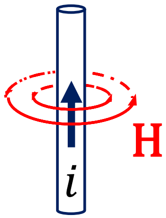
Principles of Magnetic Fields

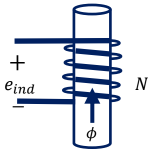
1. Ampere’s Law: a current-carrying conductor produces a magnetic field surrounding it

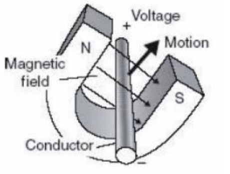
$$\oint_C \mathbf{H} \cdot d\mathbf{l} = \boldsymbol{N}i$$



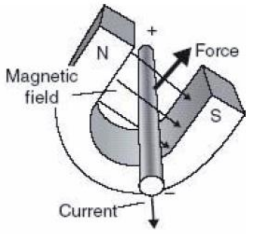
2. Faraday’s Law: the induced voltage in a circuit is proportional to the rate of change over time of the magnetic flux through that circuit

$$e_{ind} = \frac{d\lambda}{dt} = N\,\frac{d\phi}{dt}$$



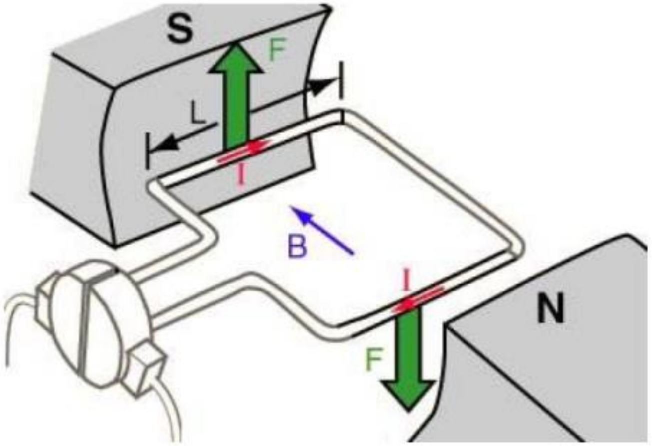


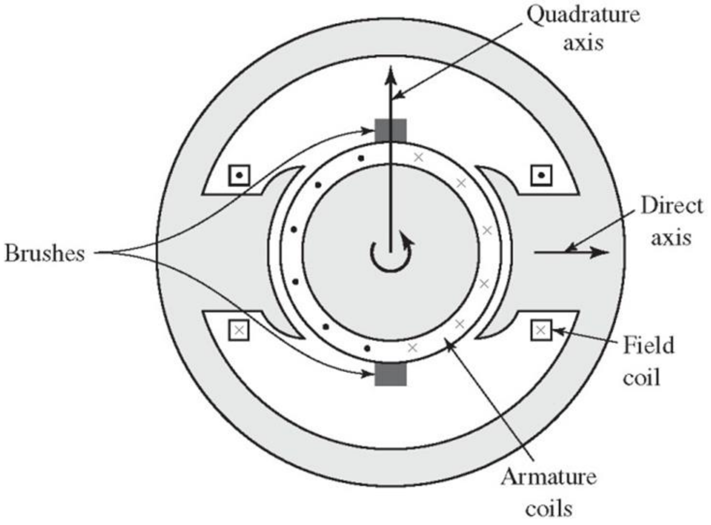
1. A current-carrying conductor in a magnetic field has a force induced on it (due to Lorentz Force)
   - *Basis for motor action*

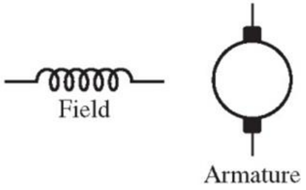


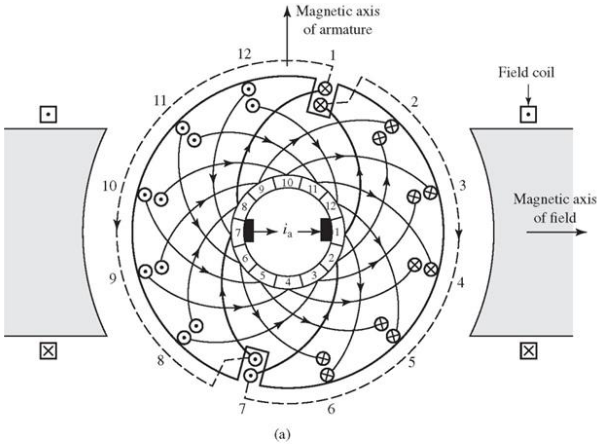
G. Masters, *Renewable and Efficient Electric Power Systems, 2nd Ed.*, Wiley IEEE Press, 2013.

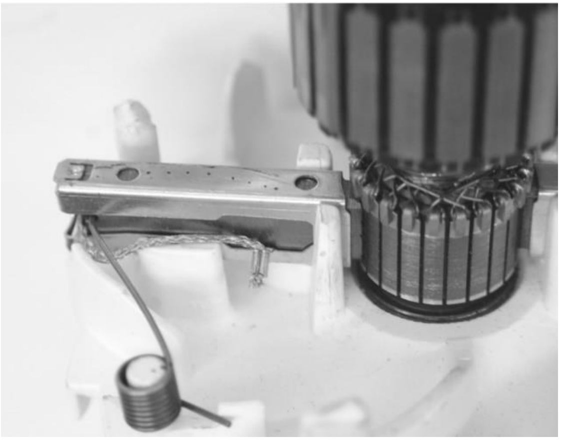
DC Machines


S
F
L
I
B
I
N
F

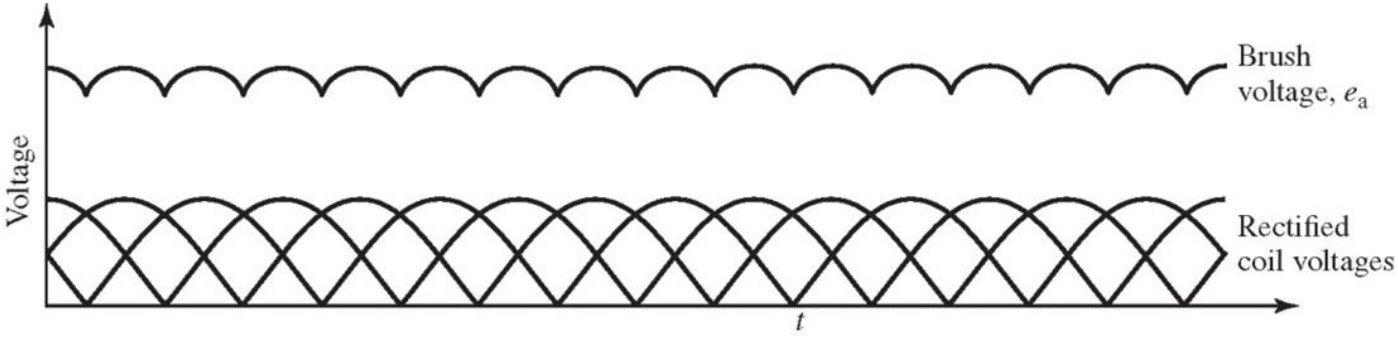

Quadrature axis
Direct axis
Brushes
Field coil
Armature coils

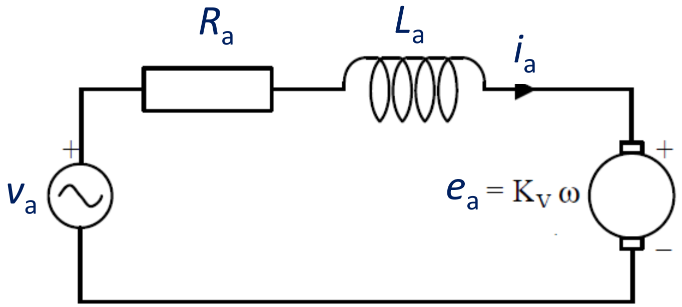

Field
Armature


Magnetic axis of armature
Field coil
Magnetic axis of field
i_a
1
2
3
4
5
6
7
8
9
10
11
12
(a)



