

PM motor design with FEMM and Lua scripting

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- Meshing and solving
- Post-processing
- Use of the Lua script

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- No load operation
- Operation under load

Torque

- Torque ripple reduction

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- 2 Introduction to Permanent Magnet Motors**
- 3 Magnetic Analysis of PM Motors**
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FEMM (Finite Element Method Magnetics)

- it is very easy to be used,
- it is organized so as to easily understand how a finite element method works,
- it is freeware, so that anyone can download it and use it.

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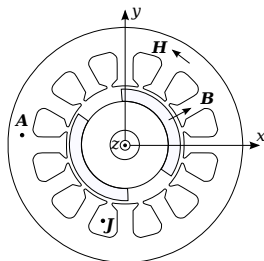
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In a 2D field problem

- current density $\mathbf{J} = (0, 0, J_z)$
- vector magnetic potential $\mathbf{A} = (0, 0, A_z)$
- magnetic field strength $\mathbf{H} = (H_x, H_y, 0)$
- flux density $\mathbf{B} = (B_x, B_y, 0)$



Motor section in the plane (x, y) .

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The first step is to define the problem:

- **Type:** select a planar symmetry, i.e. the motor section is studied in the plane (x, y) ;
- **Units:** select the measure unity for drawing, e.g. millimeter;
- **Frequency:** select the frequency, e.g. equal to zero for magnetostatic analysis;
- **Depth:** select the length of the structure, along the z axis, normal to the plane (x, y) , e.g. $L_z=100$ mm.

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The steps of a finite element problem are

- **pre-processing**: preparing the field problem (using the editor `femme.exe`);
- **mesh**: subdivision of the domain in small elements (using `triangle.exe`);
- **solution**: solution of the field problem (using `fkn.exe`);
- **post-processing**: analysis of the field solution and computation of integral quantities (using the editor `femmview.exe`).

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- Drawing
 - points
 - segments
 - arcs
- Mark
 - labels
 - groups
- Properties
 - materials
 - boundary conditions
 - circuits

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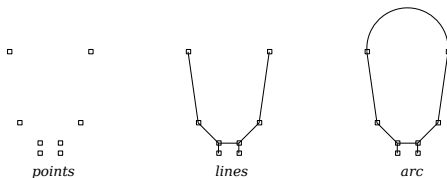
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- Points
- Segments
- Arcs



Example of drawing a stator slot.

Motor drawing

Stator drawing

Air gap drawing

Rotor drawing

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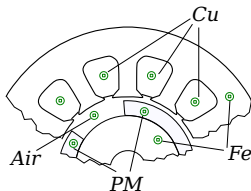
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Labels

- to give a name to the block;
- to assign the material properties, e.g. the electrical conductivity, and the relative magnetic permeability;
- to assign a current density to the block.



Label and material used.

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Stator Label

object	label
lamination stack	Fe
wedges	Air
slot no. 1	Cu1
slot no. 2	Cu2
slot no. 3	Cu3
...	...

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Stator Groups

object	label	group
lamination stack	Fe	1000
wedges	Air	1000
slot no. 1	Cu1	1001
slot no. 2	Cu2	1002
slot no. 3	Cu3	1003
...	...	...

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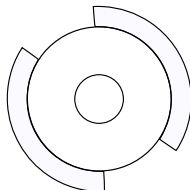
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Other Groups

object	label	group
air gap	Air	0
rotor	...	10



group = 10

Sketch of the rotor, as group 10.

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Four main boundary conditions

- **Dirichlet:** a given value of A_z along a line.
- **Neumann:** flux density lines normal to a line.
- **Periodic:** $A_{z,segment1} = A_{z,segment2}$.
- **Anti-periodic:** $A_{z,segment1} = -A_{z,segment2}$.

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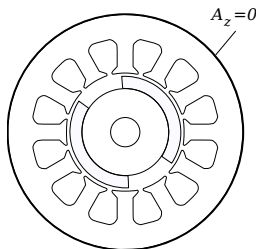
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How to do

- 1 A boundary condition $A_z = 0$ is defined in the problem.
- 2 The external lines are selected.
- 3 The boundary condition is assigned.



Boundary condition assigned along
the outer periphery of the stator.

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The material of the objects can be defined or selected from a given `Material Library`.

How to do

The appropriate material is assigned to the object:

- ① Fe is assigned to stator and rotor laminations,
- ② Cu is assigned to the stator slots,
- ③ NdFeB is assigned to the rotor PMs,
- ④ Air is assigned to the air spaces.

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Current

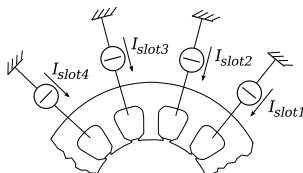
Stator currents are defined as "circuit"
ideal current source connected to one or more blocks.

I_{slot1} : current source connected to first slot,

I_{slot2} : current source connected to second slot,

I_{slot3} : current source connected to third slot,

... and so on.



External circuits connected to the coil sides

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Current density

An alternative is to assign a current density to the various materials, e.g. to materials of the stator slots.

The peak value of current density in the slot is defined as

$$\hat{J}_{slot} = k_{fill} \sqrt{2} J_C$$

With $k_{fill} = 0.4$,
With $J_C = 6 \text{ Arms/mm}^2$
It is $\hat{J}_{slot} = 3.4 \text{ A/mm}^2$.

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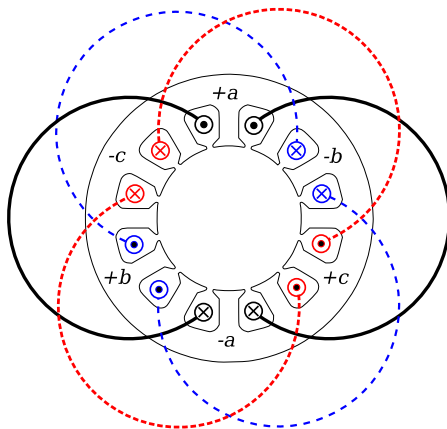
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Classical representation of the stator winding

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Slot matrix

- Matrix dimension is $m \times Q$
- The generic element k_{jq} indicates the how much the q -th slot is filled by conductors of the j -th phase.
- $k_{jq} = 1$ means that the q -th slot is completely filled by conductors of the j -th phase;
- $k_{jq} = 0.5$ means that only 50% of the q -th slot is filled by conductors of the j -th phase;
- $k_{jq} = 0$ means that no conductor of the j -th phase is within the q -th slot.
- sign indicates the direction.

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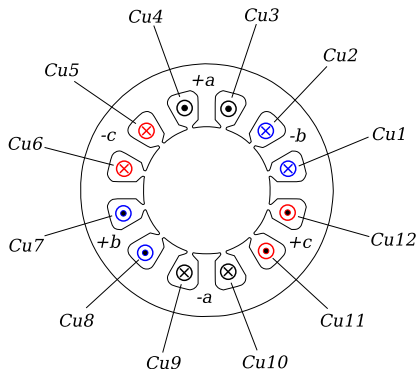
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Definition of the labels of the stator slots.

Slots Matrix

q	1	2	3	4	5	6	7	8	9	10	11	12
a	0	0	1	1	0	0	0	0	-1	-1	0	0
b	-1	-1	0	0	0	0	1	1	0	0	0	0
c	0	0	0	0	-1	-1	0	0	0	0	1	1

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Current assignment

The current in the q -th slot can be expressed as

$$I_{slot,q} = n_c (k_{a,q} I_a + k_{b,q} I_b + k_{c,q} I_c)$$

where

q	1	2	3	4	5	6	7	8	9	10	11	12
$k_a =$	0	0	1	1	0	0	0	0	-1	-1	0	0
$k_b =$	-1	-1	0	0	0	0	1	1	0	0	0	0
$k_c =$	0	0	0	0	-1	-1	0	0	0	0	1	1

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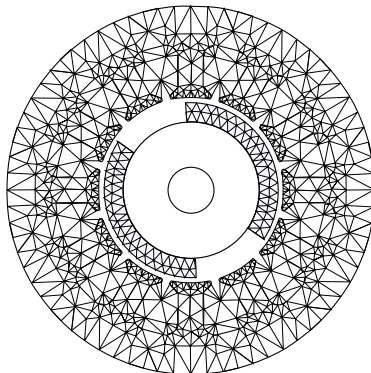
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Mesh of the structure

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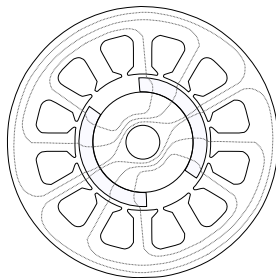
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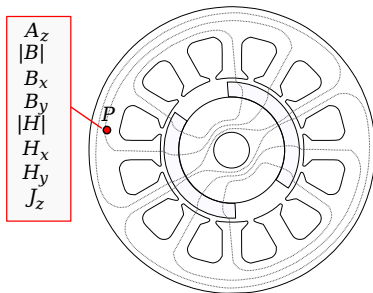
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Flux lines of the solved structure



Electric and magnetic quantities detected in the point P of the solved structure.

