1. **Ampere’s Law**: a current-carrying conductor produces a magnetic field surrounding it

\[ \oint_C \mathbf{H} \cdot d\mathbf{l} = N_i \]

2. **Faraday’s Law**: the induced voltage in a circuit is proportional to the rate of change over time of the magnetic flux through that circuit

\[ e_{ind} = \frac{d\lambda}{dt} = N \frac{d\phi}{dt} \]

1. A current-carrying conductor in a magnetic field has a force induced on it (due to Lorentz Force)
   - **Basis for motor action**
DC Machines
Equivalent Circuit

\[ e_a = K_a \phi_d \omega_m = K_v \omega_m \]

\[ e_a i_a = T_e \omega_m \]

\[ T_e = K_a \phi_d i_a = K_a \phi_d \left( v_a - K_a \phi_d \omega_m \right) / R_a \]

\[ \omega_m = \frac{(v_a - i_a R_a)}{K_a \phi_d} = \frac{(v_a - \frac{T_e}{K_a \phi_d} R_a)}{K_a \phi_d} \]
Control

Speed control:

- Flux control or voltage control

\[ E_a = V - I_a R_a = K_a \phi_d \omega \]

\[ \implies \omega = \frac{(V - I_a R_a)}{K_a \phi_d} \]

Torque Control:

- Armature current \((I_a)\)

\[ P_{mech} = E_a I_a = K_a \phi_d \omega I_a \]

\[ \Rightarrow \text{Torque} = \frac{P_{mech}}{\omega} = K_a \phi_d I_a \]
Torque/Power vs speed capability of motors
BLDC Motor

MITSUBA Special motor for solar car
- motor model: M1096D-II, M0548D-II
- controller model: M0899C, M0948C

Diagram of BLDC Motor:
- Cylindrical rotor
- Permanent magnets
- 3-phase stator winding

Graph showing
- Phase A current (Ia)
- Phase B current (Ib)
- Phase C current (Ic)
- Torque
- Voltage (Ea, Eb, Ec)
**Solar car motor**

MITSUBA Special motor for solar car

- Motor model: M1096D-II, M0548D-II
- Controller model: M0896C, M0848C

### Main Features
- Specially designed for purpose of solar car race
- Very high efficiency of direct drive motor (wheel in motor)
- Very small cogging torque brushless DC motors (32-pole, 36-slot)
- The efficiency more than 95%!! (including motor controller efficiency)
- Very high efficiency with wide range
- An adapter compatible with MITSUBA M1596D motor is available (cp)
- Very light weight motor (less than 11kgs!!)
- Very light weight motor controller (less than 3kgs!!)
- Very low current consumption motor controller
- Current control mode or manual PWM mode can be selected
- User can adjust many kinds of parameters by yourself
- Very high efficient generating brake

### M0548-II & M1096-II Specification

<table>
<thead>
<tr>
<th>System</th>
<th>M0548-II</th>
<th>M1096-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>System name</td>
<td>M0548-II</td>
<td>M1096-II</td>
</tr>
<tr>
<td>System outline</td>
<td>500W 48V</td>
<td>1000W 96V</td>
</tr>
<tr>
<td>Motor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model number</td>
<td>M0548D-II</td>
<td>M1096D-II</td>
</tr>
<tr>
<td>Dimension</td>
<td>( \phi 262 \text{mm} \times 147 \text{mm} )</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>7.4kg</td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>DC brushless motor in wheel type (direct drive type)</td>
<td></td>
</tr>
<tr>
<td>Nominal power</td>
<td>500W</td>
<td>1000W</td>
</tr>
<tr>
<td>Maximum power</td>
<td>About 2kW (see note)</td>
<td>About 2.5kW (see note)</td>
</tr>
<tr>
<td>Efficiency</td>
<td>More than 94% (including motor controller efficiency)</td>
<td></td>
</tr>
<tr>
<td>Nominal load rotation speed</td>
<td>It is preparing it</td>
<td>675rpm</td>
</tr>
<tr>
<td>Rotating direction</td>
<td>Forward-left turn (when see the wheel) / right turn optionally</td>
<td></td>
</tr>
</tbody>
</table>