Equivalent Circuit





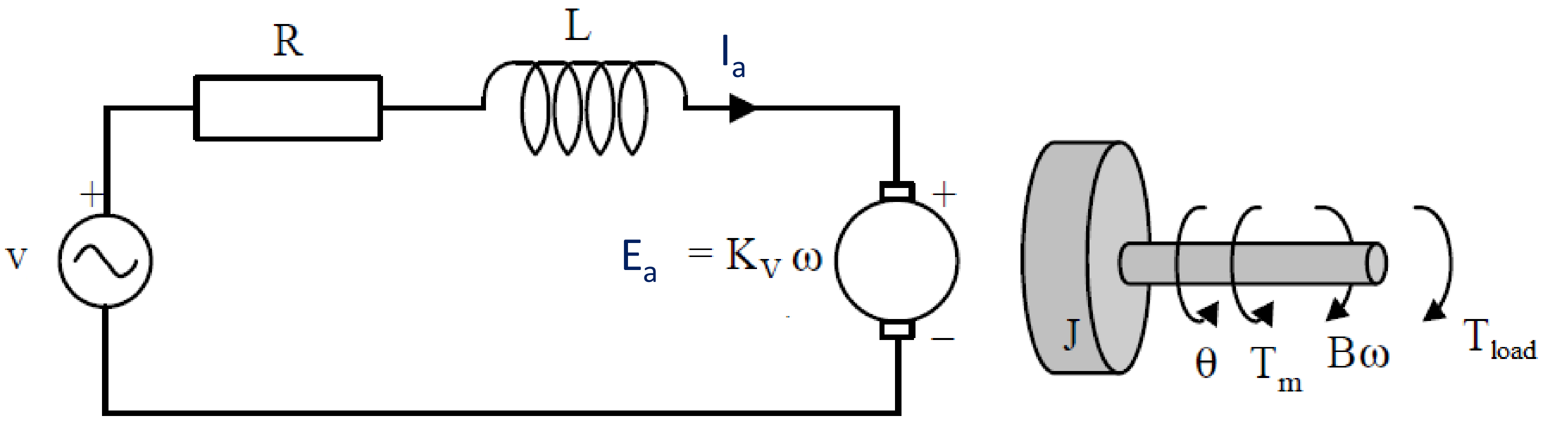
$$e_a = K_a\,\phi_d\,\omega_m = K_v\,\omega_m$$

$$e_a\,i_a = T_e\,\omega_m$$

$$T_e = K_a\phi_d i_a = K_a\phi_d\,(v_a - K_a\phi_d\omega_m)/R_a$$

$$\omega_m = \frac{(v_a - i_a R_a)}{K_a\phi_d} = \frac{(v_a - \frac{T_e}{K_a\phi_d}R_a)}{K_a\phi_d}$$

Control



Speed control:

- Flux control or voltage control

$$E_a = V - I_a R_a = K_a \phi_d \omega$$

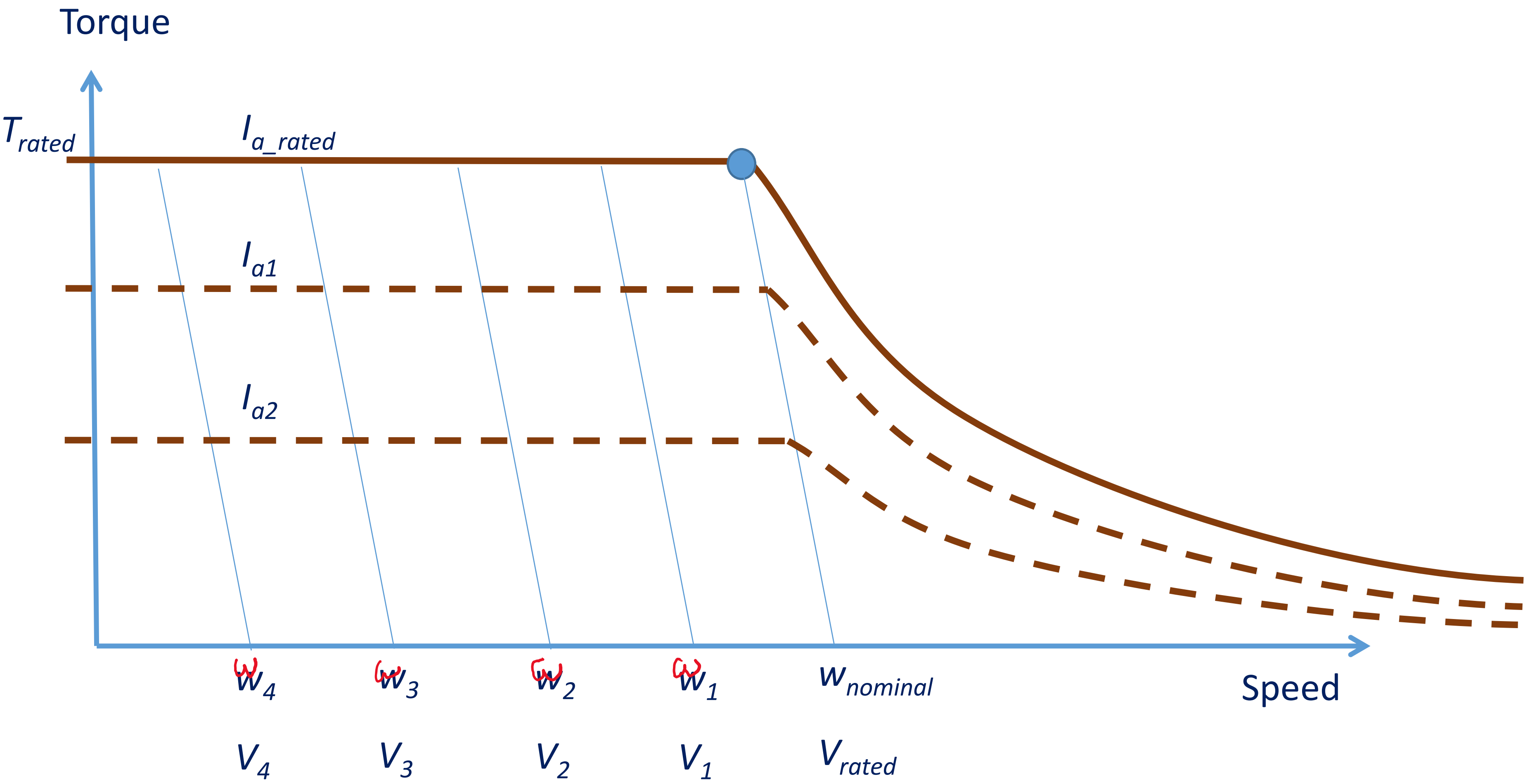
$$\Rightarrow \omega = (V - I_a R_a)/K_a \phi_d$$

Torque Control:

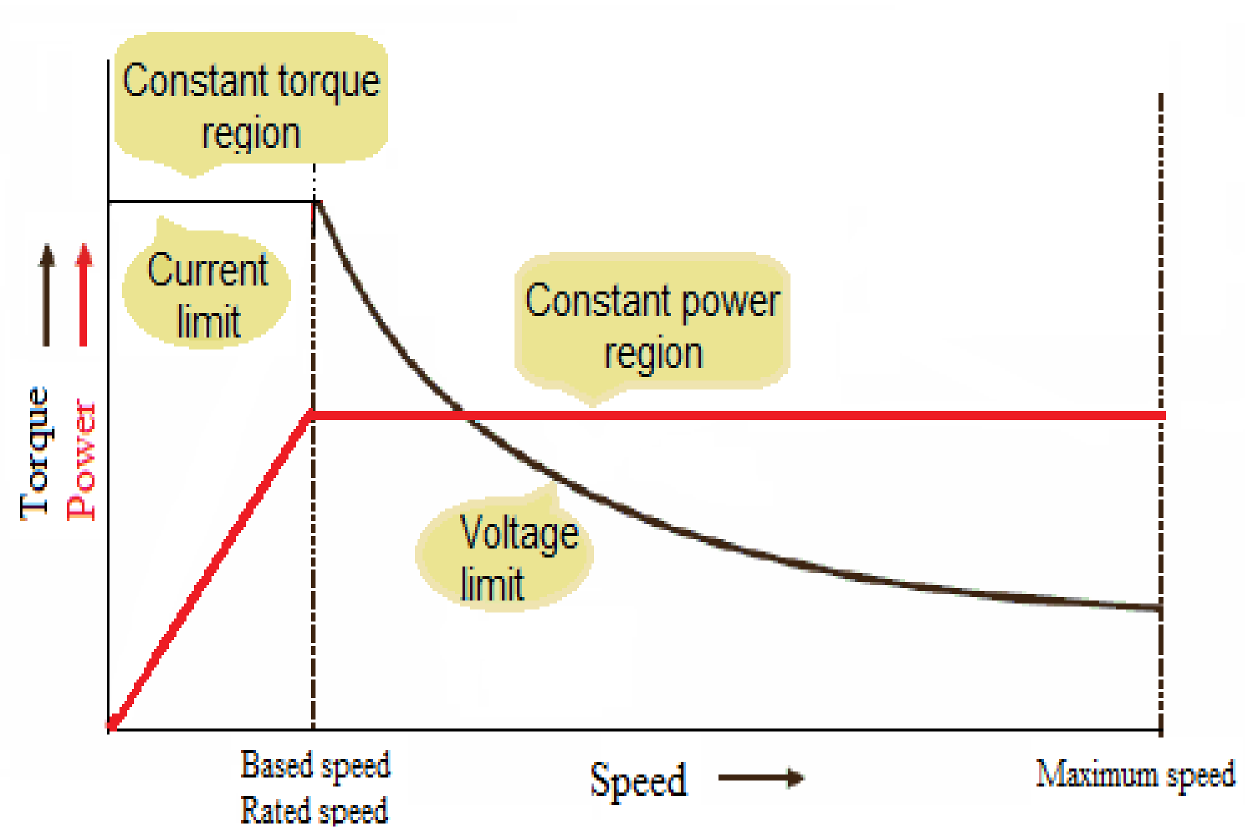
- Armature current (Ia)