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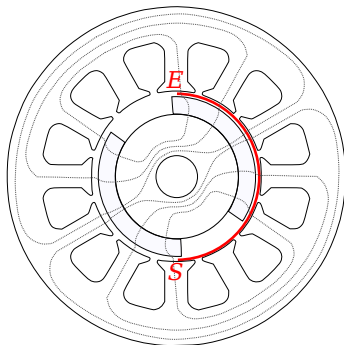
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$$\Phi = L_z \int_{line} B_n dl$$



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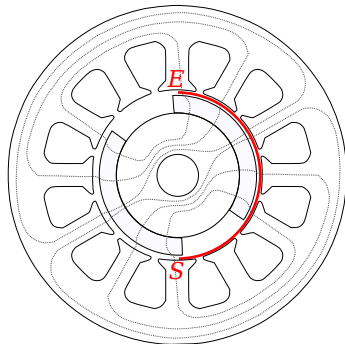
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Magnetic flux computation from a line integration.

$$\Phi = L_z \cdot (A_{z,S} - A_{z,E})$$



Magnetic flux from magnetic vector potential

$$\int_S \mathbf{B} \cdot \mathbf{n} dS = \int_S \text{curl} \mathbf{A} \cdot \mathbf{n} dS = \oint_{l_S} \mathbf{A} \cdot \mathbf{t} dl$$

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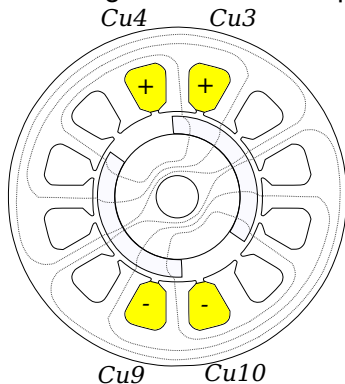
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Slots containing the coil sides of phase *a*



$$A_z \longrightarrow \frac{1}{S_{slot}} \int_{S_{slot}} A_z dS$$

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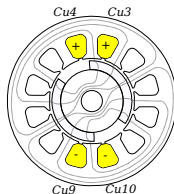
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$$\Lambda_a = n_c L_z \frac{1}{S_{slot}} \left(\begin{aligned} &+ \int_{S_{slot,3}} A_z dS \\ &+ \int_{S_{slot,4}} A_z dS \\ &- \int_{S_{slot,9}} A_z dS \\ &- \int_{S_{slot,10}} A_z dS \end{aligned} \right)$$

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Using the slot matrix

q	1	2	3	4	5	6	7	8	9	10	11	12
$k_a =$	0	0	1	1	0	0	0	0	-1	-1	0	0
$k_b =$	-1	-1	0	0	0	0	1	1	0	0	0	0
$k_c =$	0	0	0	0	-1	-1	0	0	0	0	1	1

$$\Lambda_a = n_c L_z \frac{1}{S_{slot}} \sum_{q=1}^Q \int_{S_{slot,q}} k_{a,q} A_z dS$$

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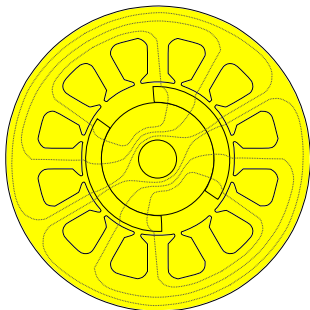
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The whole structure is selected

The magnetic energy

$$W_m = L_z \int_{S_{all}} \left(\int H dB \right) dS$$

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The magnetic energy

$$W_m = L_z \int_{S_{all}} \left(\int H dB \right) dS$$

The magnetic coenergy

$$W'_m = L_z \int_{S_{all}} \left(\int B dH \right) dS$$

The integral of $\mathbf{A} \cdot \mathbf{J}$

$$W_{AJ} = L_z \int_{S_{all}} A_z J_z dS$$

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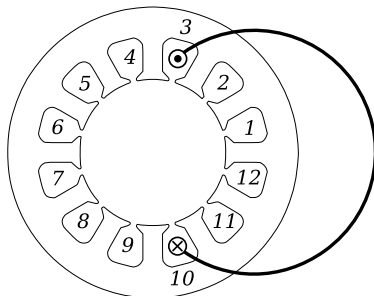
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The aim is to modify the current flowing in the coil, whose sides are in the slots 3 and 10.



Coil sides in slot 3 and slot 10.

The geometrical data

```
S_slot = 36.8 -- (mm2)
k_fill = 0.4
J_c = 6 -- (A/mm2)
J_slot = k_fill * sqrt2 * J_c
I_max = S_slot * J_slot
```

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Current value

$$I_{\text{slot}} = I_{\text{max}} * (n / N_{\text{sim}})$$

Current assignment to slot 3 and slot 10

```
modifycircprop("Islot", 3, +I_slot)
modifycircprop("Islot", 10, -I_slot)
analyse()
```

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For given current

$I_a = +4$ -- current of the a-phase

$I_b = -2$ -- current of the b-phase

$I_c = -2$ -- current of the c-phase

Using the slot matrix, the computation of the current in the q -th slot becomes

$$I_{\text{slot}[q]} = k_a[q] * I_a + k_b[q] * I_b + k_c[q] * I_c$$

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Starting from d - and q -axis values

$I_d = -3$ -- I_d is the d -axis current

$I_q = +4$ -- I_q is the q -axis current

the $dq \rightarrow abc$ transformation is used

```
Ia = Id*cos(thetame) - Iq*sin(thetame)
Ib = (-Id/2 - Iq*sqrt(3)/2) * cos(thetame)
    + (-Id*sqrt(3)/2 + Iq/2) * sin(thetame)
Ic = (-Id/2 + Iq*sqrt(3)/2) * cos(thetame)
    + (+Id*sqrt(3)/2 + Iq/2) * sin(thetame)
```

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This is an alternative to assign the current.

After computing the current density

```
Islot = ka[q]*Ia + kb[q]*Ib + kc[q]*Ic  
Jslot = Islot / S_slot
```

it is assigned to the slot block

```
modifymaterial("Cu" .. q, 4, Jslot)
```

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Slot cross area (slot 3):

```
groupselectblock(1003)  
Sup = blockintegral(5)  
clearblock()
```

Integral of A_z (slot 3):

```
groupselectblock(1003)  
intA3_r, intgA3_i = blockintegral(1)  
clearblock()
```

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After selecting the whole domain

```
groupselectblock()
```

magnetic energy, coenergy, integral of $\mathbf{A} \cdot \mathbf{J}$ are computed:

```
Energy = blockintegral(2)  
Coenergy = blockintegral(17)  
AJ_intgr = blockintegral(0)
```

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The rotor configurations

- SPM rotor,
- inset rotor,
- IPM rotor.

Four-pole 24-slot motors.

