ECE563 Electrical machine design

Principle of Design

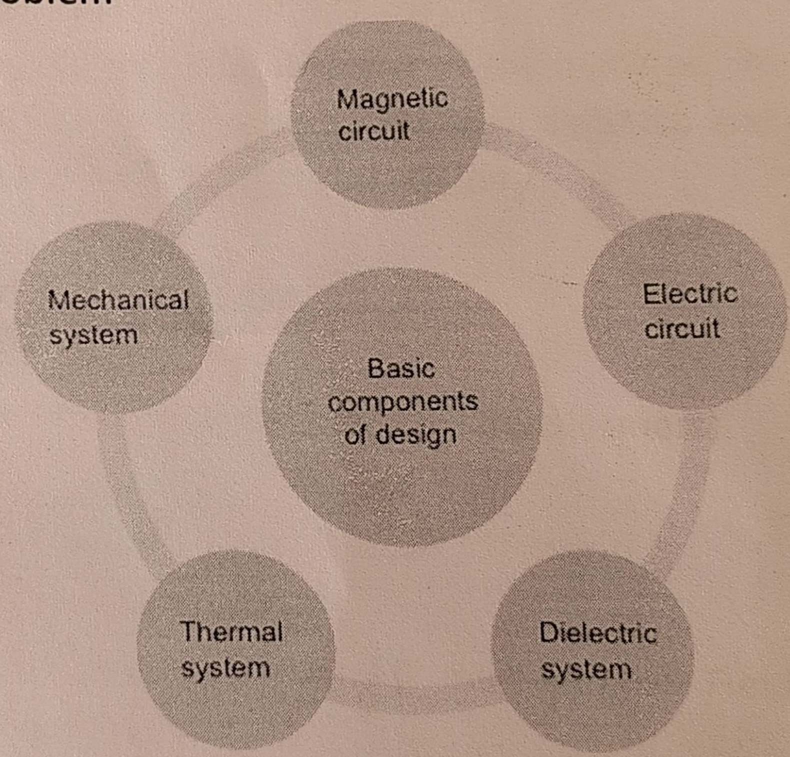
An electric machine is a device that converts energy between electrical and mechanical forms. It consists of stationary and moving parts working together. These machines are widely used in transportation, aerospace, defence, and various industrial systems such as pumps, fans, blowers, and compressors.

Creating such machines requires good engineering design. Engineering design means applying scientific and technical knowledge to develop machines that perform specific tasks efficiently and economically.

Every machine is built from several components or elements. Each component may be designed individually and then combined with others through methods like welding or riveting to form the complete machine. The final assembled machine must meet performance requirements while remaining cost-effective and efficient.

Therefore, the goal of engineering design is to determine the correct dimensions and specifications for every part of the machine. This must be done using available materials while ensuring low cost, minimal size and weight, and maintaining high performance and durability.

Classification of Design Problem



Magnetic Design or Magnetic Circuit Design

Magnetic circuit design focuses on creating a path for magnetic flux (magnetic field) inside a machine. The goal is to produce the amount of magnetic flux needed for proper machine operation while using the least amount of electrical energy.

To achieve this, the design must:

- **Use minimal ampere-turns**: Ampere-turns represent the magnetizing effort (current × number of coil turns). Using fewer ampere-turns means the machine consumes less current, making it more efficient.
- **Reduce core losses**: Core losses are energy losses in the magnetic material (the core) due to hysteresis and eddy currents. A good magnetic design minimizes these losses by choosing suitable materials and shapes.

Electric Circuit Design

This involves designing the armature and field windings of an electric machine. The windings must be arranged in a suitable pattern to generate the required electromotive force (EMF). A good design also ensures that copper losses (heat losses due to current in the windings) are kept low to improve efficiency.

Dielectric System Design

This focuses on choosing and designing the insulation that separates different parts of the machine that operate at different voltages. Proper insulation ensures that current flows only where it is intended, preventing short circuits and ensuring safe operation.

Thermal System Design

This deals with managing the heat produced inside the machine due to electrical and magnetic losses. It includes designing cooling systems, ventilation ducts, and other heat-dissipation methods. The goal is to keep the machine operating within a safe temperature range.

