Electric Motors and Generators

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Introduction

- In this lecture we consider various forms of rotating **electrical machines**
- These can be divided into:
  - **generators** – which convert mechanical energy into electrical energy
  - **motors** – which convert electrical energy into mechanical energy
- Both types operate through the interaction between a *magnetic field* and a set of *windings*

A Simple AC Generator

- We noted earlier that Faraday's law dictates that if a coil of *N* turns experiences a change in magnetic flux, then the induced voltage *V* is given by

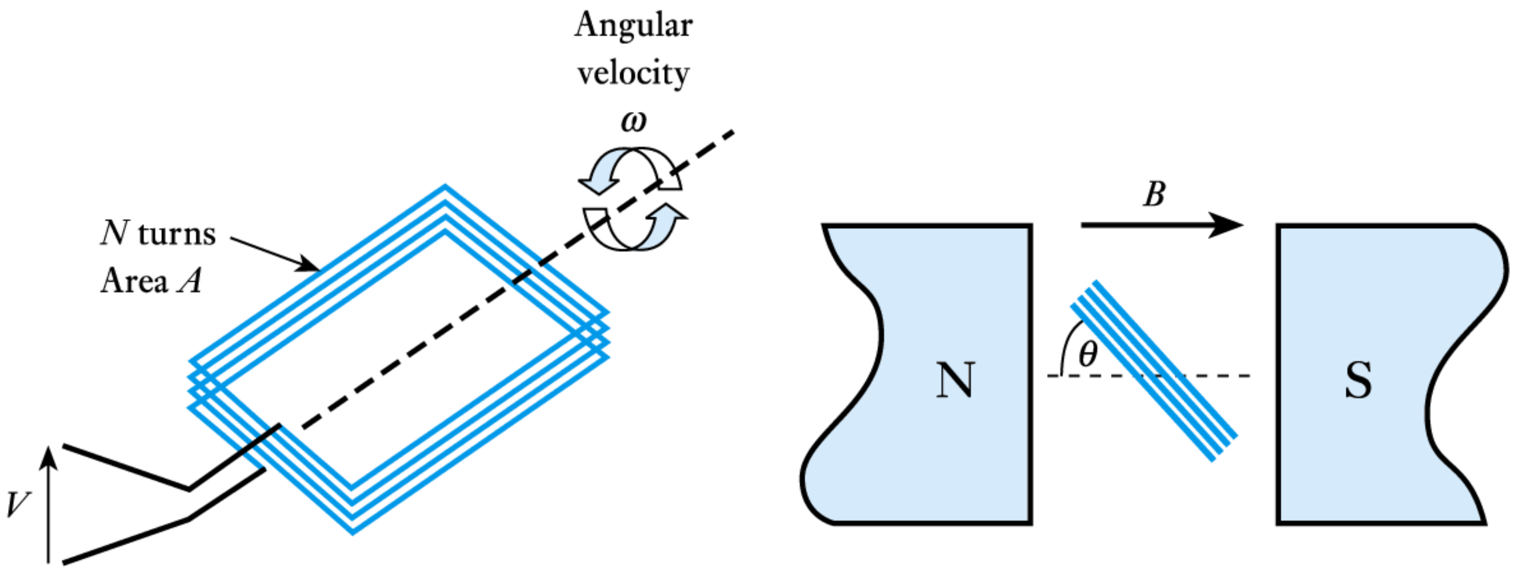
$$V = N\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

- If a coil of area *A* rotates with respect to a field *B*, and if at a particular time it is at an angle θ to the field, then the flux linking the coil is $BA\cos\theta$, and the rate of change of flux is given by

$$\frac{d\Phi}{dt} = BA\frac{\mathrm{d}(\sin\theta)}{\mathrm{d}t} = \frac{\mathrm{d}\theta}{\mathrm{d}t}\cos\theta = \omega\cos\theta$$