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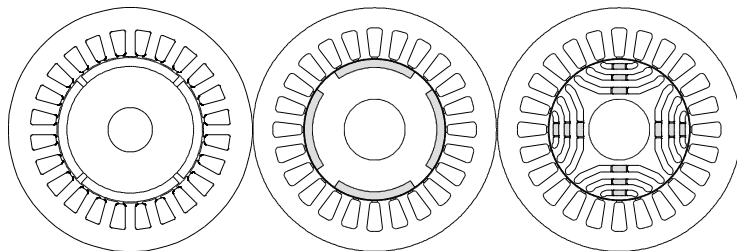
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The rotor configurations

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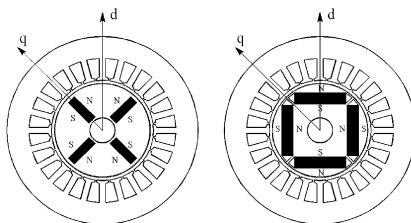
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Direction of the magnetization of the PMs

- tangentially magnetized PMs,
- radially magnetized PMs.



... with two or more flux-barriers per pole.

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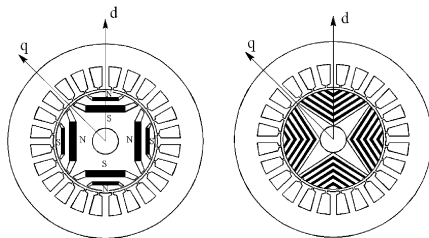
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IPM motor with
(a) two flux-barriers per pole, and
(b) axially laminated rotor.

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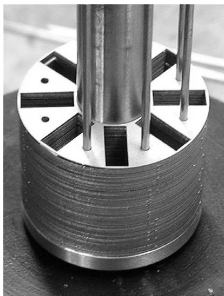
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(a) IPM rotor with tangentially magnetized PMs,
(b) an IPM motor and laminations with radially
magnetized PMs.

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Two main types of magnetic materials

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The soft magnetic materials

are easily magnetized and demagnetized, and they are used to carry magnetic flux.

The hard magnetic materials

are hardly magnetized and demagnetized, and they are generally referred to as permanent magnets.

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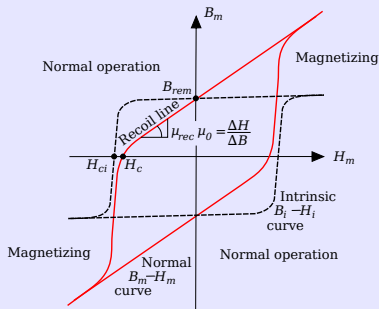
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Hard magnetic material hysteresis loop and characteristic parameters.



The PMs are magnetized in quadrant I (or III) and operate in quadrant II (or IV). Properties and performance characteristics are described on quadrant II.

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Two important quantities associated with the demagnetization curve

- residual flux density (or remanence) B_{rem} ,
- the coercive force H_C .

PMs are designed to operate on the linear part of the demagnetization curve, between B_{rem} and H_C .

The differential relative magnetic permeability

of the recoil line is labelled μ_{rec} and is slightly higher than unity.

RecoilLine

$$B_m = B_{rem} + \mu_{rec}\mu_0 H_m$$

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Demagnetization

When the flux density becomes lower than B_{knee} the PM is demagnetised and it exhibits lower flux density versus field strength.

This means that the PM is “irreversibly” demagnetized (in the sense that it requires a new process of magnetization).

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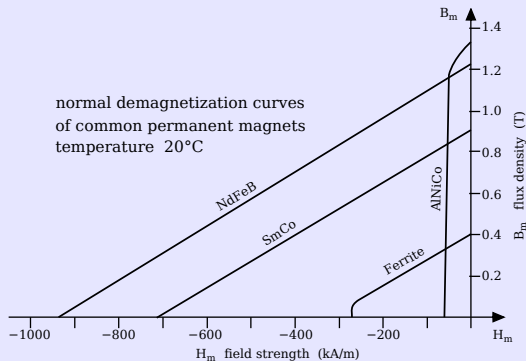
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Demagnetization curves of common PM materials.



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Main properties of hard magnetic material

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Main properties of PMs

	B_{rem} (T)	H_c (kA/m)	T_{max} (°C)	$\{B_m H_m\}_{max}$ (kJ/m ³)	$\Delta B_{rem} / \Delta T$ (%/°C)
Ferrite	0.38	250	300	30	-0.20
AlNiCo	1.20	50	540	45	-0.02
SmCo	0.85	570	250	140	-0.04
NdFeB	1.15	880	180	260	-0.12

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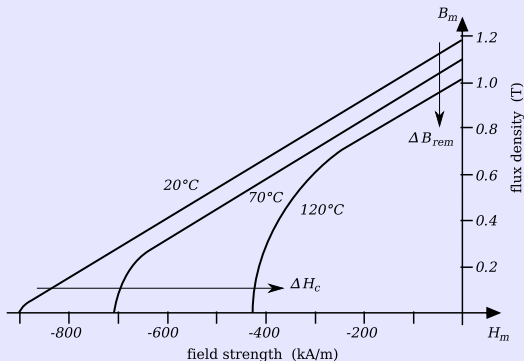
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Effect of the temperature on PM demagnetization curve.



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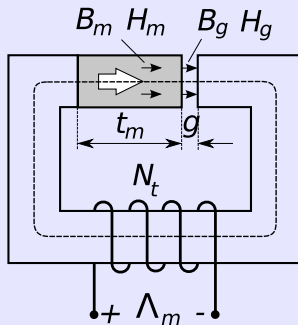
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Ampere law

$$H_m t_m + H_g g = 0$$

Gauss law

$$\Phi = B_m A_m = B_g A_g$$

together the two constitutive equations of air and PM.

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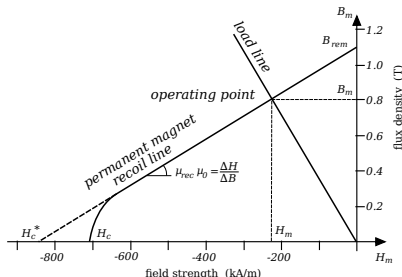
- Torque ripple reduction

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The load line

$$B_m = - \left(\mu_0 \frac{t_m}{g} \frac{A_g}{A_m} \right) H_m$$

The operating point of the PM is determined as the intersection of the PM demagnetization curve and the load line.



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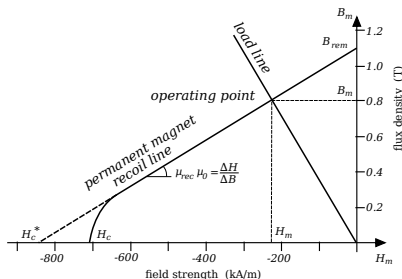
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Flux density under load

$$B_m = B_{rem} \frac{1}{1 + \frac{\mu_{rec} g}{t_m} \frac{A_m}{A_g}}$$



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Load line

$$B_m = - \left(\mu_0 \frac{t_m}{g} \frac{A_g}{A_m} \right) H_m + \mu_0 \frac{A_g}{A_m} \frac{N_t I}{g}$$

The load line remains a straight line, but it is translated along the H_m axis of a quantity ΔH_i proportional to the current.

It should be verified that the minimum flux density is not below the knee of the PM demagnetizing curve, where an irreversible demagnetization of the PM occurs.

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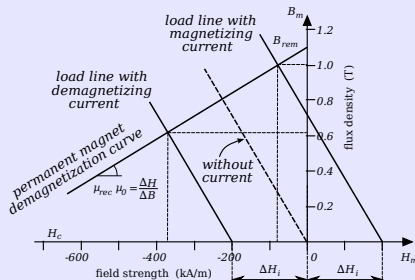
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PM operating point with current.



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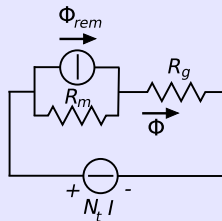
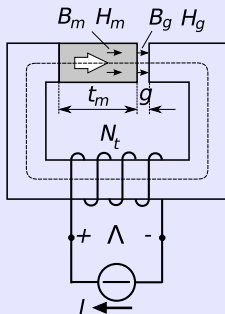
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Magnetic circuit and equivalent magnetic network.