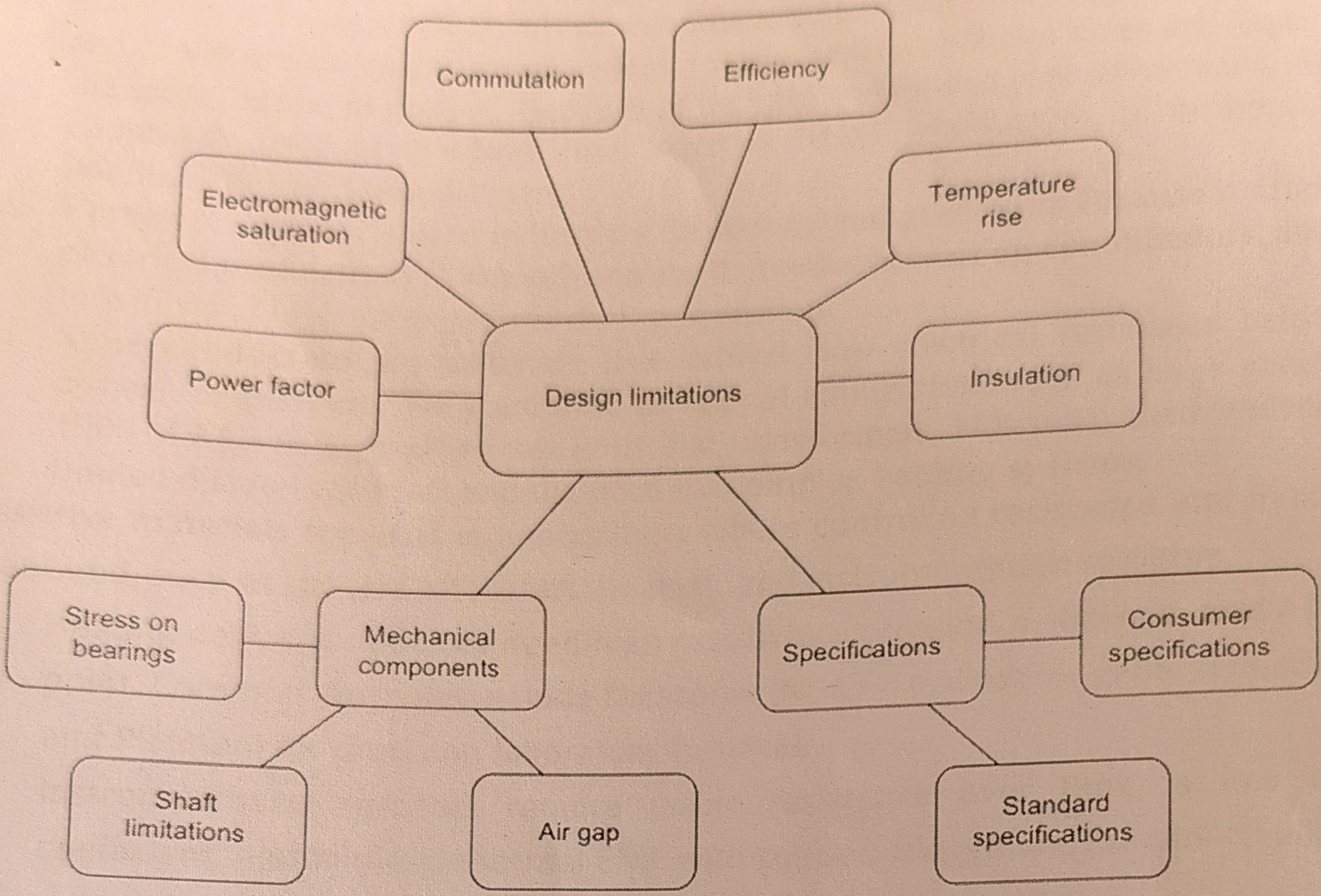
Mechanical System Design

This involves designing the physical structure of the machine, such as the frame, shaft, and bearings. The mechanical parts must be strong, durable, and capable of withstanding mechanical stresses and vibrations during operation.

