Direct Current Machines

Principles, Construction, DC Motors, Characteristics.
Last Week – Synchronous Machines

• Synchronous Machine Principles
• Rotor Types
• Applications
  • Examples: Wind Turbines, Electric Vehicles
• Equivalent Circuit and Phasor Diagram
  • Effect of Different Loads, Power / Angle Relation
• Generator Operation
  • Islanding and parallel operation, Machine on “Infinite Busbar”
• Motor Operation
Today – Direct Current Machines

- DC Machine Principles
- Applications
- Design and Construction
- Windings
- DC Machine Equations, Connections & Characteristics
- DC Motor Operation
DC Machine Principles

The most simple rotating machine.
The Most Basic Rotating Machine

Assume a static magnetic field with a coil running through it.

Attaching a DC power source to the coil will result in a current flowing round.

Current carrying wire in a magnetic field will result in a force acting on the wire.

\[ B = \mu \cdot H \text{ in } T = \frac{N}{m \cdot A} \]

\[ d\vec{F} = ld\vec{l} \times \vec{B} \text{ in } N \]
The resulting force causes the coil to rotate for 90° from our starting position.

\[ B = \mu \cdot H \text{ in } T = \frac{N}{m \cdot A} \]

\[ F_{\text{MAX}} = I \cdot l \cdot B \text{ in } N \]
The resulting force causes the coil to rotate for 90° from our starting position.

In order to rotate further, the force, hence the current must change direction.

This is done by a so-called commutator. This is the basic principle of the DC machine.

\[
B = \mu \cdot H \quad \text{in} \quad T = \frac{N}{m \cdot A}
\]

\[
F_{MAX} = I \cdot l \cdot B \quad \text{in} \quad N
\]
Shaped Poles

• In order to have the field constant across most of the distance, the magnetic poles are shaped as illustrated on the left.

• A DC current through the field windings generates the homogenous field between the “pole shoes”.

![Diagram of shaped poles with magnetic field lines](image)
Shaped Poles / Pole Shoes

- In order to have the field constant across most of the distance, the magnetic poles are shaped as illustrated on the left.
- A DC current through the field windings generates the homogenous field between the “pole shoes”.
- DC machines have their armature windings usually on their rotor.
Applications

Motors, mostly.
DC Generators

- While **DC generators** were some of the earliest commercially successful designs, these days they are obsolete.
- DC power is now generated by synchronous machines with solid-state rectifiers.

Edison’s “Long Legged Mary”, a commercial DC generator from 1884.
(pictures from EdisonTechCenter.org)
DC Motors

The high torque of DC motors makes them valuable in a number of industrial applications.

- Adjustable motor speed over wide ranges.
- Constant mechanical output or constant torque.
- Rapid acceleration or deceleration.
- Responsive to feedback signals.
- Series motors for traction.
## DC Motors

<table>
<thead>
<tr>
<th>Industry</th>
<th>Application</th>
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</thead>
<tbody>
<tr>
<td>Steel</td>
<td>Metal rolling mill, coiler drive, winders</td>
</tr>
<tr>
<td>Paper</td>
<td>Wet end calendar, tension reel, drier, winder</td>
</tr>
<tr>
<td>Textiles</td>
<td>Weaving machinery</td>
</tr>
<tr>
<td>Plastics</td>
<td>Extrusion</td>
</tr>
<tr>
<td>Mining</td>
<td>Underground locomotive, conveyor belts, elevators</td>
</tr>
<tr>
<td>Material handling</td>
<td>Conveyors, cranes, elevators</td>
</tr>
<tr>
<td>Recreation</td>
<td>Ski lift, shuttle, amusement park</td>
</tr>
<tr>
<td>Machine tool</td>
<td>Metal lathe, veneer lathe, mills, saws</td>
</tr>
<tr>
<td>Transit</td>
<td>Cooling fan, compressor</td>
</tr>
<tr>
<td>General purpose</td>
<td>Misc.</td>
</tr>
</tbody>
</table>
Switched Reluctance Motors

- Brushless DC motors.
- \# Stator poles > \# Rotor poles
- Use of power electronics to switch between different field windings to facilitate rotation.
- Simple design, but difficult to control.
- Very high rotational speeds possible (up to 110,000 rpm).