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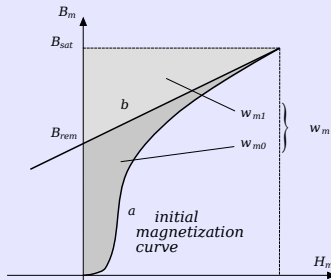
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Magnetic energy density in PM

$$w_m = \int_0^{B_m} H_m dB_m$$

BH characteristic and energy density of a hard magnetic material



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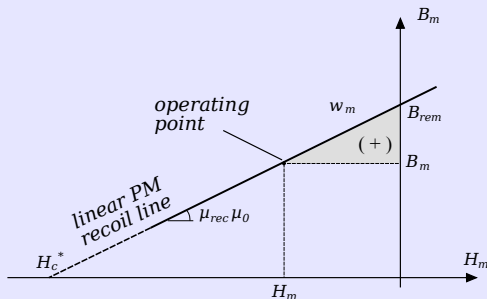
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Operating point and corresponding energy density



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Magnetic Energy Computation for Energy Conversion Aim

$$w_m = \frac{1}{2\mu_{rec}\mu_0} (B_{rem} - B_m)^2 = \frac{1}{2}\mu_{rec}\mu_0 H_m^2$$

Magnetic coenergy

$$w'_m = \int_0^{H_m} B_m dH_m$$

that is a negative coenergy.

Magnetic coenergy

$$w'_m = \int_{H_C^*}^{H_m} B_m dH_m$$

that is a positive coenergy.

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The difference between the coenergy density

$$\int_{H_c^*}^{H_m} B_m dH_m - \int_0^{H_m} B_m dH_m = \frac{1}{2} H_c^* B_{rem}$$

is a constant quantity.

The change of the magnetic coenergy is the same with the two calculation procedures.

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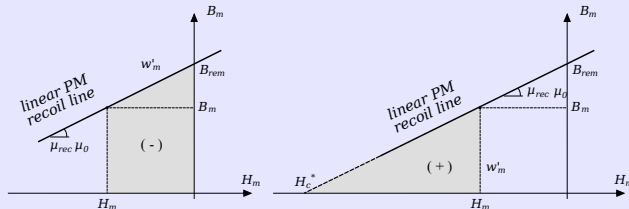
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Operating point and magnetic coenergy density



If the linear recoil line is adopted

$$w'_m = \frac{1}{2} \mu_{rec} \mu_0 (H_m - H_c^*)^2 = \frac{1}{2 \mu_{rec} \mu_0} B_m^2$$

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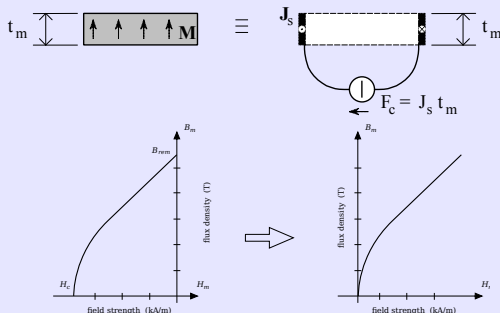
Others

PM approximated by a current-source coils

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A PM can be represented by an equivalent distribution of current density



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References

- The stator reference frame is characterized by the a -, b -, and c -axis (or the equivalent α - β reference frame).
- The rotor reference frame is characterized by the d - and q -axis.
- The relative position between the rotor and the stator reference frames is individuated by the electrical angle ϑ_m^e .

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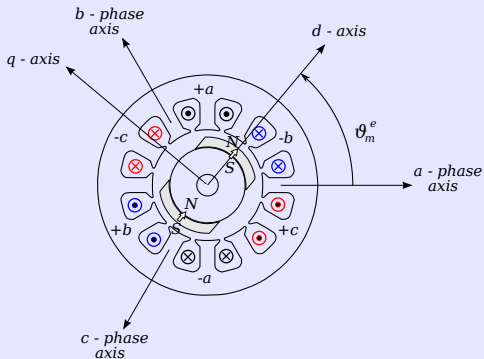
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Reference frames



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Space vector in stator reference frame

$$\vec{i}_s^s = i_a + i_b e^{j2\pi/3} + i_c e^{j4\pi/3}$$

or

space vector $\vec{i}_s^s = i_{s,\alpha}^s + j i_{s,\beta}^s$

$$i_{s,\alpha}^s = i_a - \frac{1}{2}i_b - \frac{1}{2}i_c$$

$$i_{s,\beta}^s = \frac{\sqrt{3}}{2}(-i_b + i_c)$$

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Space vector in rotor reference frame

$$\vec{i}_s^r = \vec{i}_s^s e^{-j\vartheta_m^e}$$

or

Space vector $\vec{i}_s^r = i_{sd} + j i_{sq}$

$$i_{sd} = i_{s,\alpha}^s \cos(\vartheta_m^e) + i_{s,\beta}^s \sin(\vartheta_m^e)$$

$$i_{sq} = -i_{s,\alpha}^s \sin(\vartheta_m^e) + i_{s,\beta}^s \cos(\vartheta_m^e)$$

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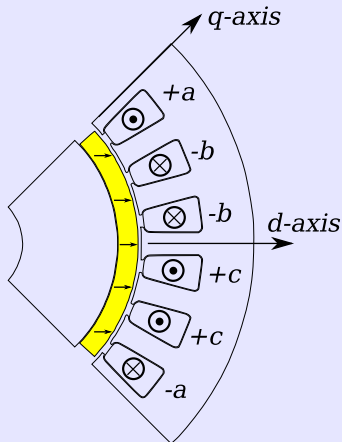
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Geometry of one pole of the SPM motor



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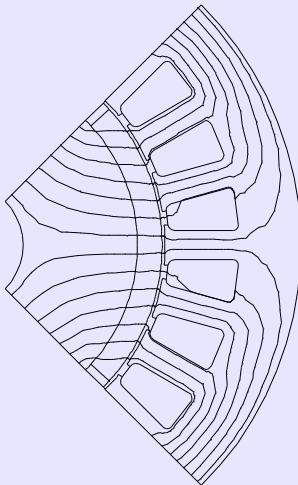
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Flux lines



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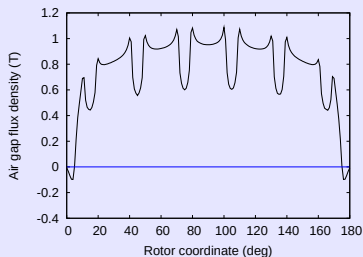
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Flux density distribution



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Flux linkages

$$\Lambda_a = n_c L_{stk} \sum_{q=1}^{Q_s} k_{a,q} \frac{1}{S_{slot}} \int_{S_{slot}} A_z dS$$

$$\Lambda_b = n_c L_{stk} \sum_{q=1}^{Q_s} k_{b,q} \frac{1}{S_{slot}} \int_{S_{slot}} A_z dS$$

$$\Lambda_c = n_c L_{stk} \sum_{q=1}^{Q_s} k_{c,q} \frac{1}{S_{slot}} \int_{S_{slot}} A_z dS$$

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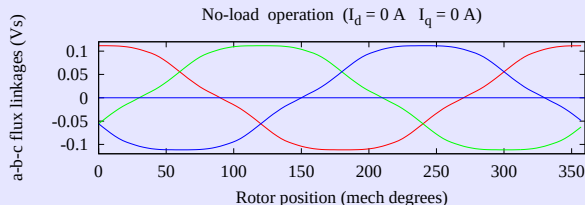
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Flux linkages versus rotor position



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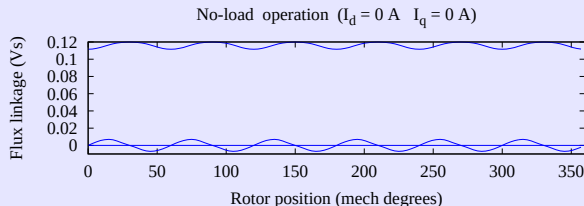
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The d - and q -axis flux linkages versus rotor position.



PM flux linkage

At no-load there is only d -axis flux linkage, while the q -axis flux linkage is equal to zero.

Therefore, at no load, the PM flux linkage is $\Lambda_m = \Lambda_d$.