### Controller

<table>
<thead>
<tr>
<th>Controller</th>
<th>M0548C</th>
<th>M0896C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>W143mm \times D128mm \times H71mm</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>1.3kg</td>
<td></td>
</tr>
<tr>
<td>Cooling operation</td>
<td>Natural air cooling</td>
<td></td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>48V</td>
<td>96V</td>
</tr>
<tr>
<td>Input voltage range</td>
<td>18-72V</td>
<td>70-150V</td>
</tr>
<tr>
<td>Operation</td>
<td>120 degrees Square-wave control</td>
<td></td>
</tr>
</tbody>
</table>

### Control mode
- Current control: checking input current and automatic adjust PWM DUTY
- Manual PWM control: direct control PWM Duty
- Reverse switch: available (with speed limit)
- Generation brake system: power adjust and voltage limiter (program by use)

Note: Maximum power which depend on voltage and battery.
Series Parallel Select Upgrade (1 of 2)

- Two coils can be used in parallel or series
- Must do the switching ourselves as well
- Not sure about switching when car is in motion
  - Additional $1000
Reluctance Machines
Magnetic Circuit

Assuming linear isotropic material ($B = \mu H$) and ignoring ‘leakage flux’

Applying Ampere’s law around the mean path: $Hl_c = Ni = \mathcal{F}$ (mmf of coil)

Assuming uniform flux density in the core: $\phi = BA$

$$\phi = \mu HA = \frac{\mu A}{l_c} \mathcal{F} = \mathcal{F}/\mathcal{R}$$

Equivalently:

$$\mathcal{F} = \mathcal{R}\phi$$

where $\mathcal{R} = \frac{l_c}{\mu A}$ is the core’s **reluctance**

(analogous to electrical resistance).
Inductance

For a winding with $N$ turns, its \textit{flux linkage}: $\lambda = \sum_{i=1}^{N} \phi_i$, where $\phi_i$ is the flux linking the $i^{th}$ turn

For a concentrated winding: $\lambda = N\phi$

The \textit{inductance} $L$ relates the flux linkage $\lambda$ to winding current $i$:

$$\phi = \frac{\lambda}{N} = \frac{\mathcal{F}}{\mathcal{R}} = \frac{Ni}{\mathcal{R}} \quad \rightarrow \quad L = \frac{\lambda}{i} = \frac{N^2}{\mathcal{R}}$$

In multi-winding magnetic circuits, \textit{mutual inductances} relate the flux in one winding to the current in another
Energy Approach to Electromechanical Energy Conversion

Electrical Energy \( v, i \)

Electromagnetic field

Mechanical work, \( f, x \)

Losses (neglect)

Energy:

\[ \int i \, v \, dt \]
\[ \int i \, d\lambda / dt \, dt \]
\[ \int i \, d\lambda \]

Stored Energy, \( W_m \)

Losses
Energy Approach

Neglecting Losses,

\[
dW_m/dt = \int i \, d\lambda - \int f \, dx
\]

\[
dW_m = W_m^b - W_m^a
\]

\[
= \int_{a}^{b} i \, d\lambda - f \, dx
\]

State variables, \( \lambda, x \)

\[
dW_m(\lambda, x) = \frac{\partial W_m(\lambda, x)}{\partial \lambda} \, d\lambda + \frac{\partial W_m(\lambda, x)}{\partial x} \, dx
\]

\[
dW_m = \int i \, d\lambda - f \, dx
\]

\[
f = -\frac{\partial W_m(\lambda, x)}{\partial x}
\]
Stored energy in magnetic field

