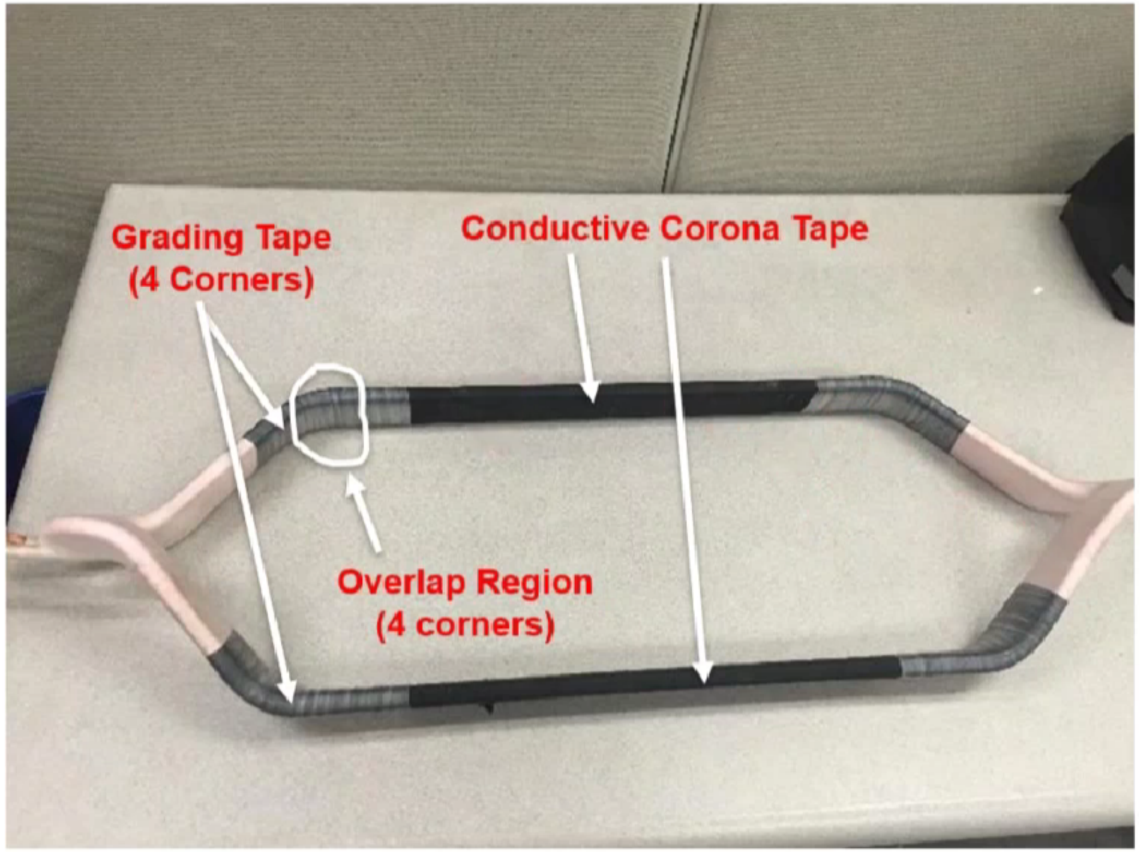


Stress grading tape reduces the overall surface voltage difference present at the end of the conductive tape coming out of the slot.



Without Grading Tape, note the voltage leakage

With Grading Tape, voltage leakage is reduced



Recent Trend

Recent trend in the area of insulation material:

- Reducing the **thermal impedance** of the groundwall
- Increasing the design **electric stress** by enhancing PD resistance

The reductions in groundwall thickness over the past decade have partly been due to:

- Better materials and processing to reduce the size and number of groundwall **voids**
- More **consistent tape thickness** and the availability of taping machine
- Increasing the **percentage of mica** within the groundwall, to increase PD resistance
- Development of other materials that increase the percentage of PD resistant materials in the groundwall

Recent Trend

At present, the working electric field strength of the single-bar

VPI insulation system can reach **3.2 kV/mm**

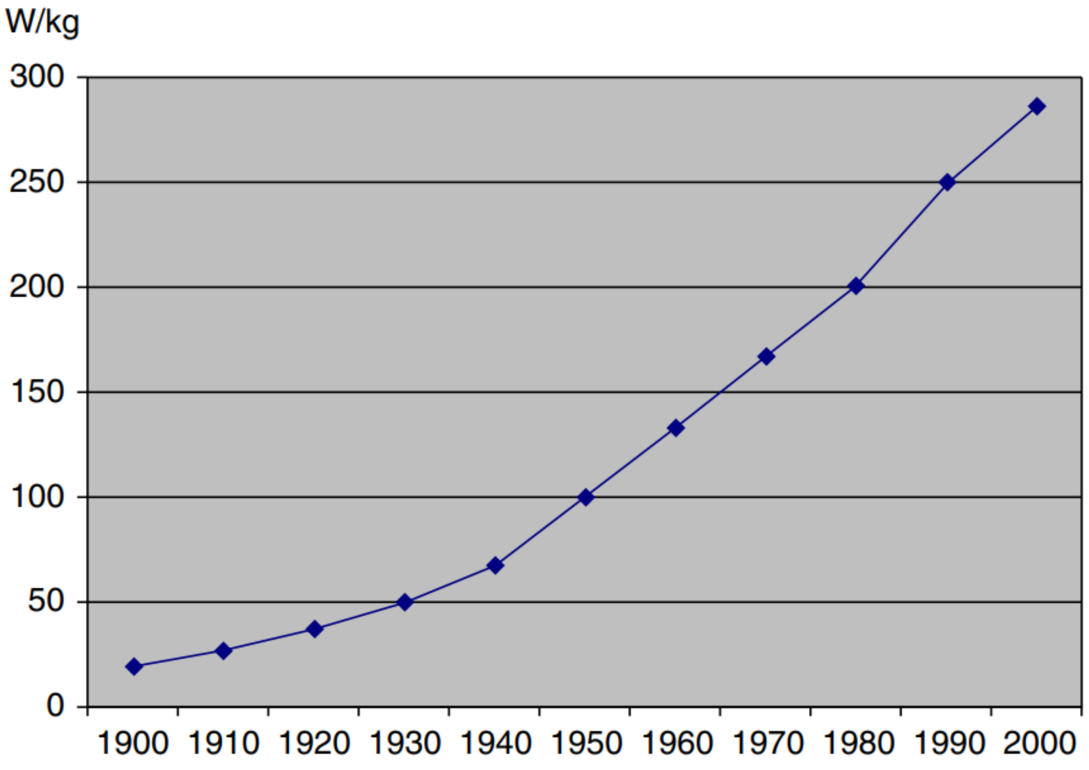


Figure 4.1 Power output per kilogram for rotating machines versus year