$$P_{mech} = E_a I_a = K_a \phi_d \omega I_a$$

$$\Rightarrow \text{Torque} = P_{mech}/\omega = K_a \phi_d I_a$$


Torque
T_{rated}
I_{a_rated}
I_{a1}
I_{a2}
ω w_4
ω w_3
ω w_2
ω w_1
$w_{nominal}$
Speed
V_4
V_3
V_2
V_1
V_{rated}

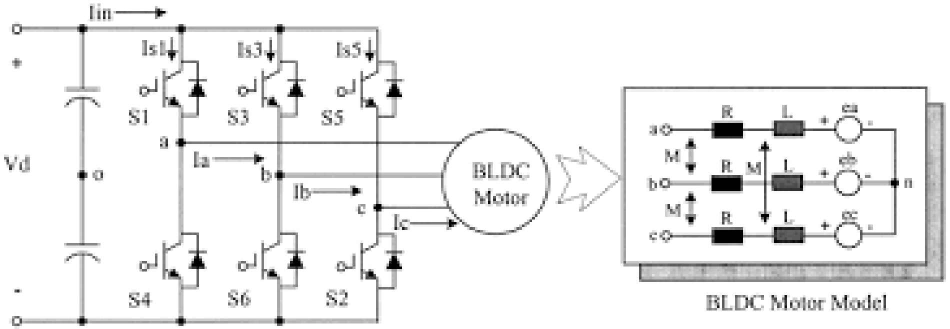
Torque/Power vs speed capability of motors

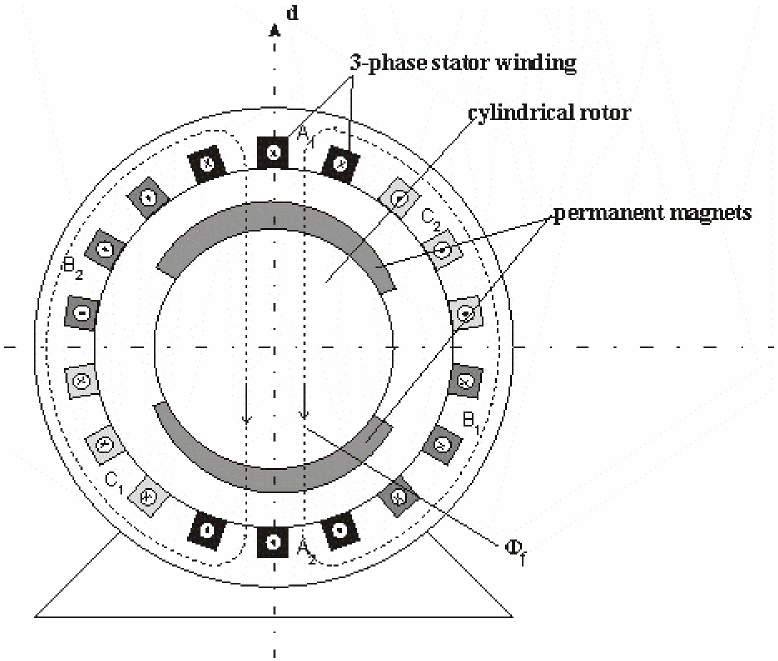


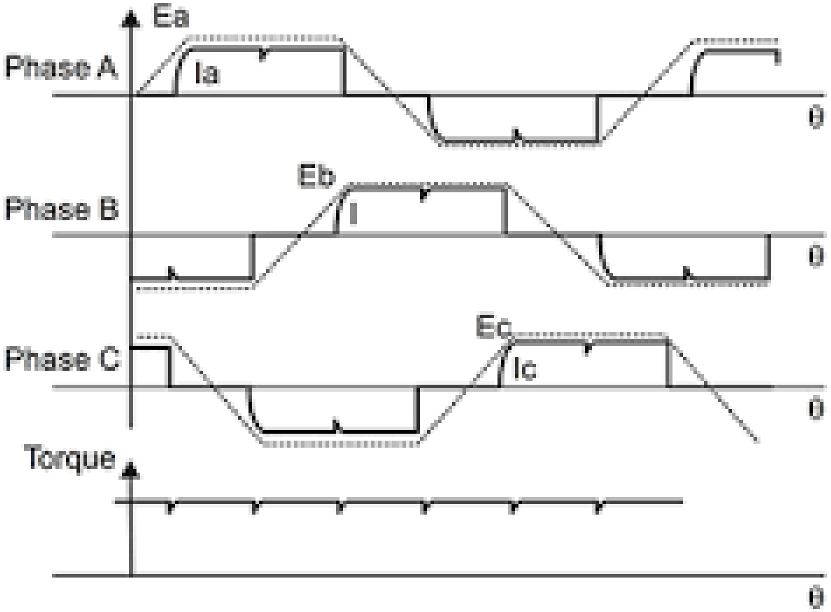
BLDC Motor

MITSUBA Special motor for solar car

(motor model : M1096D-Ⅱ, M0548D-Ⅱ
controller model : M0896C , M0848C)