For linear systems,

\[ W_m = \int_0^\lambda \frac{1}{L(x)} \lambda d\lambda = \frac{1}{2} \frac{\lambda^2}{L(x)} \]

\[ f^e = -\frac{1}{2} \lambda^2 \frac{\partial}{\partial x} \frac{1}{L(x)} \]

\[ f^e = -\frac{1}{2} i^2 \frac{\partial}{\partial x} L(x) \]
If each phase is excited with a constant current at positions where \( \frac{dL}{d\theta} > 0 \)
A) Phase A energized
   Rotor at holding position

B) Phase B energized
   Bent magnetic flux causes
   the rotor to be pulled towards
   B phase pole on stator

C) Phase B energized
   Rotor at holding position

D) Phase C energized
   Bent magnetic flux causes
   the rotor to be pulled towards
   C phase pole on stator

E) Phase C energized
   Rotor at holding position

F) Phase A energized
   Bent magnetic flux causes
   the rotor to be pulled towards
   A phase pole on stator
Power supply rating:

Inverter VA rating = \frac{\text{area}(W_{\text{rec}} + W_{\text{net}})}{T}

Net output = \frac{\text{area}(W_{\text{net}})}{T}

\frac{\text{Inverter VA rating}}{\text{Net output}} = \frac{\text{area}(W_{\text{rec}} + W_{\text{net}})}{\text{area}(W_{\text{net}})}

Where T is the length of one step (s)
Electrical Machine Design

- Electrical machine design is a mix of art & science, in contrast to modeling and analysis.
- Many design parameters and trade-offs across different domains (electromagnetics, mechanical, thermal, controls, materials, economics, etc.)
- No unique solution, and difficult to set up as an ‘inverse problem’ without major simplifications and narrowing down of the design space.
- Optimal design depends heavily on the emphasis on the overall objectives.
- Typically, an iterative process: design -> analysis -> design refinement -> analysis, ...
- Start with design goals – many: cost, efficiency, size, etc.
- Initial sizing to generate a “concept” and down-select a configuration based on approximate performance prediction.
- Useful to start with a low fidelity assessment and an approach for a quick sizing, to get things going. This may be where your expertise in machine design is most impactful.
- The remaining steps can be done somewhat mechanically if equipped with adequate analysis tools and sufficient time. An optimization tool may also help.
  - Electromagnetics design to size windings, laminations, magnets
  - Thermal design to keep temperature/loss within limits and specifications
  - Mechanical design to ensure proper rotor construction (specifically high-speed machines)
Design Constraints

The materials used for the machine and other features like cooling impose design limitations.

- **Flux density**: Saturation of iron poses a limitation on account of increased core loss and excessive excitation required to establish a desired value of flux. It also introduces harmonics.
- **Current density**: Higher current density reduces the volume of copper but increases losses
- **Temperature**: limitation on account of possible damage to insulation and other materials temperature sensitive materials (PM, composites etc)
- **Voltage stresses**: limitation on account of breakdown by excessive voltage gradient, mechanical forces or heat.
- **Mechanical stresses**: poses a limitation particularly in case of large and high speed machines.

Also need to consider additional requirements from customer, manufacturer or standards – efficiency, dynamic performance, fault tolerance, etc
Materials

- Lamination steels:
  - Cold-rolled steel: cheap, for mass production, high loss
  - Electrical (silicon) steel: Mxx grades, balance performance (loss) with cost
  - Cobalt-iron steel: Permedur, Hiperc, Vacoflux, Vacodur, ... high cost (10 – 100x electrical steel), low loss, highest flux density, used in many high performance applications
  - All lamination steels need to be heat-treated to achieved desired properties
  -> trade-off between magnetic (core loss) and mechanical performance (strength)

- Conductors / magnet wire:
  - Copper unless temperatures are beyond what copper can handle (i.e., 300°C +)
  - More important choice is magnet wire insulation (material, thickness). Choice depends on expected temperature and voltage levels

- Insulation:
  - Nomex papers (10 – 20 mil) to provide phase-phase and phase-ground (lamination stack) insulation
  - Electrical-grade resin sprayed onto the lamination stacks (3 – 5 mil thick)
  - High-temperature ceramic insulators in extreme temperatures