Analytical estimation

$$\Phi = B_g \frac{\pi D L_{stk}}{2p}$$

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Computation of the voltage under load

Assuming a constant mechanical speed ω_m (i.e. electrical speed $\omega = p\omega_m$):

$$e(t) = \frac{d\lambda(t)}{dt} = \frac{d\lambda(\vartheta_m^e)}{d\vartheta_m^e} \omega$$

It is more convenient:

- to express the flux linkage waveform by means of its Fourier series expansion.
- Then, each harmonic of the series is derived, and then all harmonics of EMF are summed together.
- The final EMF waveform is achieved.

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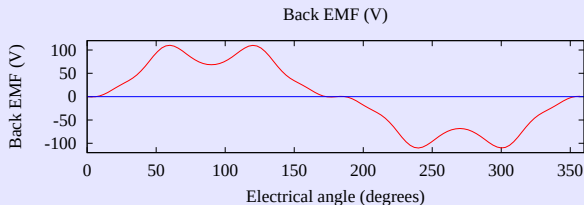
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No load phase EMF



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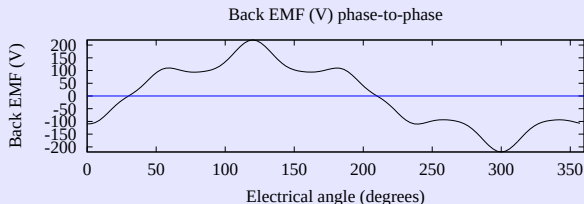
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No load phase-to-phase EMF



A simple code to achieve the Fourier serie expansion is as follows

```
for n = 1 : Nharmo,
A(n) = 0;
B(n) = 0;
for tt = 1 : Ntheta,
A(n) = A(n) + 2/Ntheta * Flink(tt) *
cos(n*thetae(tt)*pi/180);
B(n) = B(n) + 2/Ntheta * Flink(tt) *
sin(n*thetae(tt)*pi/180);
C(n) = sqrt(A(n)^2 + B(n)^2);
F(n) = atan2(B(n), A(n));
end;
end;
```

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The EMF waveform is achieved as

```
w = 300;  
for tt = 1: Ntheta;  
EMF(tt) = 0;  
for n = 1 : Nharmo,  
Ce(n) = n * C(n);  
EMF(tt) = EMF(tt) + w * Ce(n) *  
sin(n*thetae(tt)*pi/180 + F(n));  
end;  
end;
```

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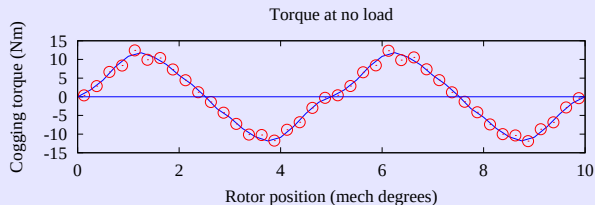
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Cogging torque versus rotor position



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Before starting the analysis under load

it is mandatory to adopt the correct reference.

This means to know the correct position of the rotor with respect the stator reference frame.

How to position the rotor in phase with the stator

The reference position between the rotor and the stator is when the d -axis (i.e., the rotor reference axis) is parallel with the a -phase axis (i.e., the stator reference axis).

When the rotor is in such a position, $\vartheta_m^e = 0$.

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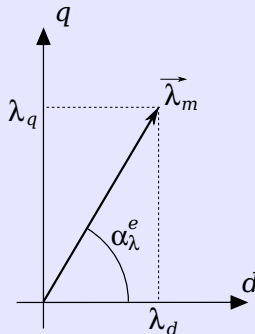
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Flux linkage space vector and its components



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If $\alpha_{\lambda}^e=0$, then the rotor is in phase with the stator, otherwise the rotor has to be rotated of a mechanical angle corresponding to the electrical angle of the flux linkage vector, that is:

$$\vartheta_m = -\frac{\alpha_{\lambda}^e}{p}$$

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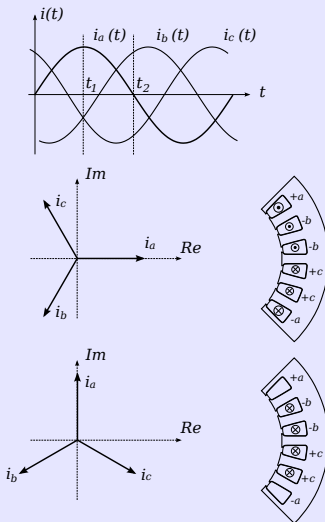
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Three phase current



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Time instant t_1

$$\begin{aligned}i_a(t_1) &= \hat{I} \\i_b(t_1) &= -\hat{I}/2 \\i_c(t_1) &= -\hat{I}/2\end{aligned}$$

Time instant t_2

$$\begin{aligned}i_a(t_2) &= 0 \\i_b(t_2) &= \sqrt{3}\hat{I}/2 \\i_c(t_2) &= -\sqrt{3}\hat{I}/2\end{aligned}$$

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d -axis stator current

- A positive d -axis current is magnetizing, increasing the flux produced by the PM.
- Conversely a negative d -axis current is demagnetizing, since it weakens the PM flux.

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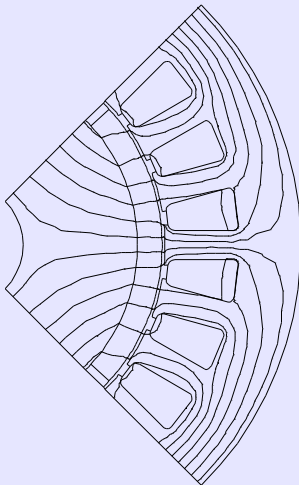
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Flux lines



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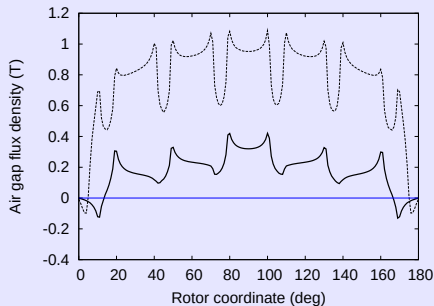
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Flux density distribution



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q -axis stator current

- The q -axis current induces a flux in quadrature to the flux due to the PM.
- Positive and negative q -axis current produces the same effect.

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No load operation

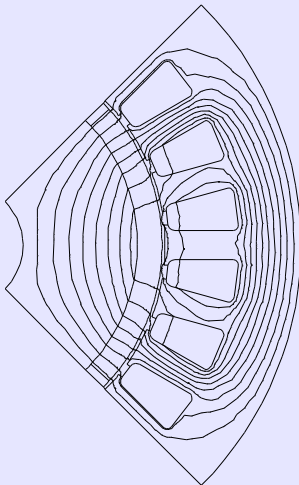
Operation under load

Torque

Torque ripple reduction

Others

Flux lines



FEM introduction

- Meshing and solving
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Magnetic Analysis

- No load operation

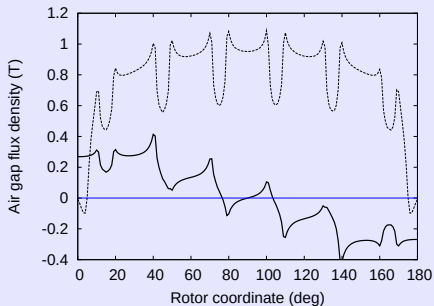
- Operation under load

Torque

- Torque ripple reduction

Others

Flux density distribution



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- No load operation

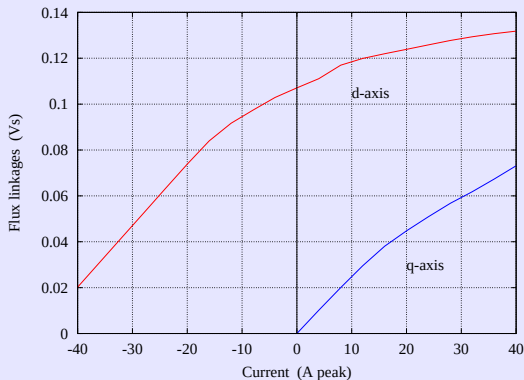
- Operation under load

Torque

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Others

d - and q -axis flux linkages versus current.