Video of simulation: https://www.youtube.com/watch?v=LJUYumwh-k
Dyson motor: https://youtu.be/yajwmhe96pg
Design & Construction

Major Components, Complexity of Design.
Main Components - Stator

- **Field winding**: the main field winding in DCM is usually the stator winding. When a current flows through the field winding, a magnetic flux is set up in the air gap.

  The main field winding can be:
  - parallel or
  - in series
  with the **armature winding**, or:
  - separately excited.
Main Components - Rotor

- **Armature winding**: in DCM usually located on the rotor. The rotor is usually laminated (eddy current reduction). Rotor windings are electrically connected to commutator segments.

- **Commutator**: made from copper segments, insulated from each other.
  - Motor: produces pseudo-stationary magnetic flux along the line joining the brushes.
  - Generator: convert oscillating emfs in individual rotor windings into DC emf across the brushes.

Image source: Groschopp USA
**Main Components - Brushes**

- **Brushes**: generally made from carbon, placed in contact with the commutator to provide electrical connection to the rotor windings. Voltage drop approx. 1 V across.

- Placed in **brush holders**, that ensure constant, well define pressure, and allow easy replacement of individual brushes.
Typical DC Motor

A. Enclosure
B. Frame
C. Bearings
D. Armature
E. Brush rigging
F. Conduit box
G. Insulation
H. Accessory mounting face
I. Lifting lugs
J. Coils

Image source: General Electric “Kinamatic” DC current motors brochure.
Maintenance

• Due to their construction, DC machines are maintenance intensive.
• Brushes wear and must be checked and replaced regularly.
• Only very small rotors don’t need regular brush replacement.
• Other maintenance relevant components are bearings and separate cooling fans.
## Example for DC Maintenance Schedule

Assuming 8 hours operation per day.

<table>
<thead>
<tr>
<th>Maintenance work</th>
<th>Maintenance interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examine <strong>brushes</strong> for wear. Under partial load or unfavourable ambient conditions (high temperature, high ambient humidity) the brushes are at particular risk.</td>
<td>Monthly</td>
</tr>
<tr>
<td>Inspect surfaces of slip ring or collector for signs of grooving.</td>
<td>Monthly</td>
</tr>
<tr>
<td>Check the <strong>brushes</strong> for free movement within the brush holders.</td>
<td>Monthly</td>
</tr>
<tr>
<td>Check <strong>bearings</strong> for noise and vibration-free operation. Check bearing temperature.</td>
<td>Monthly</td>
</tr>
<tr>
<td>Check that filters are free from dust and that cooling systems function safely.</td>
<td>Monthly</td>
</tr>
<tr>
<td>Check the commutator for concentric running.</td>
<td>Every 3 months</td>
</tr>
<tr>
<td>Check the <strong>brush</strong> pressure and all terminals for tightness.</td>
<td>Every 3 months</td>
</tr>
<tr>
<td>Re-grease <strong>bearings</strong></td>
<td>As specified</td>
</tr>
<tr>
<td>Inspect the coupling and check for radial play.</td>
<td>Annually</td>
</tr>
<tr>
<td>Thoroughly clean and inspect the <strong>bearings</strong>, commutator, windings and <strong>associated parts</strong>.</td>
<td>Annually</td>
</tr>
<tr>
<td>Wash out and grease <strong>bearings</strong>, replace if necessary.</td>
<td>Every 3 years</td>
</tr>
</tbody>
</table>

Windings

Auxiliary winding types typically found in DC machines, and their function.
DC Machine Windings

• Armature winding (usually rotor)
• Series field winding (at poles in stator, in series to armature winding)
• Shunt field winding (at poles in stator, in parallel to armature winding)
• Separately excited field winding (at poles in stator)
• Compensating winding (within poles)
• Commutating field winding (in neutral zone between poles)
When the machine is under load, the armature current will induce a magnetic field (armature quadrative-axis field) which weakens the main field under about half the pole shoe, while it is strengthened in the other half.

This results in increased voltages in the rotor, respectively at the commutator.
• When the machine is under load, the armature current will induce a magnetic field (armature quadrative-axis field) which weakens the main field under about half the pole shoe, while it is strengthened in the other half.

• This results in increased voltages in the rotor, respectively at the commutator, which can lead to arcing.

