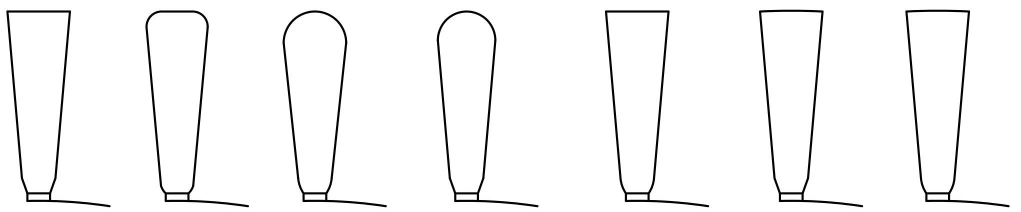
3F — Framework for FEMM

Contents

Chapter 1

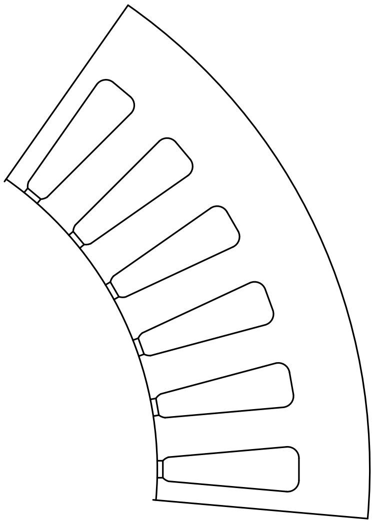
Geometry

1.1 Slots

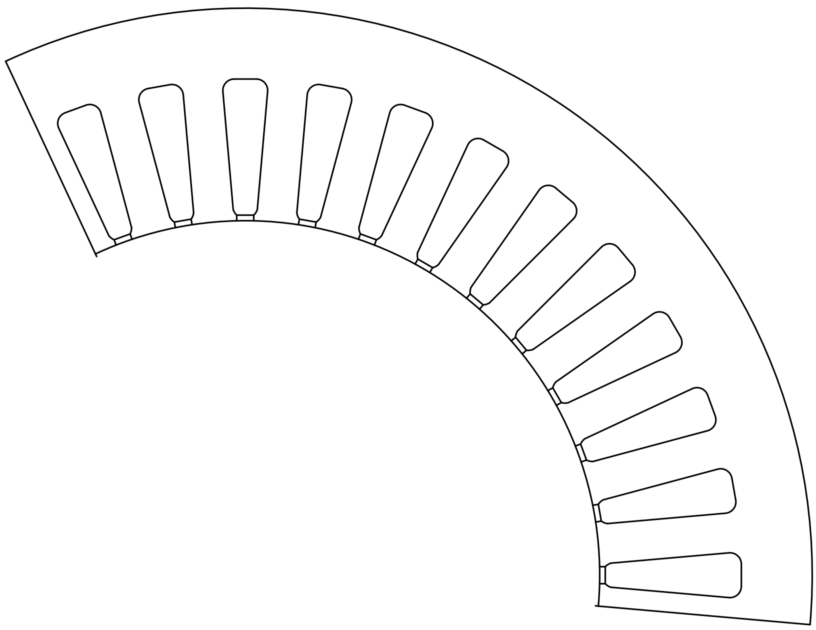


`squared` `rounded` `round` `semiround` `roundsemi` `semiarc` `roundarc`

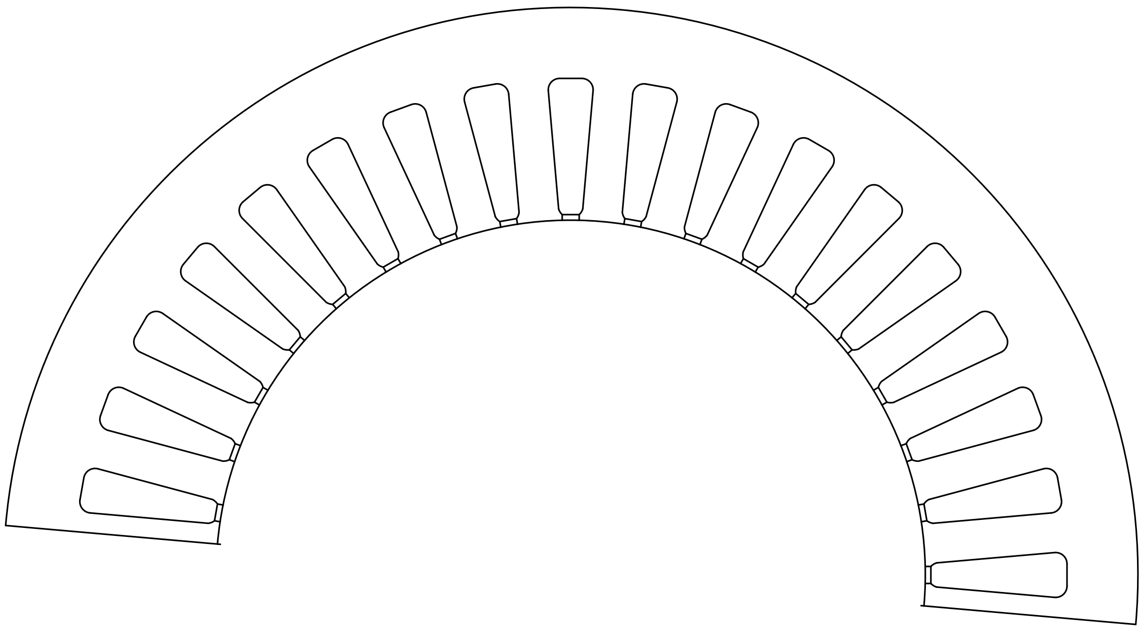
1.2 Stators



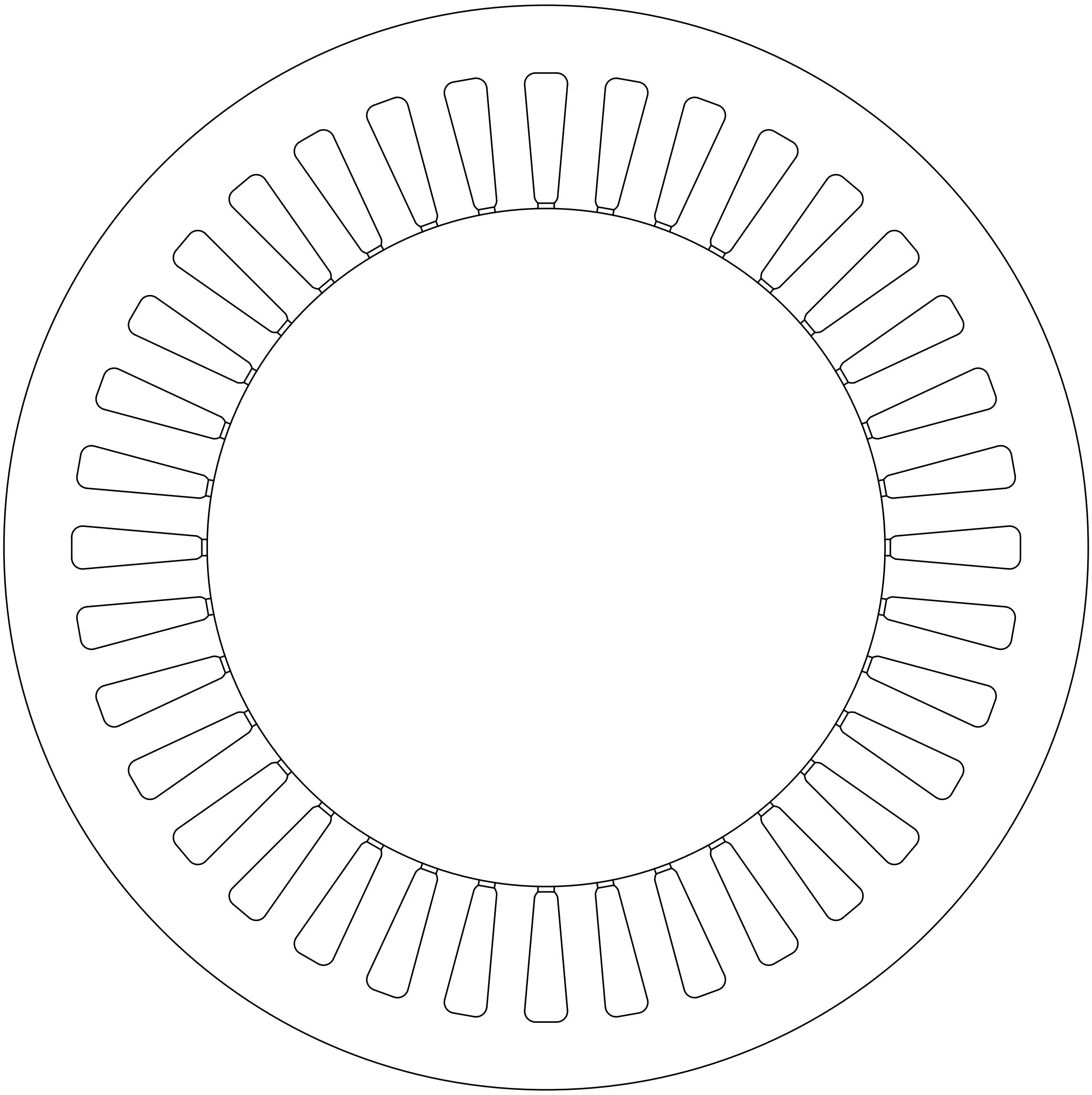
1 pole