- Thus for the arrangement shown below

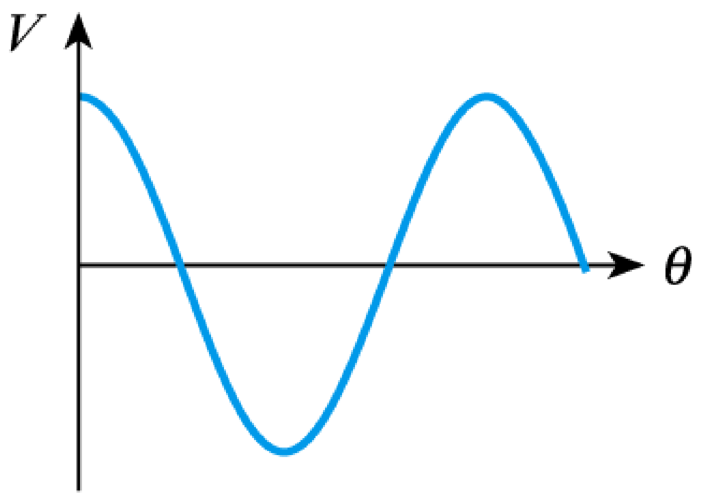
$$V = N\frac{\mathrm{d}\Phi}{\mathrm{d}t} = NBA\frac{\mathrm{d}(\sin\theta)}{\mathrm{d}t} = NBA\omega\cos\theta$$



(a) Coil arrangement

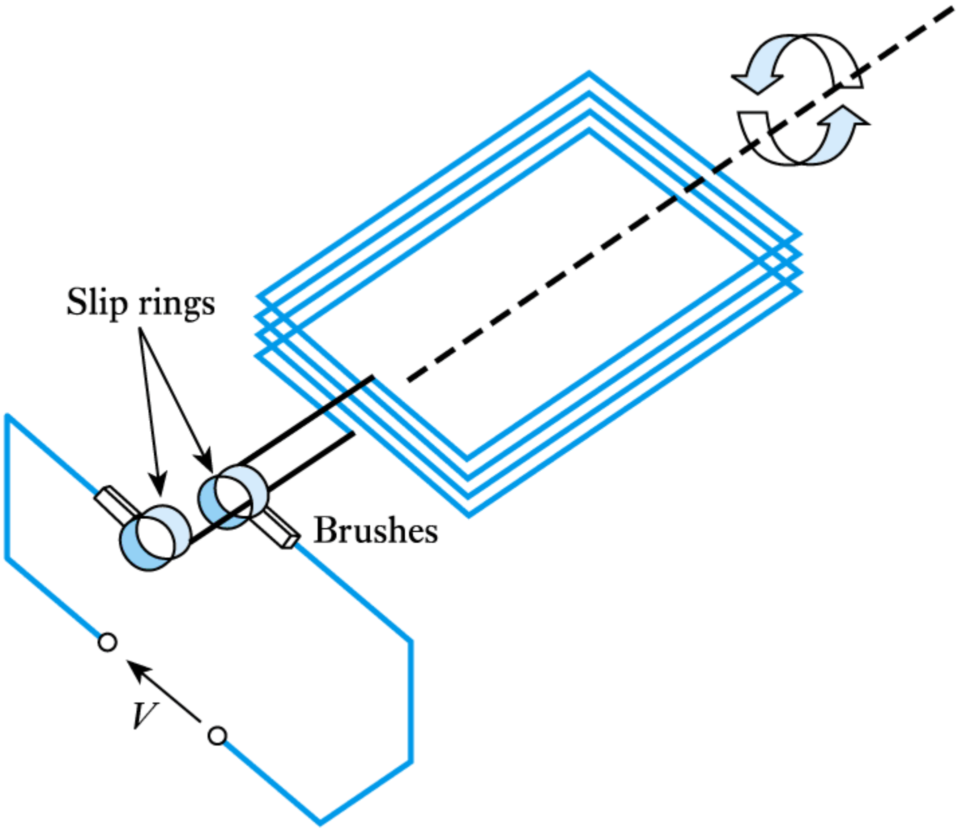
(b) Relationship between coil and field

- Therefore this arrangement produces a sinusoidal output as shown below



(a) (b)