Specifications and Standards

- kW/kVA rating of machine
- Rated voltage of machine (or voltage ratio in transformers)
- Full-load current
- Number of phases, if any
- Operating frequency/rated speed
- Type of connection (wye/delta in AC machine) or Field excitation (shunt/series/compound in DC machine)
- Class of insulation provided
- Type of enclosure of the machine
- Frame size of machine

Design constraints



Limitations imposed on the design of electrical machines

Materials for Electric Machines

Electric machines are built from different material groups, each selected for its specific electrical, magnetic, thermal, or mechanical properties. The four major categories are conductive, resistive, insulating, and magnetic materials.

1. Conductive Materials

Conductive materials are used to carry electric current through windings, coils, commutators, slip rings, and other transmission paths. To perform effectively, they must offer high electrical conductivity, low resistivity with a low temperature coefficient, good mechanical strength along with ductility and malleability, and resistance to corrosion.

a. Copper is the primary choice for most electrical machines because it has very low resistivity, excellent ductility and machinability, strong tensile properties, and naturally resists corrosion through the formation of a protective oxide layer. It can be easily shaped into coils, windings, busbars, and cables. Copper alloys such as bronze, brass, Cu–Ag, Cu–Be, Cu–Cd, and Cu–Cr are also used when higher mechanical strength is needed, although this improvement in strength comes with a trade-off of increased resistivity.

b. Aluminium is about 3.3 times lighter and cheaper than copper, and it is sufficiently malleable to be used effectively as a conductor. However, it has higher electrical resistivity and lower mechanical strength, which means larger conductor sizes are required to carry the same current as copper. Because of its light weight and cost advantages, aluminium is commonly used in overhead lines such as ACSR conductors, in busbars, and in the windings of small transformers.

c. Carbon (Graphite) is used in brushes for motors and generators because it offers moderate electrical conductivity, a smooth surface that reduces wear on commutators, and the ability to withstand high temperatures during operation.

d. **Superconductors** are materials that exhibit zero electrical resistance below a certain critical temperature. They are used in special applications such as large generators (over 1000 MW) and high-efficiency coils and transformers. However, their widespread use is limited due to high costs and the need for complex cooling systems.

2. **Resistive materials** are used in applications where controlled resistance and heat generation are required, such as starters, rheostats, heaters, and instrumentation resistors.

- Heating device conductors need high resistivity, corrosion resistance, and a high melting point. Common examples include Nichrome (Ni–Cr–Fe alloy) for general heating elements and Platinum for precision laboratory furnaces.
- Instrumentation resistors require stable resistance over time, a low temperature coefficient, and minimal thermal EMF with copper; Manganin (Cu–Mn–Ni alloy) is widely used.
- Rheostats and general resistors prioritize low cost, tolerance to wide temperature ranges, and moderate or high temperature coefficients. Constantan (Cu–Ni alloy) is a typical material.

3. **Insulating materials (dielectrics)** prevent unwanted current flow between components at different voltages. Good insulators must withstand high electrical, thermal, and mechanical stresses, as well as chemical and moisture effects. They are used in winding insulation, slot liners, bushings, cable insulation, spacers, and structural parts. Common insulators include paper, varnish, mica, epoxy resins, ceramics, PVC, rubber, and polymer films, ensuring safe isolation and controlled current flow.

4. **Magnetic Materials** are crucial in electric machines for energy conversion, forming the core, stator, rotor, poles, and yokes. They are classified based on permeability and hysteresis behavior.