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- Torque ripple reduction

Others

d -axis inductance

$$L_d = \frac{\Lambda_d - \Lambda_m}{I_d}$$

q -axis inductance

$$L_q = \frac{\Lambda_q}{I_q}$$

saliency ratio

$$\xi = \frac{L_q}{L_d}$$

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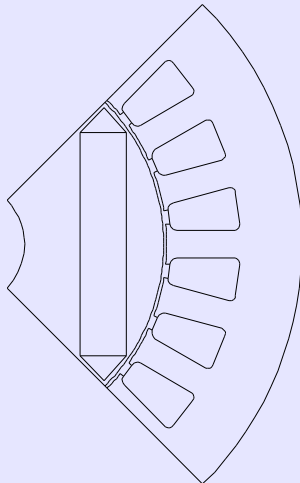
No load operation
Operation under load

Torque

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Others

Geometry



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Magnetic Analysis

- No load operation

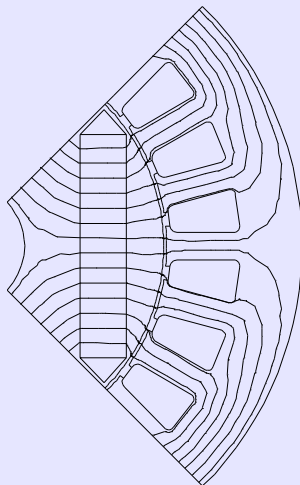
- Operation under load

Torque

- Torque ripple reduction

Others

Only PM



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- No load operation

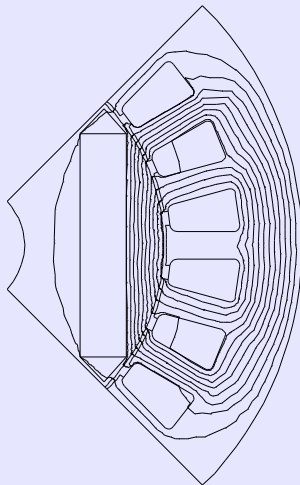
- Operation under load

Torque

- Torque ripple reduction

Others

only I_q



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- No load operation

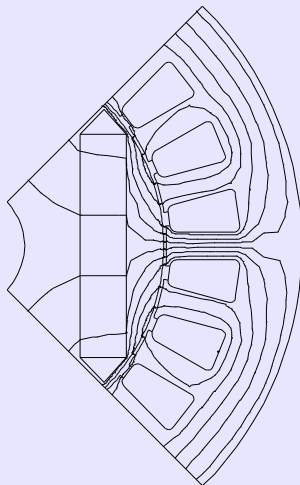
- Operation under load

Torque

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Others

only I_d



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Others

In the synchronous $d - q$ reference frame (which is rotating at the electrical angular speed ω), the d - and q -axis flux linkage components are given by

$$\begin{aligned}\lambda_d &= \Lambda_m + L_d i_d \\ \lambda_q &= L_q i_q\end{aligned}$$

The d - and q -axis voltage components

$$\begin{aligned}v_d &= R i_d + \frac{d\lambda_d}{dt} - \omega \lambda_q \\ v_q &= R i_q + \frac{d\lambda_q}{dt} + \omega \lambda_d\end{aligned}$$

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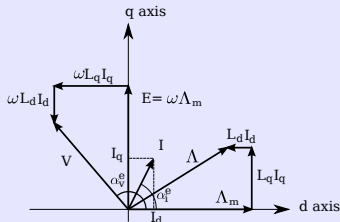
Others

Magnetic model of the PM synchronous motor

PM motor design
with FEMM and
Lua scripting

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Univ. Padova
Italy

Steady-state vector diagram in $d - q$ reference frame



FEM introduction

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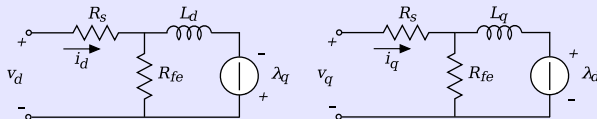
PM motor intro

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Equivalent circuit of PM synchronous motor



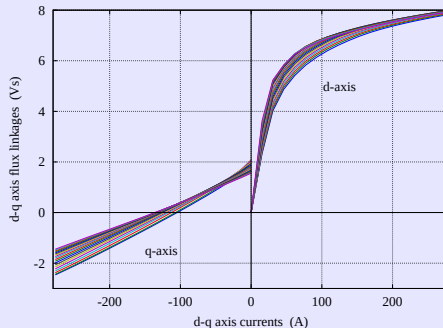
Torque

Torque ripple reduction

Others

in $d - q$ reference frame including iron losses resistance

Cross-saturation effect



$$\begin{aligned}\lambda_d &= \lambda_d(i_d, i_q) \\ \lambda_q &= \lambda_q(i_d, i_q)\end{aligned}$$

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The Electromechanical Torque

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Maxwell stress tensor

$$T_{Mxw} = \frac{D}{2} \int_{line} B_r \cdot H_t dl$$

directly from the field solution.

In the synchronous reference frame

$$T = \frac{3}{2}p(\lambda_d i_q - \lambda_q i_d) + \frac{\partial W'_m}{\partial \vartheta_m}$$

where W'_m is the magnetic coenergy, which must be considered as a state function of the state variables ϑ_m , i_d and i_q , i.e., $W'_m = W'_m(\vartheta_m, i_d, i_q)$

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The first term

$$T_{dq} = \frac{3}{2}p(\lambda_d i_q - \lambda_q i_d).$$

or

$$T_{dq} = \frac{3}{2}p(\vec{\lambda} \times \vec{i}).$$

where $\vec{\lambda} = \lambda_d + j\lambda_q$ and $\vec{i} = i_d + ji_q$
and $\times$ means the cross vector product.

It is independent of the particular reference frame.

It is not limited to the synchronous reference frame.

Therefore, it can be used in stationary and any other reference frame.

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The torque ripple is mainly described in the torque term expressed by $\frac{\partial W'_m}{\partial \vartheta_m}$.

The torque term T_{dq} is slightly affected by the harmonics of the flux linkages and it results to be suitable for the computation of the average torque.

In an ideal system,

the d - and q -axis flux linkages are constant, as well as the magnetic energy.

Therefore, the motor torque is constant and equal to T_{dq} .

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Others

When the stator currents are zero, it is $T_{dq}=0$.

Cogging torque

$$T_{cog} = \frac{\partial W'_m}{\partial \vartheta_m} = - \frac{\partial W_m}{\partial \vartheta_m}$$

Cogging torque is the ripple torque due to the interaction between the PM flux and the stator teeth.

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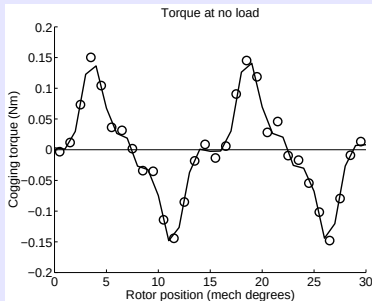
Others

Torque behavior at no load (cogging torque)

PM motor design
with FEMM and
LUA scripting

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Univ. Padova
Italy

SPM motor



Solid line: computation using Maxwell stress tensor,
Dashed line: using T_{dq} only, Circles: using $T_{dq} + \frac{\partial W'_m}{\partial \vartheta_m}$.

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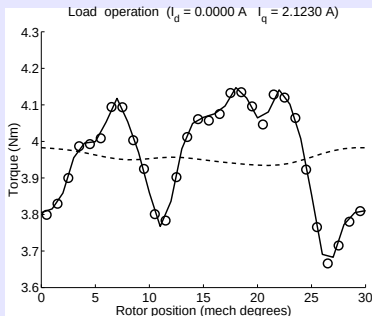
No load operation
Operation under load

Torque

Torque ripple reduction

Others

SPM motor



Solid line: computation using Maxwell stress tensor,

Dashed line: using T_{dq} only, Circles: using $T_{dq} + \frac{\partial W'_m}{\partial \theta_m}$.

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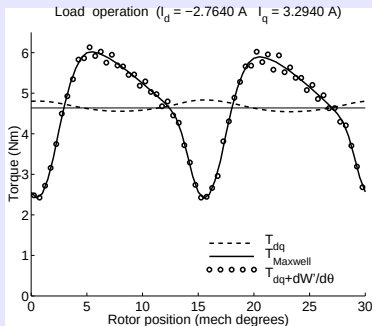
- No load operation
- Operation under load

Torque

- Torque ripple reduction

Others

IPM motor



Torque versus rotor position.