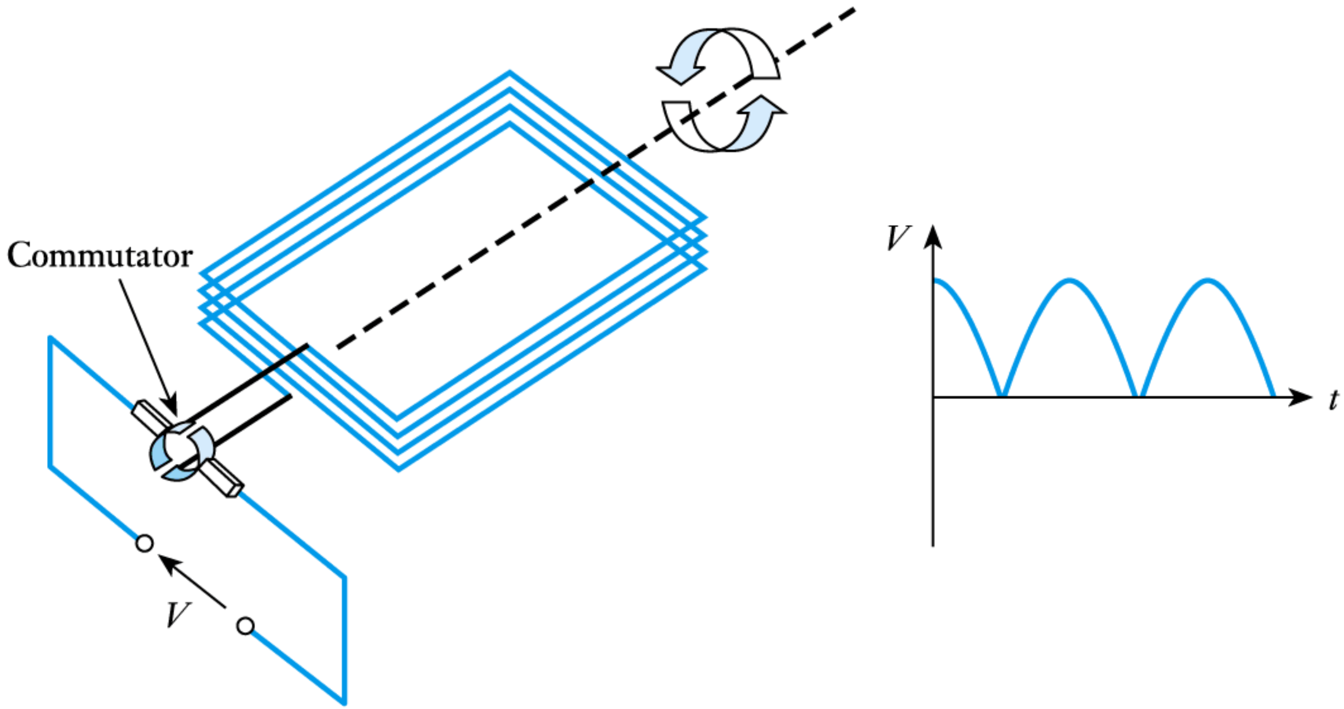
- Wires connected to the rotating coil would get twisted
- Therefore we use circular **slip rings** with sliding contacts called **brushes**



A Simple DC Generator

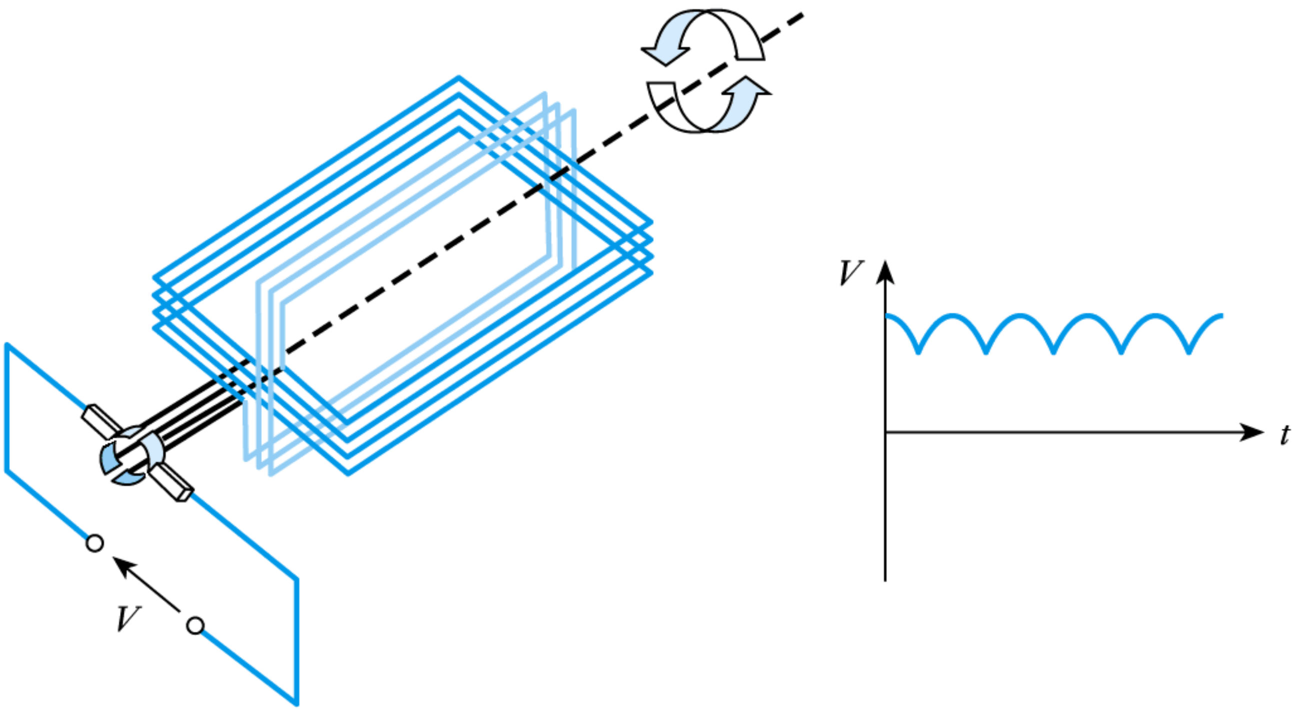
- The alternating signal from the earlier AC generator *could* be converted to DC using a rectifier
- A more efficient approach is to replace the two slip rings with a single split slip ring called a **commutator**
  - this is arranged so that connections to the coil are reversed as the voltage from the coil changes polarity
  - hence the voltage across the brushes is of a single polarity
  - adding additional coils produces a more constant output