(video: https://youtu.be/gc4l1eooPKM?t=30s)

• One way to prevent arcing at the commutator is to shift the position of the brushes (cheapest).
Compensation Winding (Compole/Interpole)

- To minimize these effects, additional compensation windings can be inserted into the stator poles.
- If the compensation winding has the same amount of turns and has the armature current flowing in opposite direction, it can completely compensate for the armature quadrative-axis field (the effect on the main field is called armature reaction).
- Hence the compensation winding is in series with the armature winding.
Commutating Field Winding

- In order to help commutation, commutating field windings can be placed in the gap between poles.
- The commutating field is generated by armature current, compensating for the armature reaction between the poles.
- As a result, the neutral zone between poles remains and arcing is prevented.
All Windings

• **Main field** due to field winding (either series, shunt or external DC current).

• **Armature field** due to armature (load) current in rotor.

• **Commutating field** due to armature current (few turns).

• **Compensating field** due to armature current (same number of turns as armature winding).

• **Resulting total field** in air gap.
Armature Winding Connections

- Armature coils
- Commutator segments
- Brushes
- Lap winding
- Wave winding
DC Machine Equations

Torque and e.m.f.
Equations

Torque:

\[ T = \frac{p \phi Z I}{\pi a} = \frac{pZ}{\pi a} \phi I = k_T \phi I \]

EMF:

\[ E = \frac{2p \phi Z n}{60a} = \frac{2pZ}{60a} \phi n = k_E \phi n \]

- \( p \) = number of poles
- \( Z \) = number of conductors
- \( a \) = parallel armature paths
- \( \phi \) = flux
- \( n \) = speed in rpm
- \( I \) = current
Basic Equivalent Circuit Diagram

**Motor operation:**
\[ V_a = E + R_a \cdot I_a + 2\Delta V \]
\[ T = k_T \Phi I_a \]

- **Transient:**
  \[ v_a \]
  \[ i_a \]
  \[ R_a, L_a \]
  \[ I_a \]
  \[ V_f, R_f \]
  \[ E, e, \Phi, \Delta V \]

- **Steady state:**
  \[ V_a \]
  \[ I_a \]
  \[ R_a, L_a \]
  \[ I_a \]
  \[ V_f, R_f \]
  \[ E, e, \Phi, \Delta V \]

**Symbols:**
- \( R_a \): Armature resistance
- \( L_a \): Armature inductance
- \( V_a \): Steady-state armature voltage
- \( v_a \): Transient armature voltage
- \( I_a \): Steady-state armature current
- \( i_a \): Transient armature current
- \( E, e \): Speed dependent emf
- \( R_f \): Field winding resistance (optional)
- \( I_f \): Steady-state field current (optional)
Speed-Torque Characteristic

\[ V_a = E + R_a \cdot I_a \]

\[ T = k_T \phi I_a \]

\[ \omega = \frac{V_a}{k} \cdot \frac{R_a}{(k \cdot \phi)^2} \cdot T \]

\( n_0 \) no load speed

\( I_r \) rated current
Equivalent Circuit Diagram Generator

Generator operation:

\[ V_a = E - R_a \cdot I_a - 2 \Delta V \]

\[ E = k_E \phi n \]

\[ T = k_T \phi I_a \]

- **\( R_a \)**: Armature resistance
- **\( L_a \)**: Armature inductance
- **\( V_a \)**: Steady-state armature voltage
- **\( V_i \)**: Transient armature voltage
- **\( I_a \)**: Steady-state armature current
- **\( i_a \)**: Transient armature current
- **\( E, e \)**: Speed dependent emf
- **\( R_f \)**: Field winding resistance (optional)
- **\( I_f \)**: Steady-state field current (optional)
DC Machine Connections

And Generator Operation.
DC Machine Connections

Classified by connection of the main field winding:

- Separately excited
- Field winding in parallel to armature: Shunt
- Field winding in series to armature
- Compound: both series and shunt field windings

<table>
<thead>
<tr>
<th>Winding type</th>
<th>Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armature</td>
<td>A1, A2</td>
</tr>
<tr>
<td>Commutation</td>
<td>B1, B2</td>
</tr>
<tr>
<td>Compensation</td>
<td>C1, C2</td>
</tr>
<tr>
<td>Series excitation</td>
<td>D1, D2</td>
</tr>
<tr>
<td>Shunt excitation</td>
<td>E1, E2</td>
</tr>
<tr>
<td>Separate excitation</td>
<td>F1, F2</td>
</tr>
</tbody>
</table>
Separately Excited

- Shunt field
- Series field
- Armature
- Commutating (compole / interpole)
- Compensating winding
Separately Excited Generator