2 poles

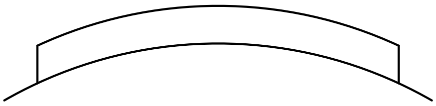


p `poles`

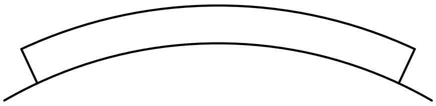


$2p$ `poles`

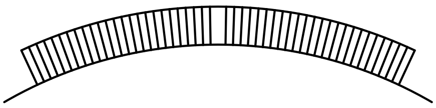
1.3 SPM Magnets



`parallel + rect`

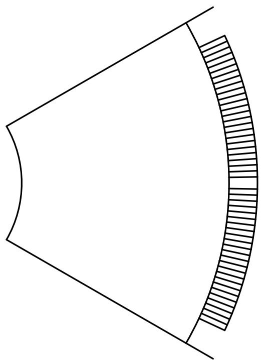


`parallel + trapz`

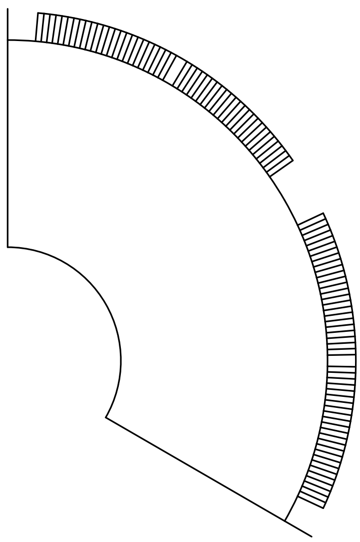


`radial (+ trapz)`

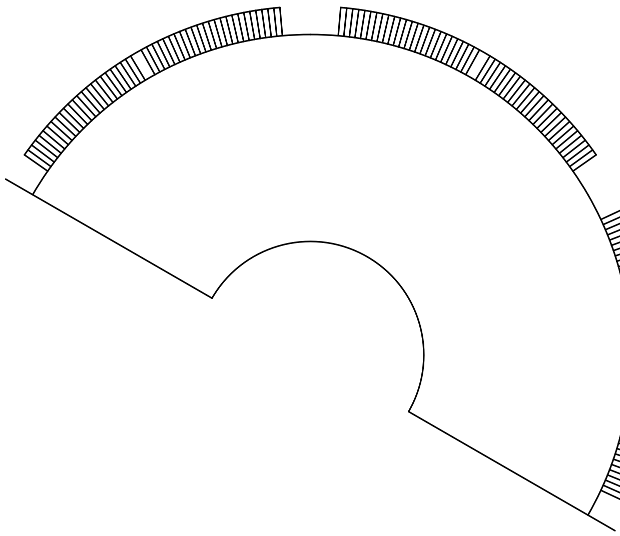
1.4 SPM Rotors