- Use of a commutator



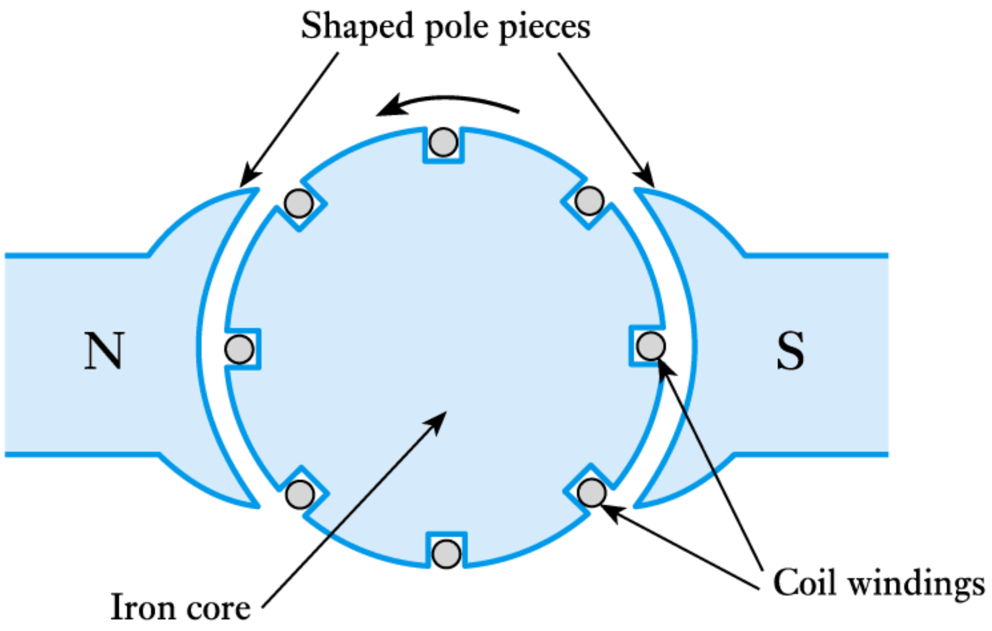
(a) (b)

- **A simple generator with two coils**



(a) (b)