Generator operation:

\[ V_a = E - R_a \cdot I_a - 2 \Delta V \]

\[ E = k_E \Phi n \quad T = k_T \Phi I_a \]

\[ I_f = \frac{V_f}{R_f} \]

Steady state:

- Armature resistance \( R_a \)
- Steady-state armature voltage \( V_a \)
- Steady-state armature current \( I_a \)
- Speed dependent emf \( E, e \)
- Field winding resistance \( R_f \)
- Steady-state field current \( I_f \)
Shunt

Diagram:

- Shunt field
- Series field
- Armature
- Commutating (compole / interpole)
- Compensating winding
Shunt Generator

Steady state:

\[ V_a = E - R_a \cdot I_a \]

\[ E = k_E \Phi n \quad T = k_T \Phi I_a \]

\[ I_f = \frac{V_a}{R_f} \]

Generator operation:

- **\( R_a \)**: Armature resistance
- **\( V_a \)**: Steady-state armature voltage
- **\( I_a \)**: Steady-state armature current
- **\( E, e \)**: Speed dependent emf
- **\( R_f \)**: Field winding resistance
- **\( I_f \)**: Steady-state field current

E drops as armature current increases, thus \( V \) decreases.
Series

Diagram showing a series electric motor with connections to the shunt field, series field, commutating (compole / interpole), armature, and compensating winding.
Series Generator

Generator operation:

\[ V_a = E - R_a \cdot I_a - R_f \cdot I_a \]

\[ E = k_E \phi n \quad T = k_T \phi I_a \]

\[ I_f = I_a \]

\[ E \propto I_a \]

Steady state:

- Armature resistance \( R_a \)
- Steady-state armature voltage \( V_a \)
- Steady-state armature current \( I_a \)
- Speed dependent emf \( E, e, \phi, n \)
- Field winding resistance \( R_f \)
- Steady-state field current \( I_f \)
Compound

- Shunt field
- Series field
- Commutating (compole / interpole)
- Armature
- Compensating winding
Compound Generator

Steady state:

\[ V_a = E - R_a \cdot I_a - R_{fD} \cdot I_a \]

\[ E = k_E \phi n \quad T = k_T \phi I_a \]

Generator operation:

Shunt winding dominating
Compound Generator

Steady state:

\[ V_a = E - R_a \cdot I_a - R_{FD} \cdot I_a \]

Generator operation:

\[ V_a = E - R_a \cdot I_a - R_{FD} \cdot I_a \]

\[ E = k_E \phi n \]

\[ T = k_T \phi I_a \]
DC Motor Operation

Speed Control.
Methods of speed control:
• Varying the armature voltage $V_a$
• Varying the armature resistance $R_a$
• Varying the air-gap flux $\phi$ (via excitation current)

\[
\omega = \frac{V_a}{k \phi} \cdot \frac{R_a}{(k \phi)^2} \cdot T
\]
Varying the Armature Voltage

Methods of speed control:

- Varying the armature voltage $V_a$

\[ \omega = \frac{V_a}{k \phi} \cdot \frac{R_a}{(k \phi)^2} \cdot T \]

\[ n \propto V_a \]
Varying the Armature Resistance

Methods of speed control:
• Varying the armature resistance $R_a$

$$\omega = \frac{V_a}{k \phi \cdot \left(\frac{R_a}{k \phi}\right)^2} \cdot T$$

$n \propto \frac{1}{R_a}$
Varying the Flux

Methods of speed control:

- Varying the air-gap flux $\phi$ (via excitation current)
- In combination with armature voltage and/or armature resistance control also called ‘field weakening’ control.

\[
\omega = \frac{V_a}{k \phi} \cdot \frac{R_a}{(k \phi)^2} \cdot T
\]
Series Motor

Steady state:

\[ I_a = I_f \]

\[ V_a = E + R_a \cdot I_a + R_f \cdot I_a \]

\[ E = k_E \phi n \]

\[ n = \frac{V_a - I_a R_a - R_f \cdot I_a}{k_E \phi} \]

Motor operation:
Compound Motor

Steady state:

Motor operation:

\[
V_a = E + R_a \cdot I_a + R_{FD} \cdot I_a
\]

\[
E = k_E \phi n
\]

\[
n = \frac{V_a - I_a R_a - R_{FD} \cdot I_a}{k_E \phi}
\]
DC Motor Starting Characteristic

- At $t = 0$, the emf $= 0$ (no motor voltage induced).
- The complete armature voltage is across the armature resistance $R_a$ and inductance $L_a$.
- Large inrush current $i_a$.
- This current is acceptable for small motors, but for large motors the inrush current must be limited.