Torque behavior at $\hat{I} = 4.3$ A and $\alpha_i^e = 130$ deg.

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Magnetic Analysis

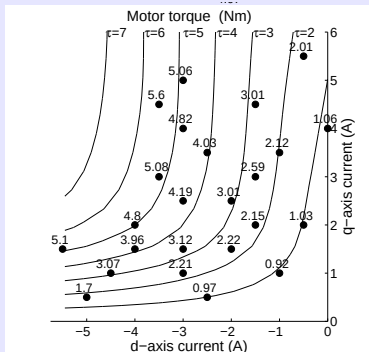
No load operation
Operation under load

Torque

Torque ripple reduction

Others

IPM motor



Torque maps.

Predicted T_{dq} and measured (dots) torque in (i_d, i_q) plane.

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Magnetic Analysis

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Operation under load

Torque

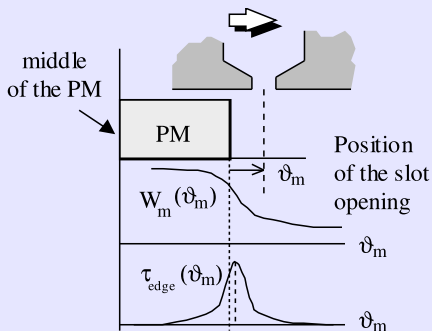
Torque ripple reduction

Others

Cogging torque phenomenon

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Lua scripting

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Univ. Padova
Italy



Simple model of the cogging torque mechanism, based on the superposition of PM edge torques τ_{edge} ,

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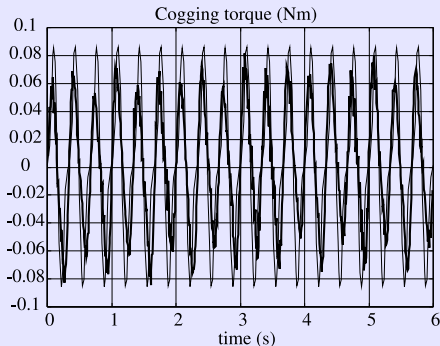
Magnetic Analysis

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Torque

- Torque ripple reduction

Others



Comparison between predicted (thin line) and measured (bold line) cogging torque (motor rated torque is 3 Nm).

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Magnetic Analysis

- No load operation
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Torque

- Torque ripple reduction

Others

Number of T_{cog} periods in a slot pitch rotation

For a rotor with identical PM poles, equally spaced around the rotor, the number of T_{cog} periods during a slot pitch rotation is given by

$$N_p = \frac{2p}{GCD\{Q, 2p\}}$$

where GCD means Greater Common Divisor.

The value of N_p is an index that shows if the elementary cogging torque waveforms are in-phase or not.

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Others

Number of T_{cog} periods in a slot pitch rotation

$2p$	2	2	2	2	4	4	4	8	8	8
Q	3	6	9	12	6	9	12	6	9	15
GCD	1	2	1	2	2	1	4	2	1	1
N_p	2	1	2	1	2	4	1	4	8	8

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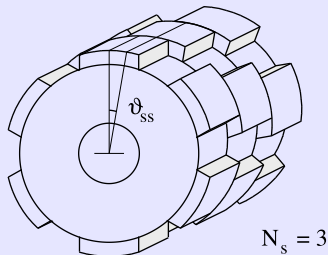
No load operation
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Torque

Torque ripple reduction

Others

Stepped Skewing



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- Torque ripple reduction

Others

rotor with PMs of different arc width



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Others

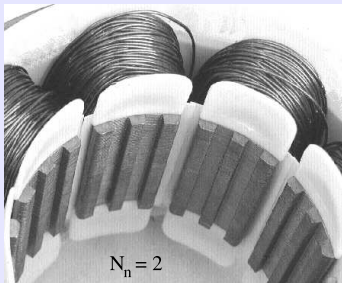
Notches in the tooth (dummy slots)



$$N_n = 1$$



$$N_n = 2$$



A proper number of notches N_n is obtained when
 $GCD\{(N_n + 1), N_p\} = 1$

FEM introduction

- Meshing and solving
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Magnetic Analysis

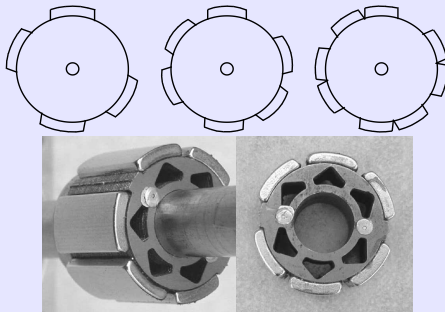
- No load operation
- Operation under load

Torque

- Torque ripple reduction

Others

Shifting of the PMs



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Magnetic Analysis

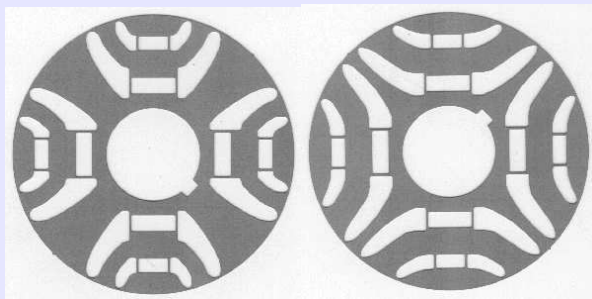
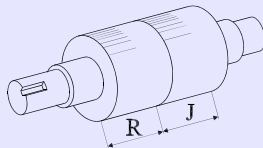
- No load operation
- Operation under load

Torque

- Torque ripple reduction

Others

Two-part rotor



Photos of the "Romeo and Juliet" laminations

FEM introduction

- Meshing and solving
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- References

Magnetic Analysis

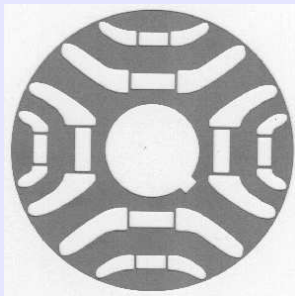
- No load operation
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Torque

- Torque ripple reduction

Others

"Machaon" rotor



It is formed by laminations with flux-barriers of different geometry, large and small alternatively under the adjacent poles.

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- Torque ripple reduction

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Torque ripple reduction (IPM motor)

PM motor design
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Lua scripting

N. Bianchi
Univ. Padova
Italy

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Others

I (A)	classic IPM		R&J		Machaoon	
	T_{avg} (Nm)	$\Delta T / T_{avg}$ (%)	T_{avg} (Nm)	$\Delta T / T_{avg}$ (%)	T_{avg} (Nm)	$\Delta T / T_{avg}$ (%)
2.64	2.14	13.1	1.96	4.84	2.182	4.757
2.84	2.39	12.2	2.18	4.91	2.430	4.720
5.30	5.02	11.6	4.63	4.92	5.240	5.784

Other predictions

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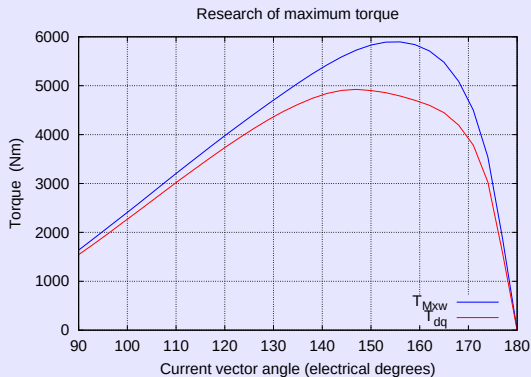
- No load operation
- Operation under load

Torque

- Torque ripple reduction

Others

Torque versus current vector angle



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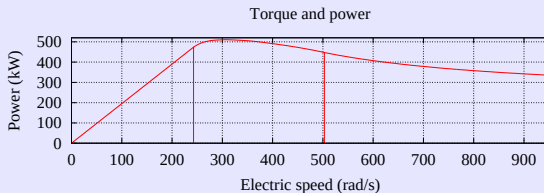
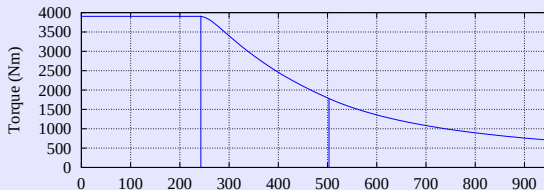
Others