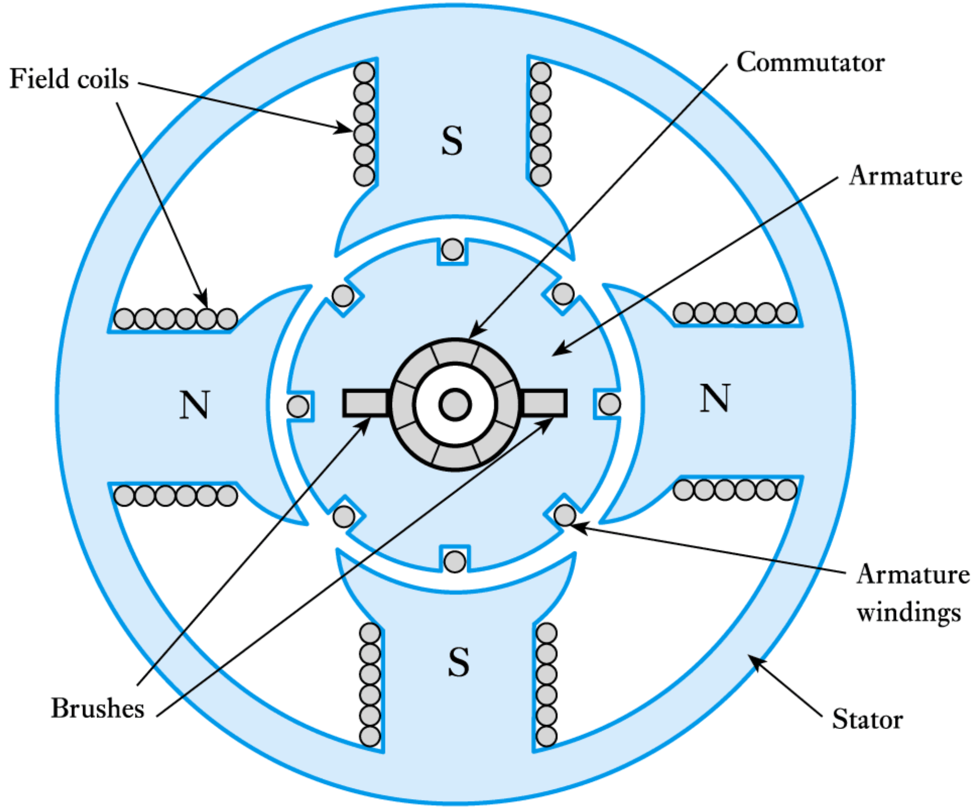
- The ripple can be further reduced by the use of a cylindrical iron core and by shaping the pole pieces
  - this produces an approximately uniform field in the narrow air gap
  - the arrangement of coils and core is known as the **armature**



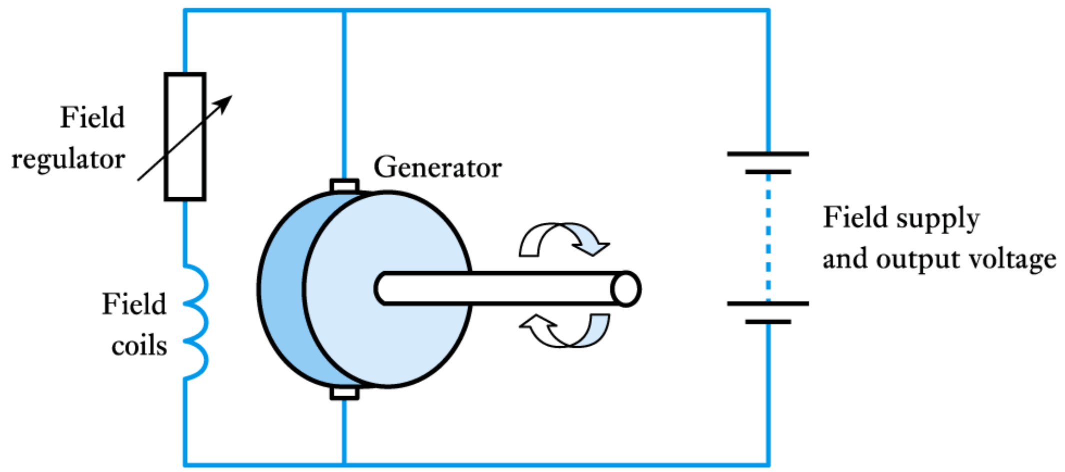
DC Generators or Dynamos

- Practical **DC generators** or **dynamos** can take a number of forms depending on how the magnetic field is produced
  - can use a **permanent magnet**
  - more often it is generated electrically using **field coils**
    - current in the field coils can come from an external supply
      - this is known as a **separately excited generator**
    - but usually the field coils are driven from the generator output
      - this is called a **self-excited generator**
  - often use multiple poles held in place by a steel tube called the **stator**