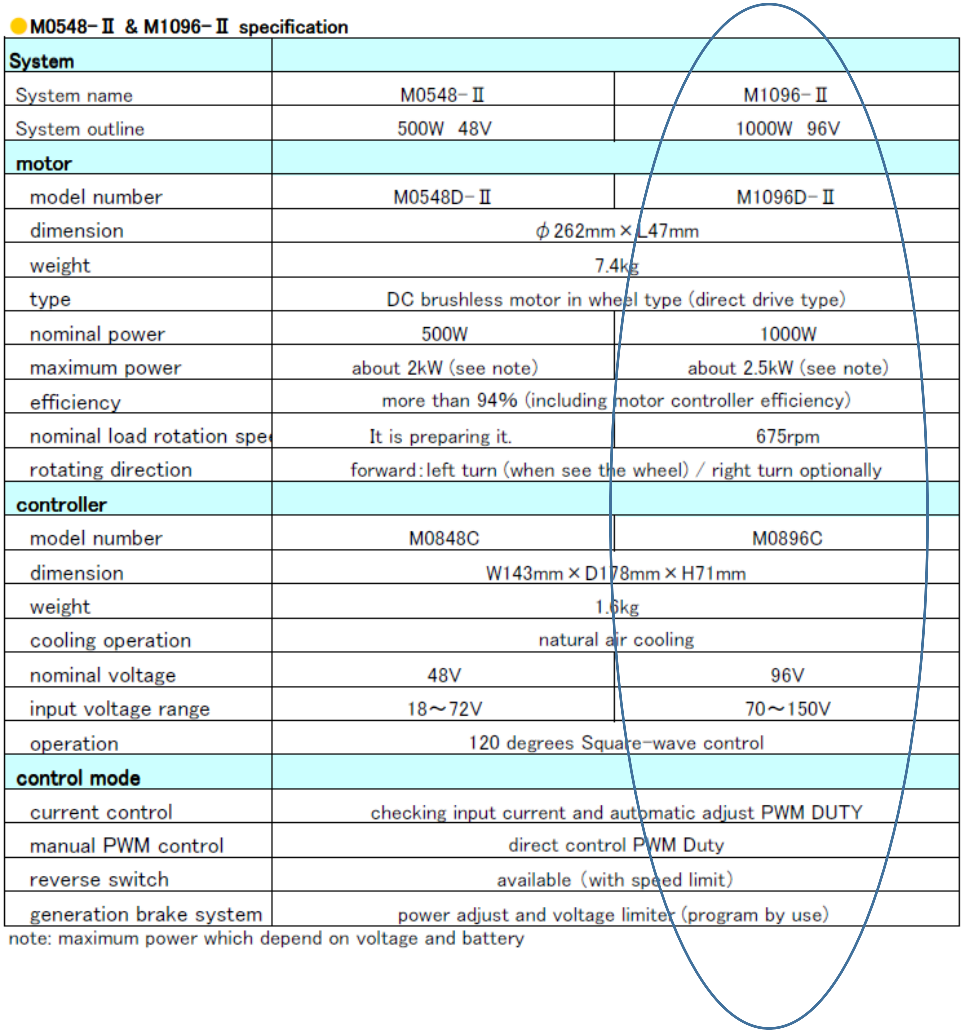
Solar car motor

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 efficienc
- ★ very high efficiency with wide range
- ★ An adapter compatible with MITSUBA M1596D motor is available (op
- ★ 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 your themselves
- ★ very high efficient generating brake



● **M0548-Ⅱ & M1096-Ⅱ specification**

System		
System name	M0548-Ⅱ	M1096-Ⅱ
System outline	500W 48V	1000W 96V
motor		
model number	M0548D-Ⅱ	M1096D-Ⅱ
dimension	ϕ262mm×L47mm	
weight	7.4kg	
type	DC brushless motor in wheel type (direct drive type)	
nominal power	500W	1000W
maximum power	about 2kW (see note)	about 2.5kW (see note)
efficiency	more than 94% (including motor controller efficiency)	
nominal load rotation spe	It is preparing it.	675rpm
rotating direction	forward:left turn (when see the wheel) / right turn optionally	
controller		
model number	M0848C	M0896C
dimension	W143mm×D178mm×H71mm	
weight	1.6kg	
cooling operation	natural air cooling	
nominal voltage	48V	96V
input voltage range	18～72V	70～150V
operation	120 degrees Square-wave control	
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)	

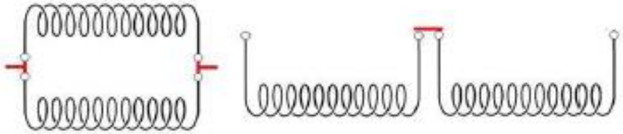
note: maximum power which depend on voltage and battery

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

NEW OPTION!!

SERIES / PARALLEL
2times rpm or 2times torque
SWITCHABLE ARRANGEMENT



parallel connection
higher rpm

series connection
higher torque

NOMURA CO. 野村商会

MITSUBA SCR PROJECT

Reluctance Machines

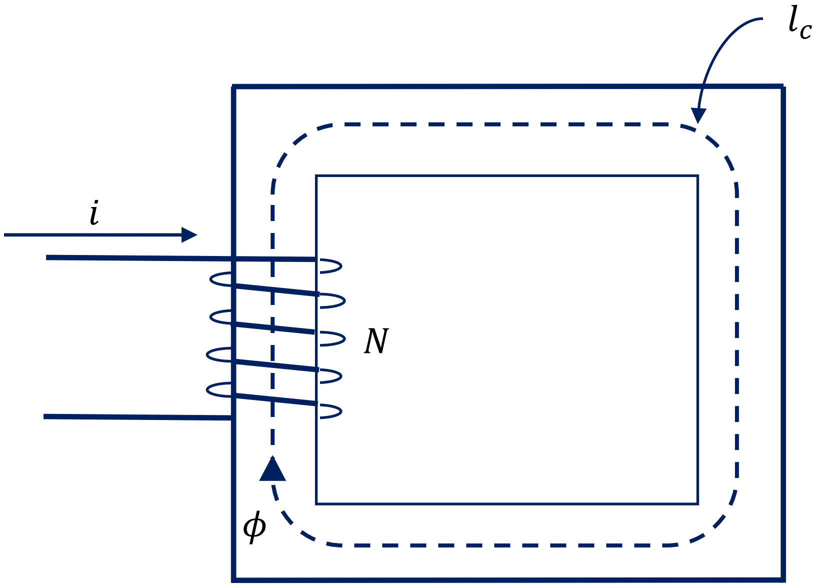
Magnetic Circuit

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: $\phi = BA$

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

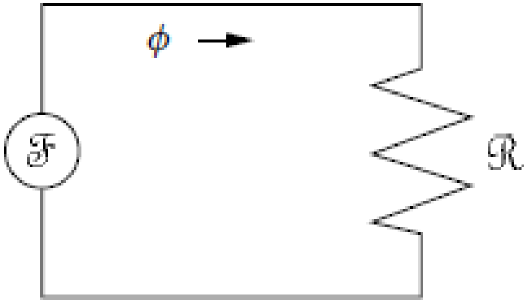


Cross-sectional area *A*

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 ***flux linkage***: $\lambda = \sum_{i=1}^{N} \phi_i$, where ϕ_i is the flux linking the i^{th} turn

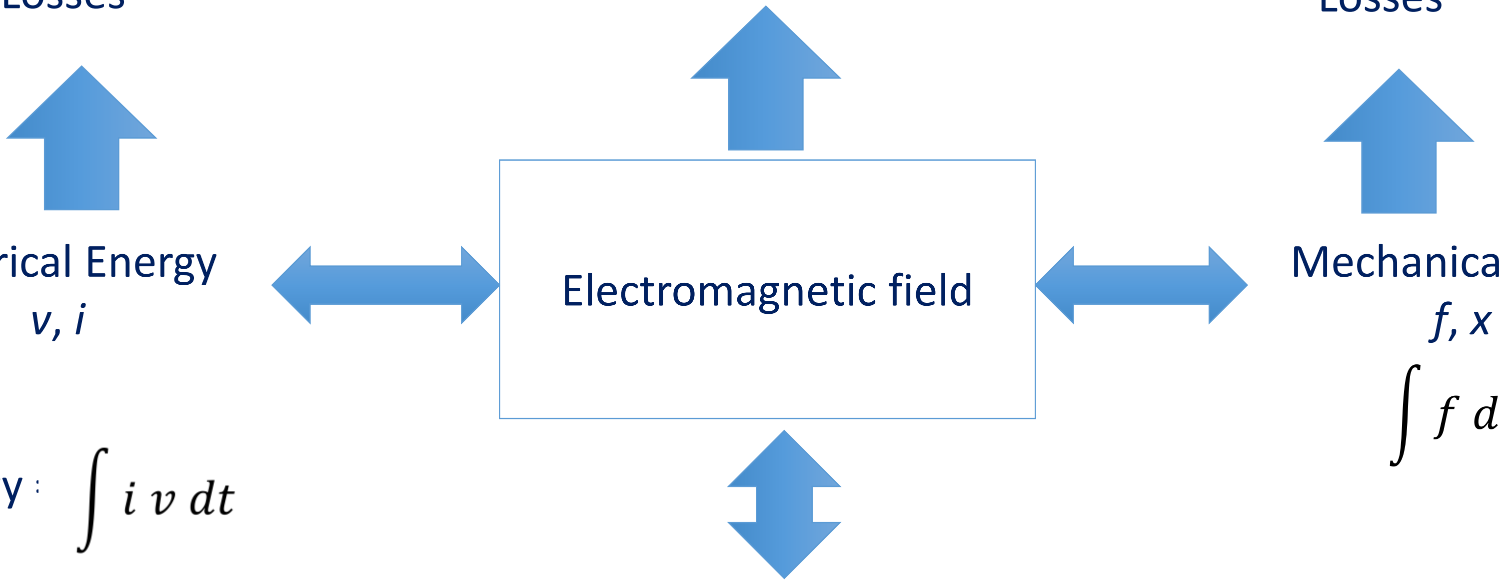
For a concentrated winding: $\lambda = N\phi$