1. Classification by Permeability:

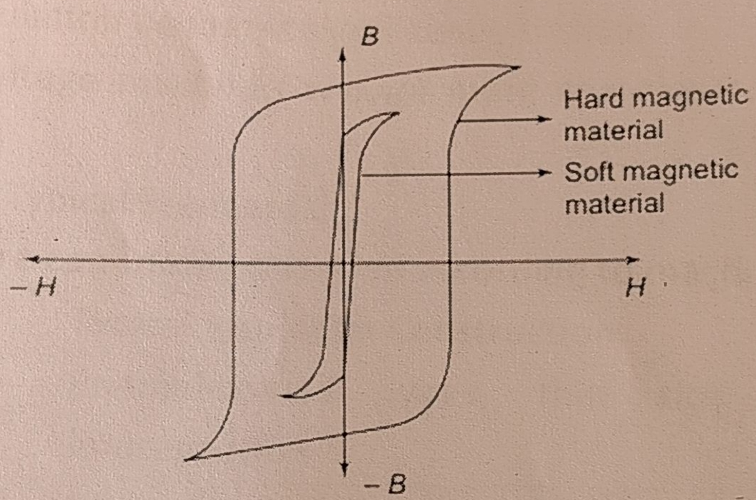
- Ferromagnetic materials: Very high permeability ($\mu_r >> 1$), easily magnetized and demagnetized, with a non-linear B–H curve. Examples include iron, silicon steel, cobalt, nickel, and alnico. They are widely used in machine cores but lose magnetism above the Curie temperature.

- Paramagnetic materials: The relative permeability is slightly greater than or equal to one ($\mu_r \geq 1$), i.e. very small positive susceptibility, e.g., air, platinum, tungsten. Paramagnetic materials are temperature dependent. Diamagnetic materials The relative permeability is less than or equal to one ($\mu_r \leq 1$), i.e., very small negative susceptibility, e.g., copper, silver, gold

Paramagnetic and diamagnetic materials are generally not used in cores.

2. Classification by Hysteresis Loop:
   - Soft magnetic materials: Narrow hysteresis loop, low core losses, easy magnetization/demagnetization. Used in motor and generator cores, transformer laminations, and electromagnets. Examples: silicon steel, soft iron, grain-oriented steel, permalloy.
   - Hard magnetic materials: Wide hysteresis loop, retain magnetism (permanent magnets). Used in permanent magnet motors, sensors, and magnetic holding devices. Examples of Magnetic Core Materials:

Solid core materials for DC machines, relays, and electromagnets include iron, silicon steel, cast steel, cast iron, and grey cast iron. Silicon steel laminations are particularly effective in AC machines because they reduce eddy current losses.



Hysteresis loops of soft and hard magnetic material

Stator Insulation System vs Voltage and Temperature

The stator insulation system is one of the most critical parts of an electrical machine because it ensures electrical separation between conductors, prevents short circuits, and maintains long-term reliability under electrical, thermal, mechanical, and environmental stresses. The insulation system must be designed in harmony with the rated voltage and operating temperature of the machine.

1. **Role of the Stator Insulation System**

The stator insulation system primarily performs three tasks:

1. Conductor insulation: insulating the copper or aluminium turns in coils.
2. Slot insulation: separating the stator core laminations from the windings.
3. Groundwall insulation: providing high dielectric strength between the winding and the stator core at system voltage.
4. Inter-turn and phase insulation – preventing turn-to-turn and phase-to-phase faults.

A proper insulation system must handle electrical, thermal, mechanical, and environmental stresses throughout the lifespan of the machine.

2. Relationship Between Rated Voltage and Insulation Requirements

2.1 Increase in Voltage Increase in required Insulation Strength, as the rated voltage of a machine increases:

- The electric field stress between turns increases.
- The dielectric strength of insulating materials must be higher.
- Inter-turn insulation thickness must increase.
- Creepage distance and clearance must be extended.
- The groundwall insulation becomes significantly thicker.

This means that higher-voltage machines require more complex and multi-layered insulation systems.

2.2 Voltage Classifications (Typical Standards)

Stator insulation systems are commonly classified according to machine voltage levels:

Machine Voltage	Typical Insulation Construction
< 1 kV (Low Voltage)	Enamel-coated wires, thin slot liners, simple varnish impregnation
1–15 kV (Medium Voltage)	Mica-glass tapes, epoxy varnish, vacuum pressure impregnation (VPI)
> 15 kV (High Voltage)	Multi-layer mica-binder tapes, resin-rich insulation, thick groundwall, and advanced VPI

2.3 Dielectric Stress Distribution

- At low voltages, turn-to-turn stress is small, so enamel insulation is sufficient.
- At medium and high voltages, stress is unevenly distributed, with the first few turns experiencing the highest stress.
- This requires graded insulation, phase separators, and corona-resistant materials.