- A four-pole DC generator

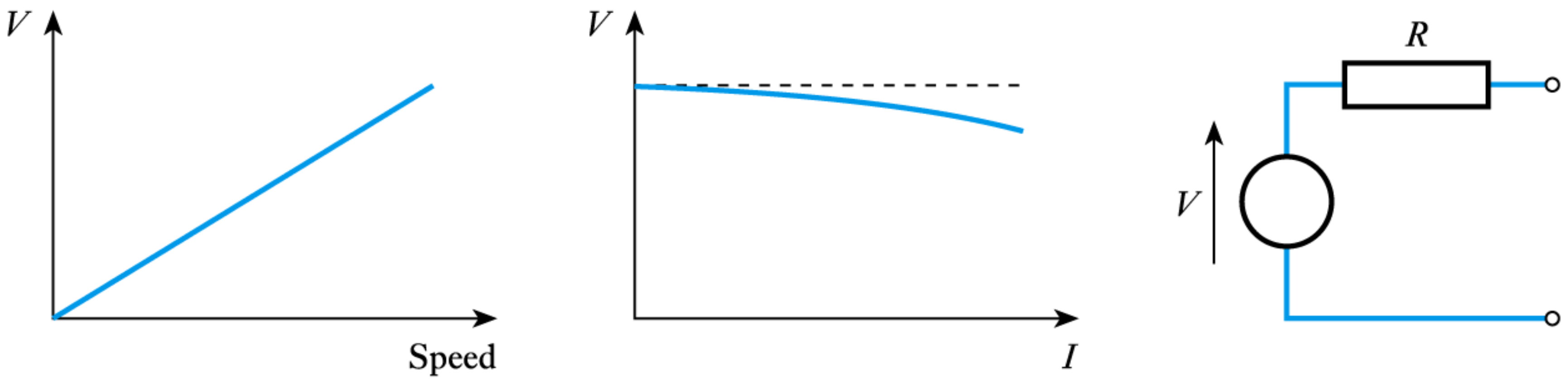


- **Field coil excitation**
  - sometimes the field coils are connected in **series** with the armature, sometimes in parallel (**shunt**) and sometimes a combination of the two (**compound**)
  - these different forms produce slightly different characteristics
  - diagram here shows a **shunt-wound generator**



DC generator characteristics

- vary slightly between forms
- examples shown here are for a shunt-wound generator



(a) Speed–voltage characteristic

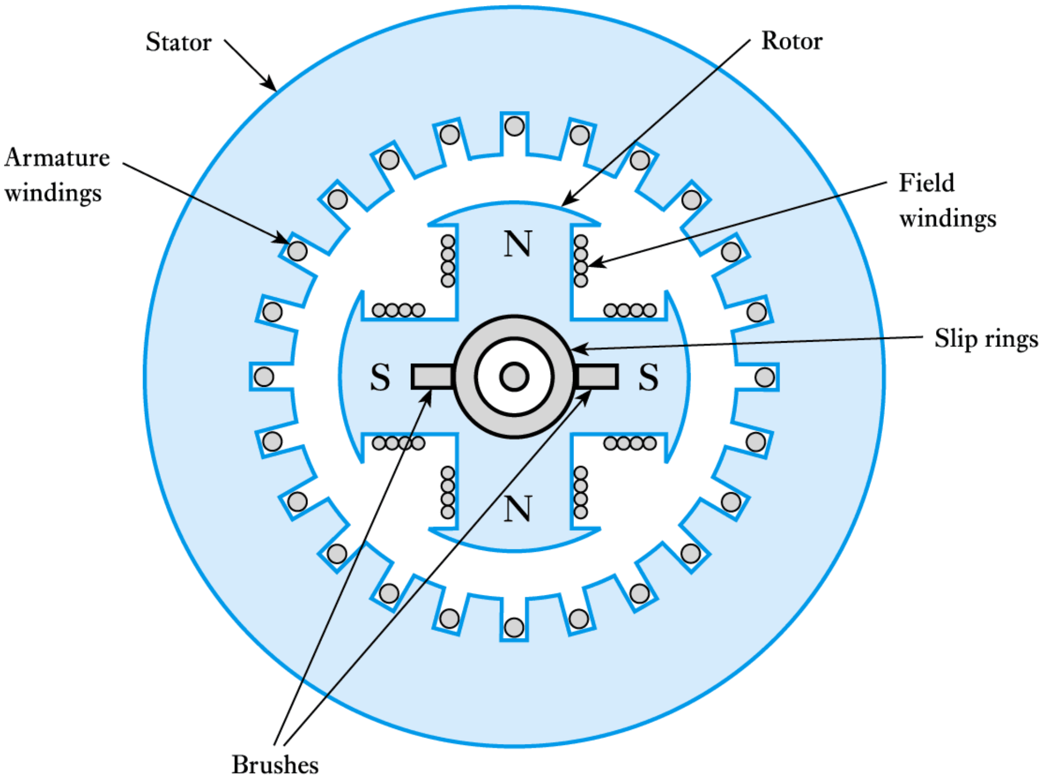
(b) Current–voltage characteristic

(c) Approximate equivalent circuit

AC Generators or Alternators

- Alternators do not require commutation
  - this allows a simpler construction
  - the *field coils* are made to rotate while the *armature* windings are stationary
    - *Note*: the armature windings are those that produce the output
  - thus the large heavy **armature windings** are in the **stator**
  - the lighter **field coils** are mounted on the **rotor** and direct current is fed to these by a set of slip rings