The ***inductance*** *L* relates the flux linkage λ 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, ***mutual inductances*** relate the flux in one winding to the current in another

Energy Approach to Electromechanical Energy Conversion



Losses

Losses (neglect)

Losses

Electrical Energy
v, i

Electromagnetic field

Mechanical work,
f, x

$$\int f\,dx$$

Energy : $\int i\,v\,dt$

$$\int i\;d\lambda/dt\;dt$$

$$\int i\,d\lambda$$

Stored Energy,
W_m

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, λ, x

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

$$dW_m = \int \; i\, d\lambda - f\, dx$$

➡ $$f = -\frac{\partial W_m(\lambda, x)}{\partial x}$$

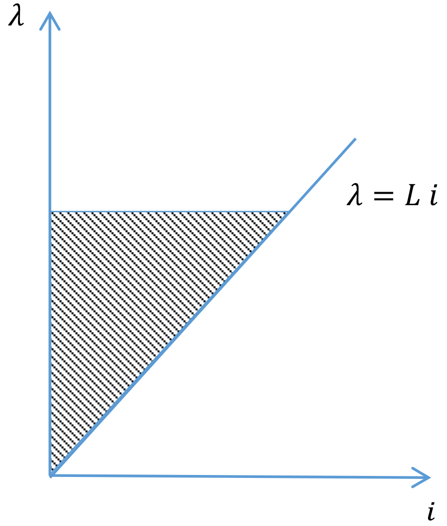
Stored energy in magnetic field

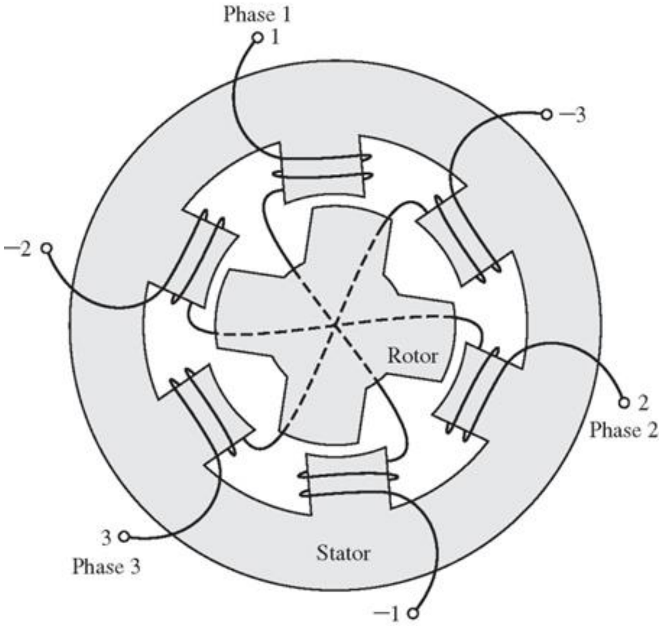
For linear systems,

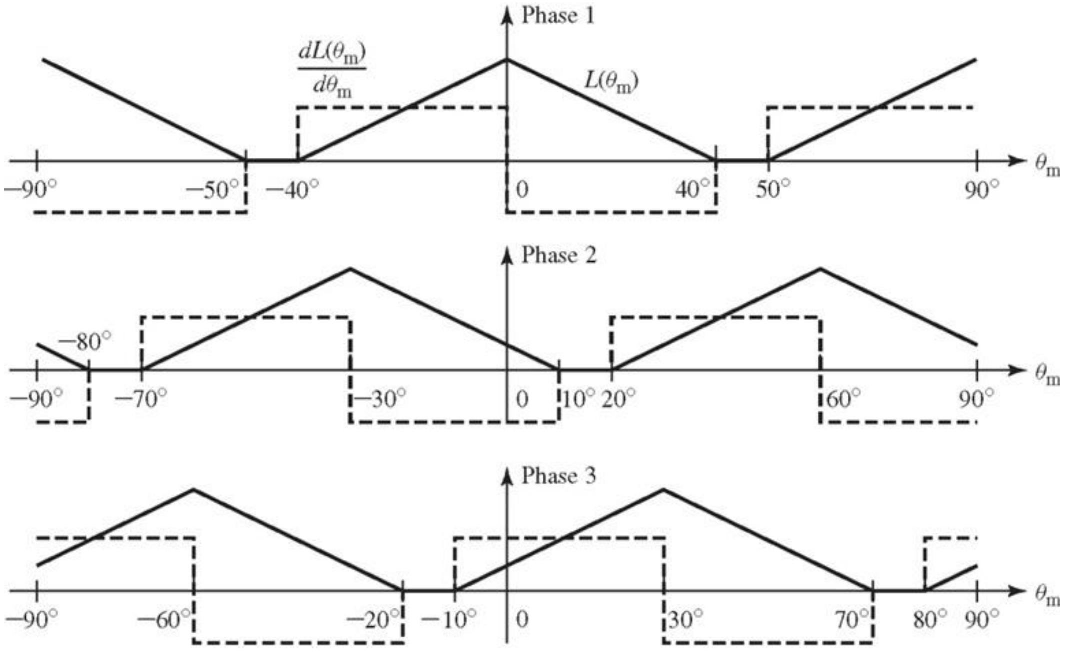
$$W_m = \int_0^\lambda \frac{1}{L(x)} \lambda d\lambda = \frac{1}{2} \frac{\lambda^2}{L(x)}$$

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

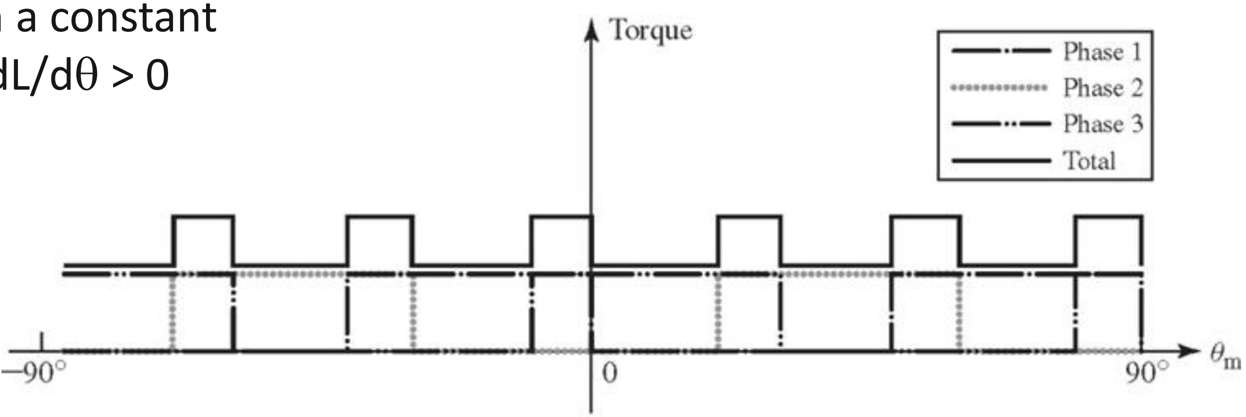
$$f^e = -\frac{1}{2} i^2 \frac{\partial}{\partial x} L(x)$$