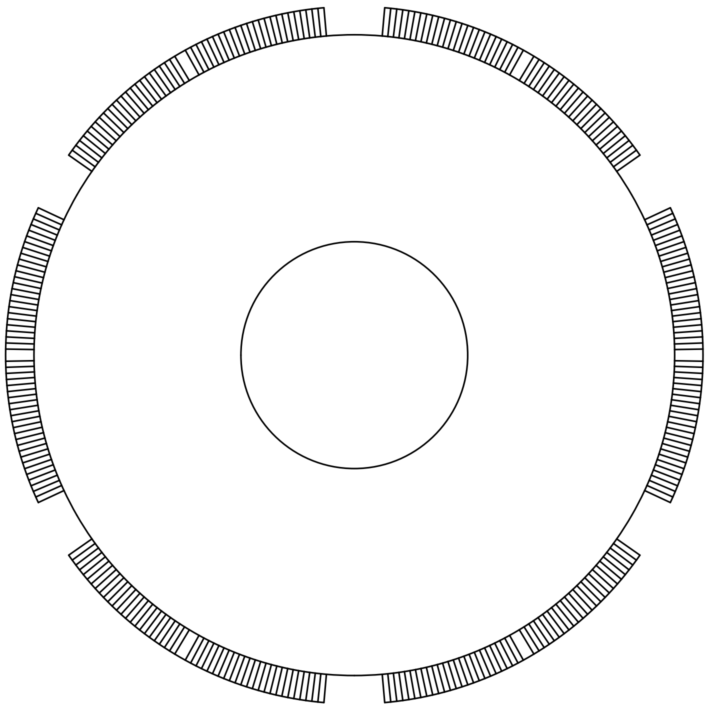
1 pole



2 poles



p poles



$2p$ poles

Chapter 2

Winding

We will characterise a winding through

Name	Math symbol	Code symbol
N. of phases	m	`m`
N. of coils	N_{coils}	`coils`
N. of turns per coil	N_{turns}	`turns`
N. of layers	N_{layers}	`layers`
N. of parallel paths	n_{pp}	`ppath`
N. of conductors in slot	n_{c}	`nc`