- Permanent magnets:
  - Neodymium magnets provide highest energy/flux density, but top out around 150°C
  - Samarium Cobalt magnets have are much more temperature stable, from cryogenic to 350°C, but have lower energy density
**Magnetic materials**

Soft magnetic materials have relatively narrow hysteresis loop and a steep magnetization curve. Properties of good soft magnetic material for machine design:

- High magnetic permeability
- High saturation induction
- Narrow hysteresis loop or low coercivity to minimize hysteresis loss
- High electrical resistivity to minimize eddy current loss
- A high curie point

Hard or permanent magnetic materials have wide hysteresis loop. Properties of good hard magnetic material for machine design:

High energy density, low temperature sensitivity, ‘resistant’ to demagnetization, high electrical resistivity,
Conducting materials

Desirable properties a good conductor should possess are listed below.

- Low value of resistivity or high conductivity
- Low value of temperature coefficient of resistance
- Highly malleable and ductile, High tensile strength
- High resistance to corrosion
- Allow brazing, soldering or welding so that the joints are reliable
- Low cost

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resistivity at 200°C</strong></td>
<td>0.0172 ohm / m/ mm²</td>
<td>0.0269 ohm/m/mm²</td>
</tr>
<tr>
<td><strong>Conductivity at 200°C</strong></td>
<td>58.14 x 10^6 S/m</td>
<td>37.2 x 10^6 S/m</td>
</tr>
<tr>
<td><strong>Density at 200°C</strong></td>
<td>8933 kg/m³</td>
<td>2689.9 kg/m³</td>
</tr>
<tr>
<td><strong>Temperature coefficient (0-100°C)</strong></td>
<td>0.393 % per °C</td>
<td>0.4 % per °C</td>
</tr>
<tr>
<td><strong>Coefficient of linear expansion (0-100°C)</strong></td>
<td>16.8x10^-6 per °C</td>
<td>23.5x10^-6 per °C</td>
</tr>
<tr>
<td><strong>Tensile strength</strong></td>
<td>25 to 40 kg / mm²</td>
<td>10 to 18 kg / mm²</td>
</tr>
<tr>
<td><strong>Mechanical property</strong></td>
<td>highly malleable and ductile</td>
<td>not as good</td>
</tr>
<tr>
<td><strong>Thermal conductivity (0-100°C)</strong></td>
<td>599 W/m °C</td>
<td>238 W/m °C</td>
</tr>
<tr>
<td><strong>Joining</strong></td>
<td>easily soldered</td>
<td></td>
</tr>
</tbody>
</table>
An ideal insulation material should possess the following properties:

- high dielectric strength
- withstand high temperature
- relatively high thermal conductivity
- low dissipation due to conduction or dielectric losses
- flexible and mechanically compliant
- withstand mechanical stresses over many cycles
- withstand vibration, abrasion, bending
- be inert to environment (moisture, oxidation, etc)

<table>
<thead>
<tr>
<th>Insulation class</th>
<th>Maximum operating temperature in °C</th>
<th>Typical materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous</td>
<td>Present</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
<td>105</td>
</tr>
<tr>
<td>E</td>
<td>E</td>
<td>120</td>
</tr>
<tr>
<td>B</td>
<td>B</td>
<td>130</td>
</tr>
<tr>
<td>F</td>
<td>F</td>
<td>155</td>
</tr>
<tr>
<td>H</td>
<td>H</td>
<td>180</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>&gt;180</td>
</tr>
</tbody>
</table>
Thermal Management

- Convection from the shell to the frame
- Conduction through the frame
- Convection & conduction through the stator core & windings
- Conduction through the rotor
- Conduction through the shaft

Heat in = power applied \times efficiency losses
Cooling Systems

Using the IPM hairpin machine we will compare three different cooling methods

1) Water jacket, e.g. Nissan Leaf, BMW i3
2) Water jacket + Internal Air, e.g. Zytek traction machine, BMW 2225xe series
3) Oil spray cooling, e.g. Toyota Prius