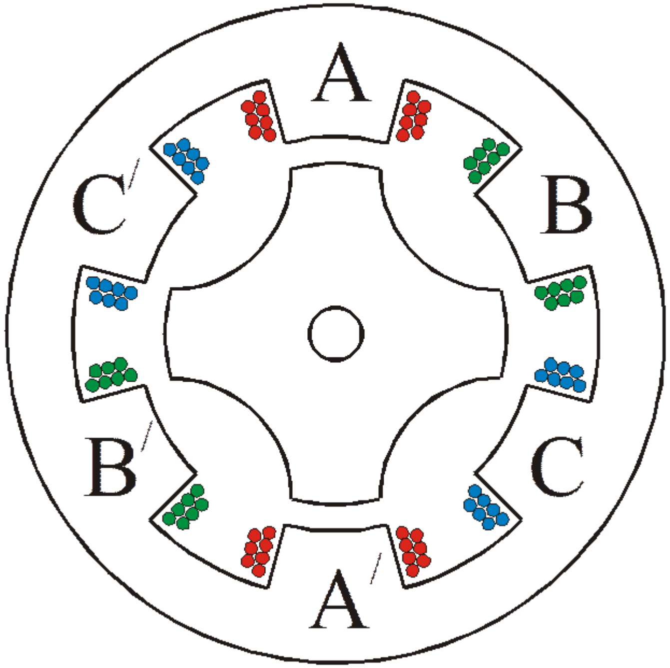


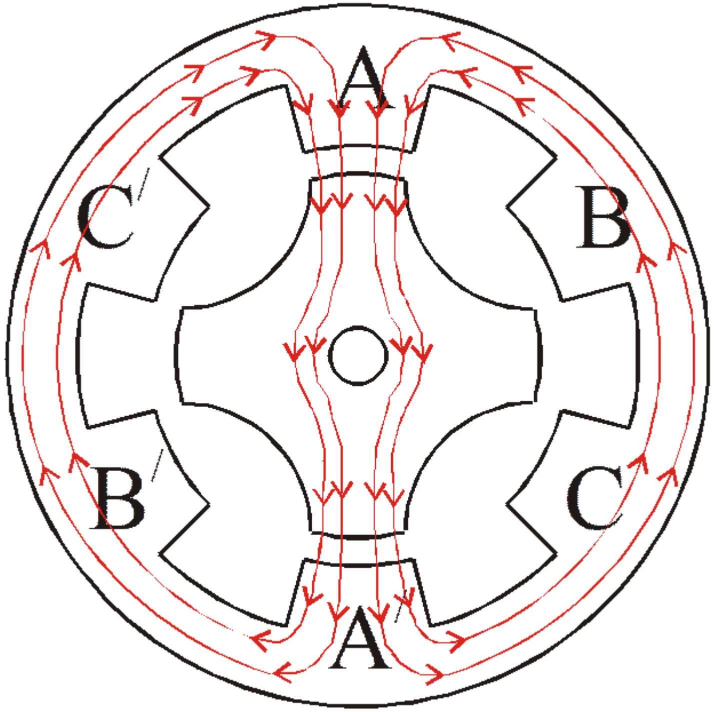


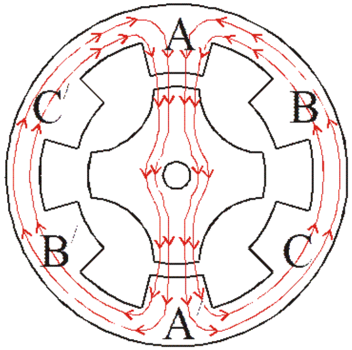


If each phase is excited with a constant current at positions where $dL/d\theta > 0$

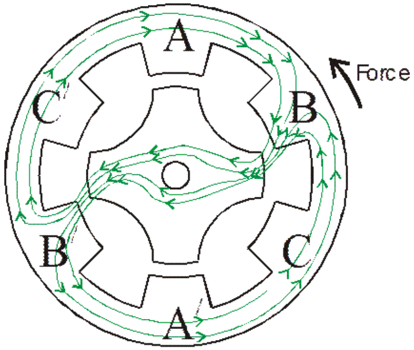



A
C'
B
B'
C
A'

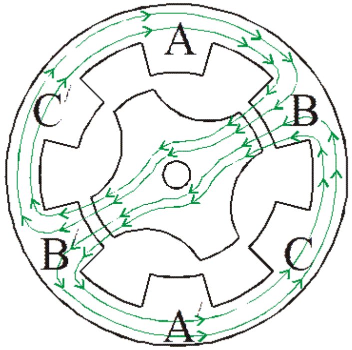

A
C'
B
B'
C
A'



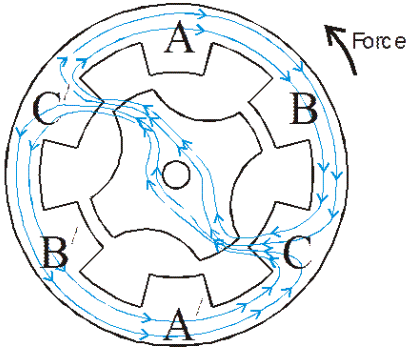
A) Phase A energized
Rotor at holding position



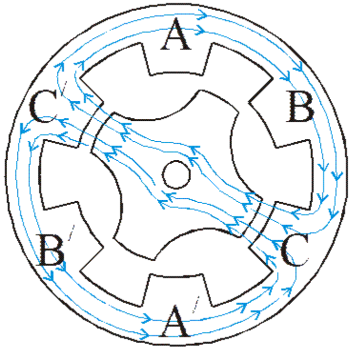
B) Phase B energized
Bent magnetic flux causes
the rotor to be pulled towards
B phase pole on stator



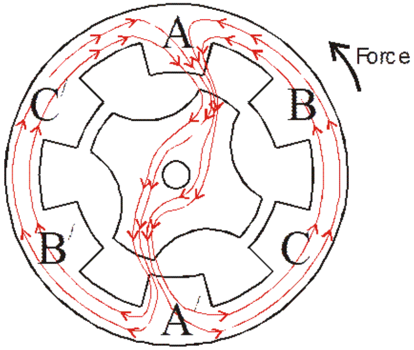
C) Phase B energized
Rotor at holding position



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

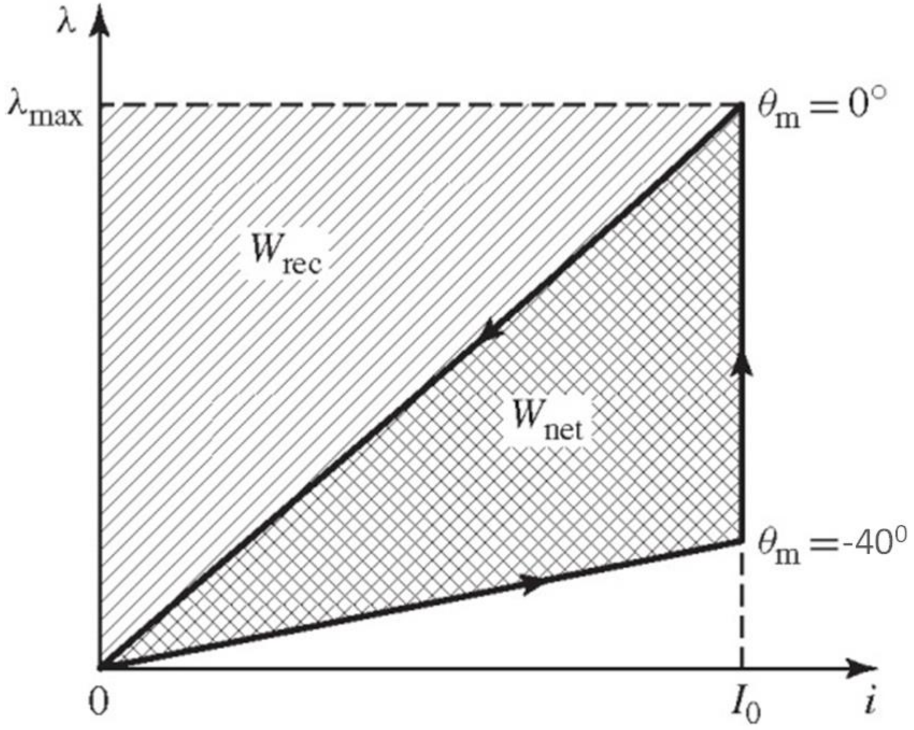
Power supply rating:

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

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

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

Where T is the length of one step (s)



Electrical Machine Design

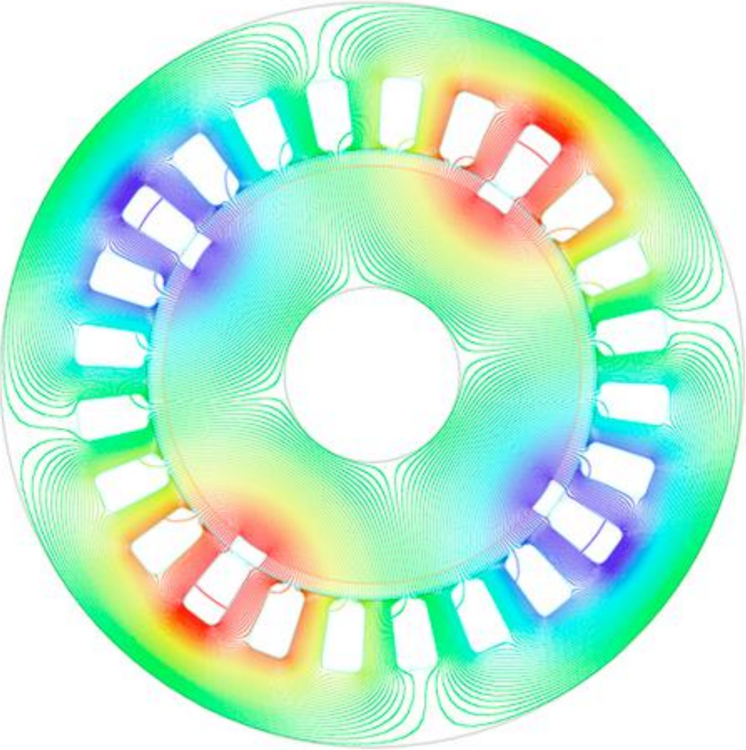
- Electrical machine design is a mix of art & science, in contrast to modeling and analysis
- Many design parameters and trade-offs across different domains (electromagnetics, mechanical, thermal, controls, materials, economics, etc.)
- No unique solution, and difficult to set up as an ‘inverse problem’ 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)