3. Temperature vs Insulation System

The life of an insulation system highly depends on its thermal endurance. According to the Arrhenius thermal aging rule, insulation life reduces drastically with temperature. A rule of thumb:

For every 10°C rise above rated temperature, insulation life is reduced by 50%.

3.1 Insulation Thermal Classes (IEC & NEMA)

Stator insulation materials are assigned thermal classes based on maximum permissible winding temperature.

Class	*Max Temperature (°C)*	*Typical Materials*
Class A	105°C	Paper, cotton, silk, some varnishes
Class E	120°C	Improved synthetic films
Class B	130°C	Mica, glass fiber with resin
Class F	155°C	Mica, epoxy, polyester
Class H	180°C	Silicone, mica-glass with high-temp resin
Class C	>180°C	Mica, ceramics, special composites

Higher class - more temperature-resistant insulation - longer lifespan.

3.2 Stator Winding Temperature Rise

Temperature rise in stator windings depends on:

- Copper losses (I^2R)
- Core losses (hysteresis + eddy)
- Cooling system (open-air cooling, forced ventilation, liquid cooling)
- Machine loading and ambient temperature

The insulation system must withstand:

- Operating temperature
- Hot spots
- Transients
- Short-circuit thermal stress

4. Combined Effect: Voltage and Temperature Stresses

In practical machine operation, the stator insulation system is simultaneously subjected to electrical (voltage) and thermal (temperature) stresses, and the combined effect is far more damaging than each acting individually. High voltage produces strong electric fields that tend to degrade insulation through partial discharges, ionization, and dielectric ageing. At the same time, elevated temperatures accelerate chemical breakdown of insulation materials, reduce mechanical strength, and speed up oxidation. When both stresses act together, temperature weakens the insulation's molecular structure, making it more vulnerable to electric field damage, while electric stress encourages localized heating and further thermal deterioration. This interaction is exponential in nature: even a small increase in temperature significantly reduces the insulation's ability to withstand voltage, and high voltage levels can rapidly accelerate thermal ageing. Therefore, insulation design must consider the combined thermal–electrical stress profile of the machine rather than treating them as separate factors.

5. Insulation Systems for Different Voltage and Temperature Levels

The type of insulation system used in a stator depends on the operating voltage class and temperature rating of the machine. For low-voltage machines (typically below 1 kV), Class A or Class B insulation systems are commonly used, consisting of materials such as paper, varnish, cotton, or polyester films. These machines generate low dielectric stress, so thin insulation layers are sufficient, and cooling can be achieved by simple air ventilation. Medium-voltage machines (1–6 kV) require stronger insulation such as Class F or Class H systems made from epoxy-mica composites, glass fibers, and high-temperature resins. These materials provide high dielectric

6. Design Considerations Linking Voltage and Temperature

Designing a reliable stator insulation system requires balancing electrical, thermal, and mechanical factors so that the insulation can withstand long-term voltage and temperature stresses. From an electrical standpoint, the insulation must possess sufficient dielectric strength, and the stator design must provide adequate creepage and clearance distances to prevent surface or air-gap breakdown. Proper selection of turn insulation thickness and the use of stress-control coatings are also essential to manage electric field distribution, especially in high-voltage machines. Thermally, the insulation must efficiently dissipate heat generated in the stator slots while maintaining acceptable temperature rises. This requires attention to the thermal conductivity of insulation materials, the arrangement of ventilation ducts, and the effectiveness of the cooling system—whether air, hydrogen, or water-based. The insulation must also comply with its assigned thermal class to ensure long-term aging resistance. Mechanically, the system must withstand slot wedge pressure, continuous vibration, and repeated thermal expansion cycles. Therefore, compatibility between copper conductors and insulating materials is crucial to prevent cracking or delamination. Overall, a stator insulation system can be considered successful only when it reliably endures the combined electrical, thermal, and mechanical stresses throughout its expected service life, typically ranging from twenty to thirty years.

The stator insulation system is directly dependent on both voltage and temperature. Higher voltages require stronger dielectric insulation, thicker groundwall systems, and corona-protection measures. Higher temperatures demand materials with higher thermal classes to prevent accelerated aging. Effective insulation design ensures reliability, efficiency, and long service life of electrical machines.