Common methods to limit the inrush current:
- Starting resistors
- Soft starter
Starting Resistors

- A cascade of ohmic resistors is switched in series with the armature circuit of the motor.
- These resistors increase $R_a$.
- With each drop in $R_a$, the motor “jumps” to the next speed-torque characteristic.
Soft Starter

• Today, soft starters are usually preferred over starting resistors.
• Soft starter consists of a chopper, which cyclically switches the armature voltage on and off with a frequency of a several kHz.
• Pulse-pause-ratio determines the average motor armature voltage.
• When the pulse duration gradually increases, so does the average armature voltage.
Converter-fed DC Drives

- Higher powered drives use a converter for a controller.
- Three phase AC voltage is being converted into a DC voltage with the desired amplitude.
- Widespread in industrial plant equipment (cranes, steel mills), but being now replaced by AC drives.
- Above 100 kW they still have advantages over AC (e.g. lower space requirements).
Converter-fed DC Drives

- Converters are thyristor-based controllable rectifiers.
- They convert AC voltage into DC with an adjustable value in a single stage process.
- $V_a$ is a result of the firing angle $\alpha$ of the thyristors.
- Armature voltage $V_a$ is not ideally smooth, but has a ripple, reducing the armature current and subsequently the available torque.
# Common Rectifier Circuits

<table>
<thead>
<tr>
<th>Rectifier Circuit</th>
<th>Description</th>
<th>Quadrants</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2H</td>
<td>single converter, two pulse, single-phase connection, half-controlled</td>
<td><img src="image1" alt="Diagram" /></td>
<td>single-direction drives up to 10 kW excitation converters</td>
</tr>
<tr>
<td>B2HZ</td>
<td>single converter, two pulse, single-phase connection, fully-controlled</td>
<td><img src="image2" alt="Diagram" /></td>
<td>single-direction drives up to 10 kW braking with negative direction of rotation possible</td>
</tr>
<tr>
<td>B2C</td>
<td>single converter, six pulse, three-phase connection, fully-controlled</td>
<td><img src="image3" alt="Diagram" /></td>
<td>single-direction drives up to 10 kW braking with negative direction of rotation possible</td>
</tr>
<tr>
<td>B6C</td>
<td>single converter, one or three-phase connection, fully-controlled</td>
<td><img src="image4" alt="Diagram" /></td>
<td>bidirectional drives up to 10 MW with reduced line disturbances torque-free interval of up to 0.01 s</td>
</tr>
</tbody>
</table>

Quadrants

• Depending on the type of converter used, the machine can operate in 1, 2 or 4 quadrants:

1. Motoring, $i_a > 0$
2. Generating, $i_a < 0$
3. Motoring, $i_a < 0$
4. Generating, $i_a > 0$

• 1,2 quadrant drives: single direction
• 4 quadrant drive: both directions
Limits of Stability

- Typical speed-torque characteristics of speed-controlled DC drive.
- Until $n_0$ area of constant flux $\phi$.
- Above $n_0$ “field weakening”-range.
Machines Overview Table

Not considering converter/inverter-fed drives.
<table>
<thead>
<tr>
<th>Type</th>
<th>Efficiency</th>
<th>Power Factor</th>
<th>Starting Torque</th>
<th>Overloading Capacity</th>
<th>Speed Control</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induction Machines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Cage</td>
<td>Very good</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Double Cage</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>Wound Rotor</td>
<td>Very Good</td>
<td>Poor</td>
<td>Very good</td>
<td>Good</td>
<td>Moderate</td>
<td>Good</td>
</tr>
<tr>
<td>Synchronous Machines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reluctance</td>
<td>Moderate</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>N/A</td>
<td>Excellent</td>
</tr>
<tr>
<td>DC excited</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Poor</td>
<td>Good</td>
<td>N/A</td>
<td>Good</td>
</tr>
<tr>
<td>DC Machines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Series, shunt, compound</td>
<td>Moderate</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Moderate</td>
</tr>
<tr>
<td>AC commutation</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Very good</td>
<td>Good</td>
<td>Very good</td>
<td>Moderate</td>
</tr>
</tbody>
</table>