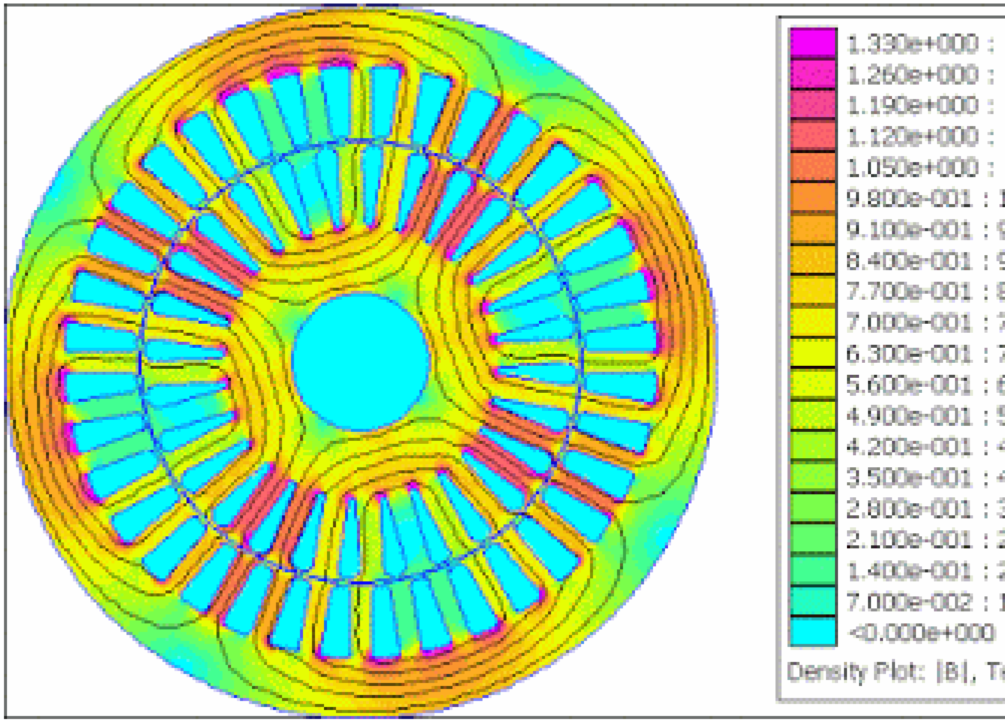
Design Constraints

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





http://www.electric-vehiclenews.com

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: Permendur, Hiperco, 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

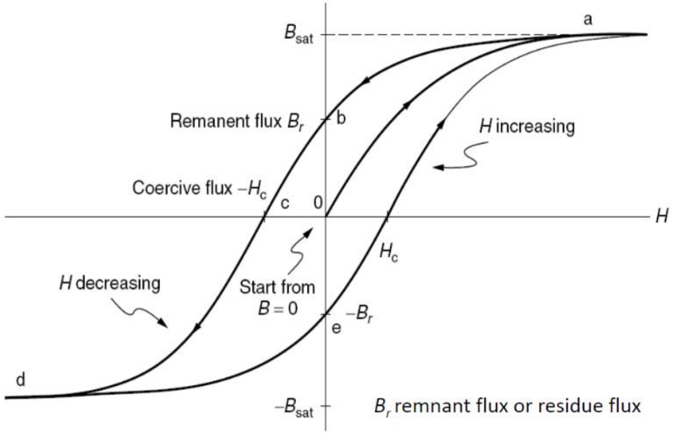
Magnetic materials

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:

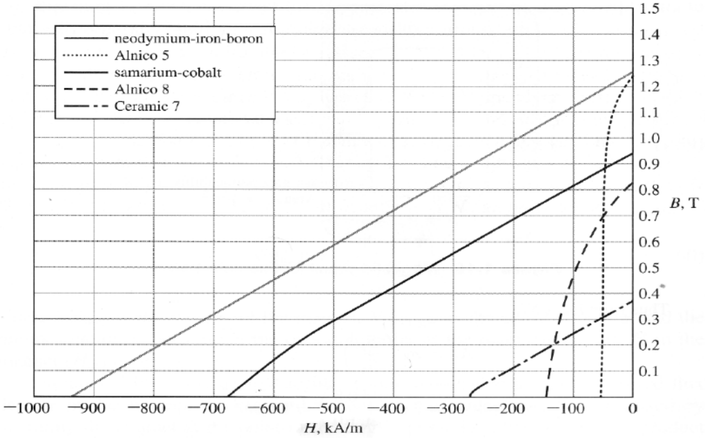
High energy density, low temperature sensitivity, 'resistant' to demagnetization, high electrical resistivity,



B_r remnant flux or residue flux

H_c coercive flux or coercivity

Soft Magnetic Material



Hard Magnetic Materials

Conducting materials

Desirable properties a good conductor should possess are listed below.

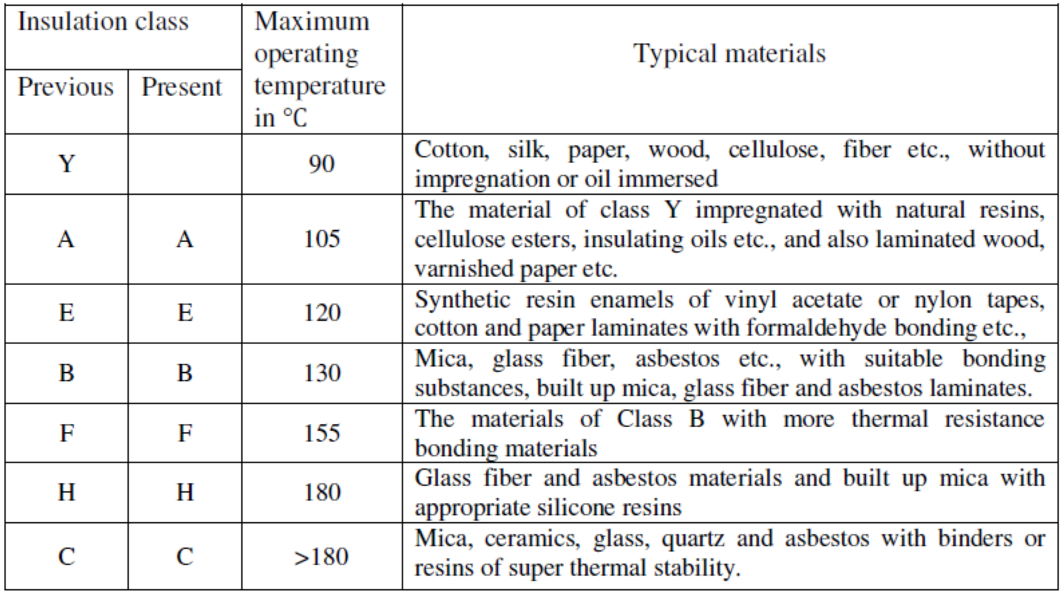
- Low value of resistivity or high conductivity
- Low value of temperature coefficient of resistance
- Highly malleable and ductile, High tensile strength
- High resistance to corrosion
- Allow brazing, soldering or welding so that the joints are reliable
- Low cost