- **A four-pole alternator**



- As with DC generators multiple poles and sets of windings are used to improve efficiency
  - sometimes three sets of armature windings are spaced 120° apart around the stator to form a **three-phase generator**
- The e.m.f. produced is in sync with rotation of the rotor so this is a **synchronous generator**
  - if the generator has a single set of poles the output frequency is equal to the rotation frequency
  - if additional pole-pairs are used the frequency is increased accordingly

Example – see Example 23.2 from course text

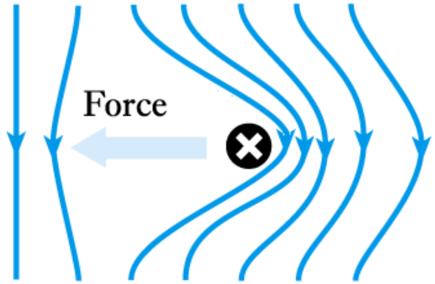
A four-pole alternator is required to operate at 60 Hz. What is the required rotation speed?

A four-pole alternator has two pole pairs. Therefore the output frequency is twice the rotation speed. Therefore to operate at 60Hz, the required speed must be 60/2 = 30Hz. This is equivalent to 30 $\times$ 60 = 1800 rpm.

DC Motors

- When current flows in a conductor it produces a magnetic field about it - as shown in (a) below
  - when the current-carrying conductor is within an externally generated magnetic field, the fields interact and a force is exerted on the conductor - as in (b)

(a) The magnetic field about a current flowing into the page

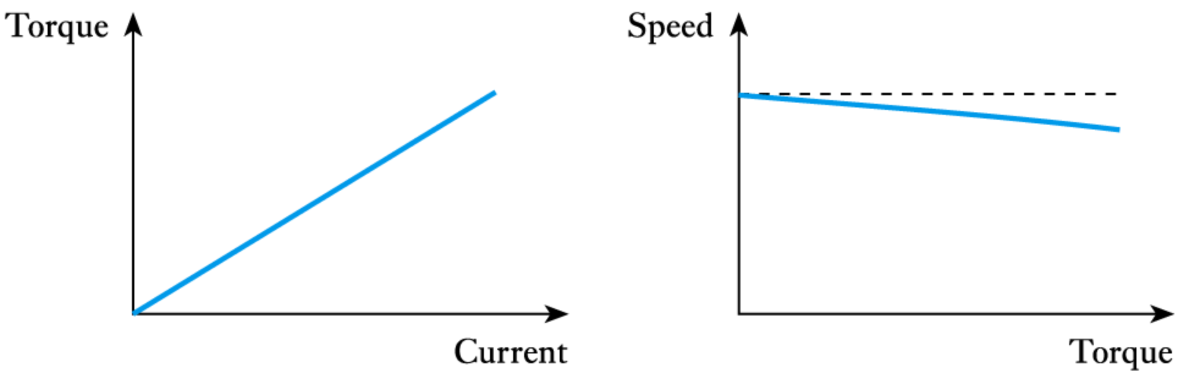


(b) The effects of an external magnetic field

- Therefore if a conductor lies within a magnetic field:
  - *motion* of the conductor produces an electric *current*
  - an electric *current* in the conductor will generate *motion*
- The reciprocal nature of this relationship means that, for example, the DC generator above will function as a DC motor
  - although machines designed as motors are more efficient in this role
- Thus the four-pole DC generator shown earlier could equally well be a four-pole DC motor

DC motor characteristics

- many forms – each with slightly different characteristics
- again can be **permanent magnet**, or **series-wound**, **shunt-wound** or **compound wound**
- figure below shows a shunt-wound DC motor