Torque versus speed curve

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Lua scripting

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Torque and power versus speed



FEM introduction

- Meshing and solving
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Torque

- Torque ripple reduction

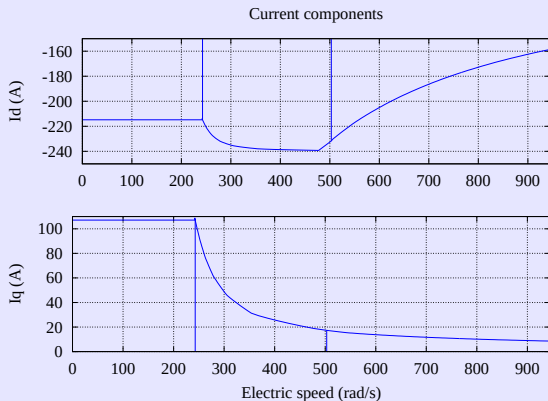
Others

Torque versus speed curve

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$d - q$ axis current versus speed



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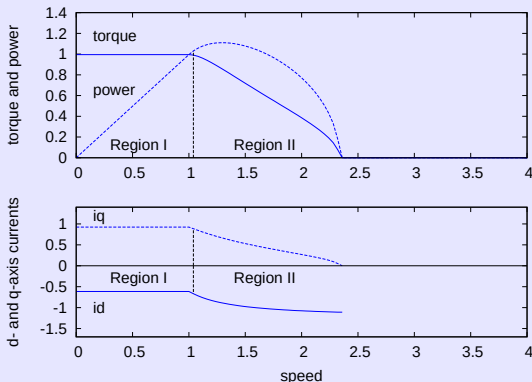
- No load operation
- Operation under load

Torque

- Torque ripple reduction

Others

Maximum torque control with voltage and current limits, in case of $\Lambda_m - L_d I_N > 0$



Torque, power, d - and q -axis currents versus speed.

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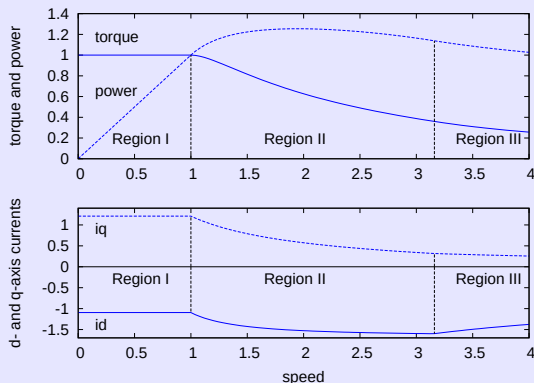
No load operation
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Others

Maximum torque control with voltage and current limits, in case of $\Lambda_m - L_d I_N < 0$



Torque, power, d - and q -axis currents versus speed.

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The short-circuit fault

In the event of a three-phase short-circuit, $v_d = v_q = 0$.
Thus,

$$I_{d,shc} = -\frac{\omega^2 L_q \Lambda_m}{R^2 + \omega^2 L_d L_q}$$

and

$$I_{q,shc} = -\frac{\omega \Lambda_m R}{R^2 + \omega^2 L_d L_q}$$

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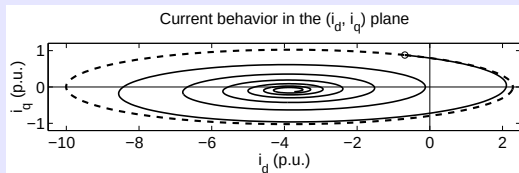
No load operation
Operation under load

Torque

Torque ripple reduction

Others

Short-circuit current trajectory in the (i_d, i_q) plane



The steady-state braking torque

$$T_{brk} = -\frac{3}{2}pR\Lambda_m^2\omega \frac{R^2 + \omega^2 L_q^2}{(R^2 + \omega^2 L_d L_q)^2}$$

The maximum braking torque

$$T_{brk}^* = \frac{3}{2}p\frac{\Lambda_m^2}{L_q}f(\xi)$$

It occurs at the speed

$$\omega^* = \frac{R}{L_q}\sqrt{\chi}$$

with $f(\xi) \approx \xi - 1$.

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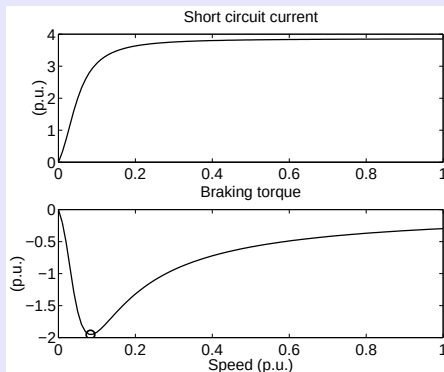
No load operation
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Short-circuit current and braking torque versus speed



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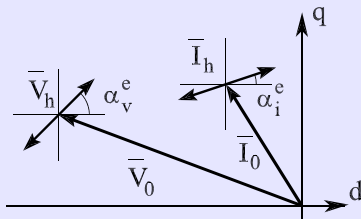
- No load operation
- Operation under load

Torque

- Torque ripple reduction

Others

Phasor diagram with steady-state and high frequency components



Such a study is repeated, varying the voltage vector angle α_v^e , so as to estimate the rotor position error signal ε .

The rotor position estimation error signal

$$\varepsilon(\alpha_v^e) = k_{st} \frac{I_{max} - I_{min}}{2} \sin 2(\alpha_v^e - \alpha_{I_{max}}^e).$$

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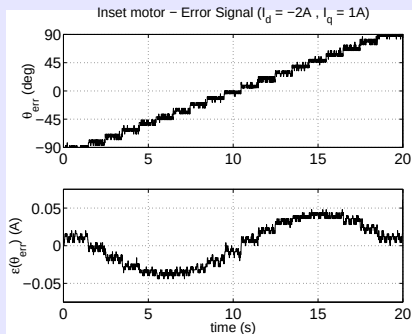
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Experimental



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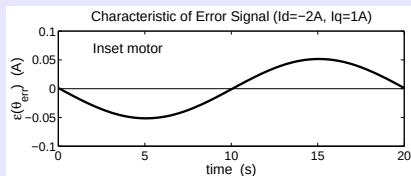
No load operation
Operation under load

Torque

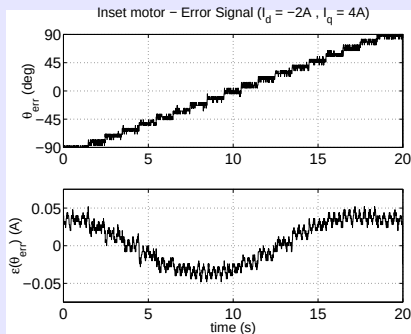
Torque ripple reduction

Others

Prediction



Experimental



FEM introduction

Meshing and solving
Post-processing
Use of the LUA script

PM motor intro

PMs
References

Magnetic Analysis

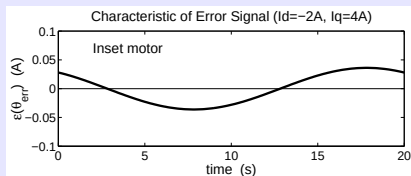
No load operation
Operation under load

Torque

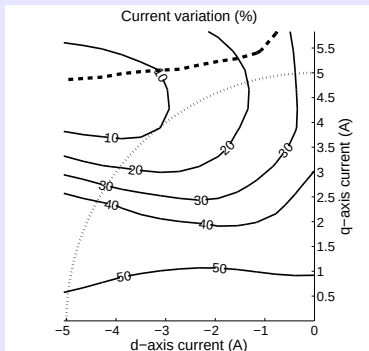
Torque ripple reduction

Others

Prediction



Contour map of the angle error in the current signal (inset motor).



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$$\Delta I_{\%} = 100 \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Thank you!

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