	Copper	**Aluminum**
Resistivity at 200^{o}C	0.0172 ohm / m/ mm^2	0.0269 ohm/m/mm^2
Conductivity at 200^{o}C	58.14 x 106S/m	37.2 x 106S/m
Density at 200^{o}C	8933 kg/m^3	2689.9 kg/m3
Temperature coefficient (0-100^{o}C)	0.393 % per ^{o}C	0.4 % per ^{o}C
Coefficient of linear expansion (0-100^{o}C)	16.8x10-6 per ^{o}C	23.5x10-6 per oC
Tensile strength	25 to 40 kg / mm^2	10 to 18 kg / mm^2
Mechanical property	highly malleable and ductile	not as good
Thermal conductivity (0-100^{o}C)	599 W/m ^{o}C	238 W/m ^{o}C
Joining	easily soldered	

Insulating Materials

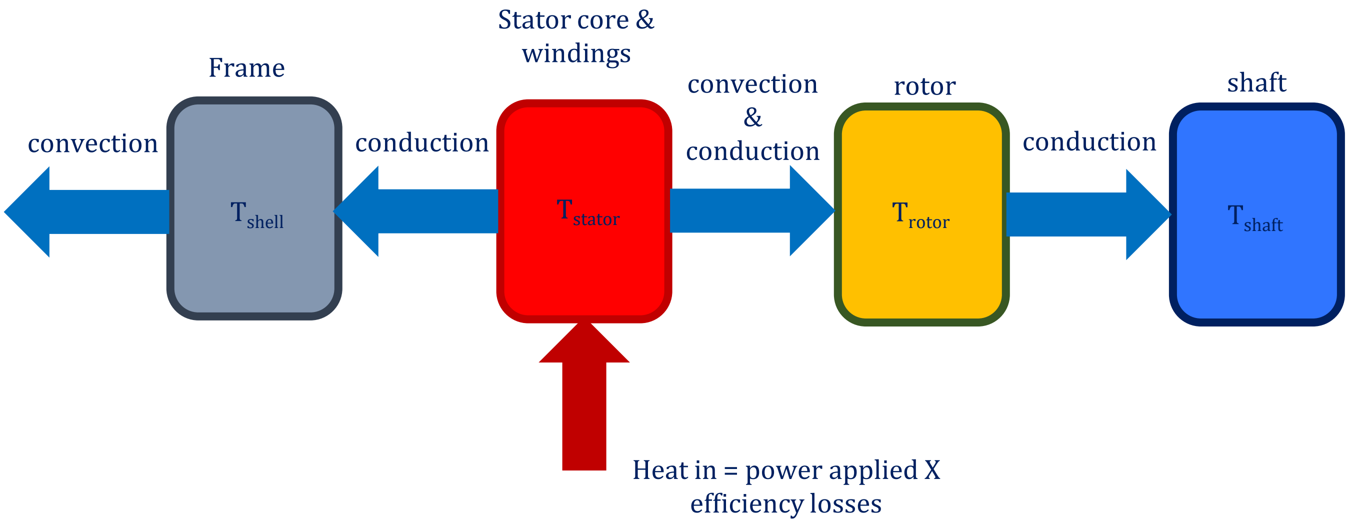
An ideal insulation material should possess the following properties:

- 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)



Insulation class		Maximum operating temperature in °C	Typical materials
Previous	Present		
Y		90	Cotton, silk, paper, wood, cellulose, fiber etc., without impregnation or oil immersed
A	A	105	The material of class Y impregnated with natural resins, cellulose esters, insulating oils etc., and also laminated wood, varnished paper etc.
E	E	120	Synthetic resin enamels of vinyl acetate or nylon tapes, cotton and paper laminates with formaldehyde bonding etc.,
B	B	130	Mica, glass fiber, asbestos etc., with suitable bonding substances, built up mica, glass fiber and asbestos laminates.
F	F	155	The materials of Class B with more thermal resistance bonding materials
H	H	180	Glass fiber and asbestos materials and built up mica with appropriate silicone resins
C	C	>180	Mica, ceramics, glass, quartz and asbestos with binders or resins of super thermal stability.

Thermal Management



convection

Frame

T_{shell}

conduction

Stator core & windings

T_{stator}

convection & conduction

rotor

T_{rotor}

conduction

shaft

T_{shaft}

Heat in = power applied X efficiency losses

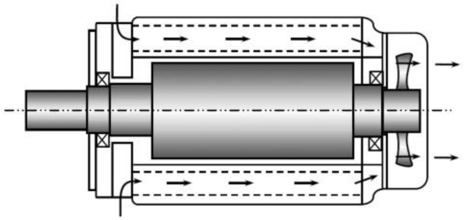


FIGURE 8.23
Open ventilating cooling system with sucked air forcing through stator cooling channels. In this design, a rotor fan is mounted at the nondrive end.

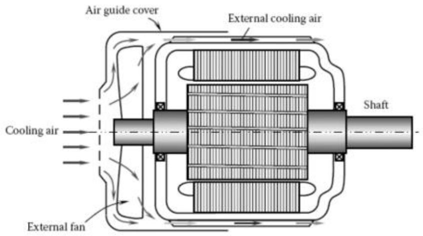


FIGURE 8.31
Cooling air is blown over the totally enclosed motor surface along axial plate fins by an external fan mounted on the shaft. No internal fan is used.

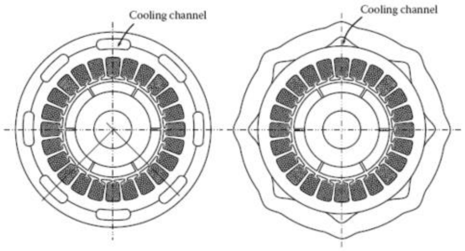


FIGURE 8.24
Arrangement of air cooling channels between the stator core and the motor housing.

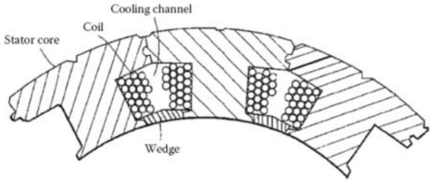
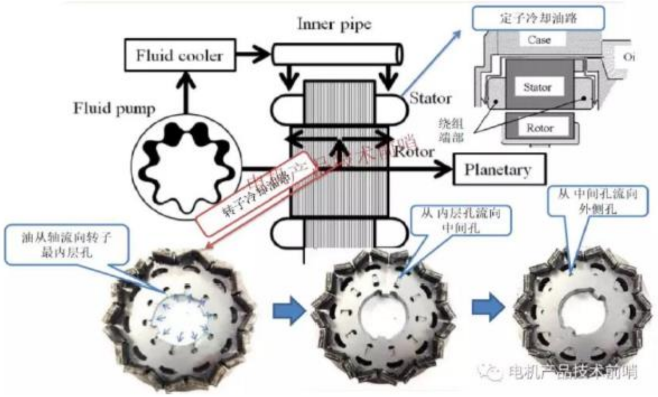


FIGURE 8.27
Cooling channels formed between stator winding coils (U.S. Patent 6,713,927) [8.34]. (Courtesy of the U.S. Patent and Trademark Office, Alexandria, VA.)

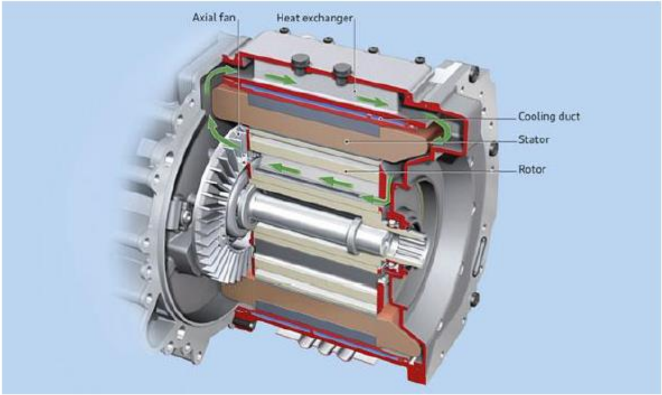
Cooling Systems

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

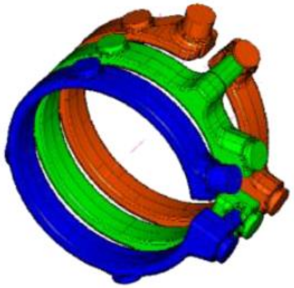
1) Water jacket, e.g. Nissan Leaf, BMW i3
2) Water jacket + Internal Air, e.g. Zytek traction machine, BMW 2225xe series
3) Oil spray cooling, e.g. Toyota Prius



3)



2)



1)