(a) Torque–current characteristic

(b) Speed–torque characteristic with a constant applied voltage

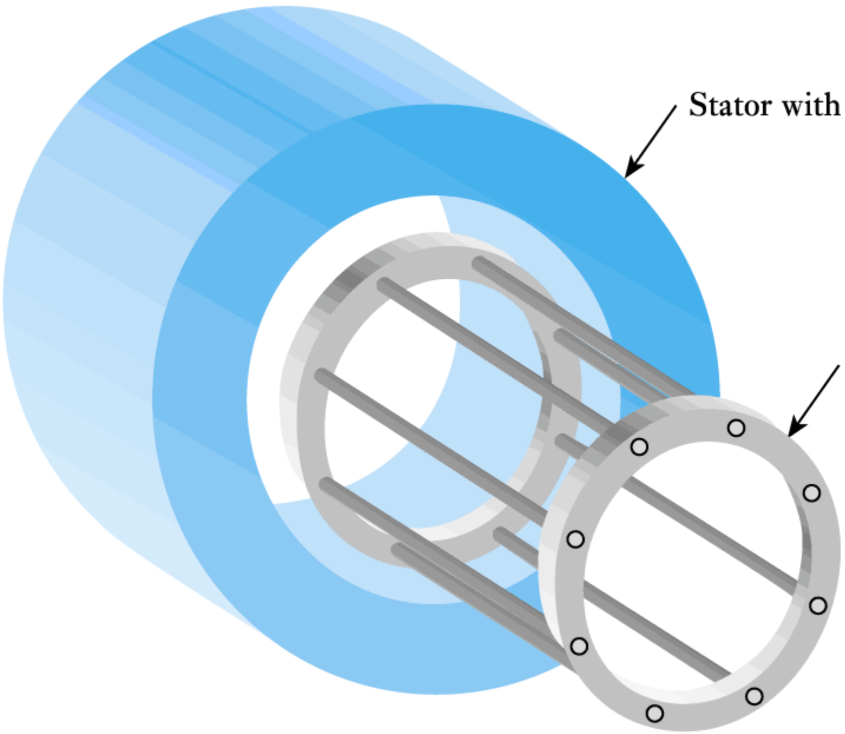
AC Motors

- AC motors can be divided into two main forms:
  - **synchronous motors**
  - **induction motors**
- High-power versions of either type invariably operate from a **three-phase supply**, but single-phase versions of each are also widely used – particularly in a domestic setting

- **Synchronous motors**
  - just as a DC generator can be used as a DC motor, so AC generators (or alternators) can be used as **synchronous AC motors**
  - **three phase motors** use three sets of stator coils
    - the rotating magnetic field drags the rotor around with it
  - **single phase motors** require some starting mechanism
  - torque is only produced when the rotor is in sync with the rotating magnetic field
    - **not self-starting** – may be configured as an induction motor until its gets up to speed, then becomes a synchronous motor

- **Induction motors**
  - these are perhaps the most important form of AC motor
  - rather than use slip rings to pass current to the field coils in the rotor, current is *induced* in the rotor by transformer action
  - the stator is similar to that in a synchronous motor
  - the rotor is simply a set of parallel conductors shorted together at either end by two conducting rings

- A squirrel-cage induction motor



- In a **three-phase induction motor** the three phases produce a rotating magnetic field (as in a three-phase synchronous motor)
  – a stationary conductor will see a varying magnetic field and this will induce a current
  – current is induced in the field coils in the same way that current is induced in the secondary of a transformer
  – this current turns the rotor into an electromagnet which is dragged around by the rotating magnetic field
  – the rotor always goes slightly slower than the magnetic field – this is the **slip** of the motor

- In **single-phase induction motors** other techniques must be used to produce the rotating magnetic field
  - various techniques are used leading to various forms of motor such as
    - capacitor motors
    - shaded-pole motors
  - such motors are inexpensive and are widely used in domestic applications

Universal Motors

- While most motors operate from either AC or DC, some can operate from either
- These are **universal motors** and resemble series-wound DC motors, but are designed for both AC and DC operation
  - typically operate at high speed (usually > 10,000 rpm)
  - offer high power-to-weight ratio
  - ideal for portable equipment such as hand drills and vacuum cleaners

Electrical Machines – A Summary

- **Power generation is dominated by AC machines**
  - range from automotive alternators to the synchronous generators used in power stations
  - efficiency increases with size (up to 98%)
- **Both DC and AC motors are used**
  - high-power motors are usually AC, three-phase
  - domestic applications often use single-phase induction motors
  - DC motors are useful in control applications

Key Points

- Electrical machines include both generators and motors
- Motors can usually function as generators, and vice versa
- Electrical machines can be divided into AC and DC forms
- The rotation of a coil in a uniform magnetic field produces a sinusoidal e.m.f. This is the basis of an AC generator
- A commutator can be used to produce a DC generator
- The magnetic field in an electrical machine is normally produced electrically using field coils
- DC motors are often similar in form to DC generators
- Some forms of AC generator can also be used as motors
- The most widely used form of AC motor is the induction motor