Typically, given a lamination stack with Q slots

$$N_{\text{coils}} = \frac{Q}{2} N_{\text{layers}}$$

so if the number of layers is one, the number of coils is half the number of slots, given the fact that a coil side occupies a full slot.

$$n_{\text{c}} = N_{\text{layers}} N_{\text{turns}}$$

This equation means that in each slot there are n_{c} conductors of any phase due to the turns in each coil side in each layer. We bring this number to the equivalent series-connected machine, through the number of parallel paths:

$$n_{\text{cs}} = \frac{n_{\text{c}}}{n_{\text{pp}}}$$

This number, n_{cs}, is related to the complete set of slots, while the previous n_{c} was related only to a part of them, due to the parallel connection of the winding. Thanks to this fact, we can compute the whole number of conductors for each phase, through

$$N_{\text{c}} = \frac{Q\, n_{\text{cs}}}{m}$$

Therefore the full number of turns for each phase, which will appear in the flux linkage, is $N_\mathrm{c}/2$. This number is valid for both the real machine and the equivalent series-connected one.

Another equivalence that we will use is the wye-equivalence. For both the wye and the delta connection of the windings, we will refer to the wye equivalent winding. Each winding sustains either the line(-to-line) voltage in the wye (delta) connection. Therefore

$$U_\mathrm{w} = \frac{U_\mathrm{N}}{\sqrt{3}} \quad [\mathrm{V}] \qquad \text{delta connection}$$

$$U_\mathrm{w} = U_\mathrm{N} \quad [\mathrm{V}] \qquad \text{wye connection}$$

In this way we can obtain the winding current directly from the power

$$I_\mathrm{w} = \frac{P}{3U_\mathrm{w}\cos\varphi} \quad [\mathrm{A}]$$

and use it as the design current for the winding itself. In fact, if each turn is made by some wires with a full section S_c, we will refer to the equivalent turn section

$$S_\mathrm{c,eq} = n_\mathrm{pp} S_\mathrm{c} \quad [\mathrm{mm}^2]$$

which sees the complete winding current, giving the current density

$$J = \frac{I_\mathrm{w}}{S_\mathrm{c,eq}} \quad [\mathrm{A/mm}^2]$$

It is important to highlight that this current density is the conductor's one, while the slot current density is given by

$$J_\mathrm{slot} = k_\mathrm{fill} J \quad [\mathrm{A/mm}^2]$$

where the fill factor, k_fill, represents the ratio between the actual conductor area in the slot and the slot section. Depending on the starting point, one can find the rms current in the slot through

$$I_\mathrm{slot} = J_\mathrm{slot} S_\mathrm{slot} = n_\mathrm{cs} I_\mathrm{w} \quad [\mathrm{A}]$$

2.1 Space vector

Given an m-phase winding symmetrically distributed, we can associate its currents to a single complex-valued variable, the *space vector*, which represents the equivalent primitive two-phase winding, with axes α and β. Thus

$$\boldsymbol{i}_{\alpha\beta} = \frac{2}{m}\left[i_a + i_b\,\mathrm{e}^{\mathrm{j}\frac{2\pi}{m}} + i_c\,\mathrm{e}^{\mathrm{j}\frac{4\pi}{m}} + \ldots + i_m\,\mathrm{e}^{\mathrm{j}\frac{(m-1)2\pi}{m}}\right] = \boldsymbol{i}^s$$

If we want to get the space vector in the synchronous reference frame, it is simply

$$\boldsymbol{i}^r = \boldsymbol{i}^s \, \mathrm{e}^{-\mathrm{j}\vartheta_\mathrm{m}^\mathrm{e}}$$

Therefore we can directly relate the dq-current to the m phase currents:[1]

$$\bar{i}_\mathrm{s} \xrightarrow{T_{ab\cdots m}^{dq}} \boldsymbol{i}^r$$

2.2 Slot matrix

The slot matrix is a useful tool for the correct and rapid assignment of currents in the slots. In fact it directly relates phase and slot currents, through

$$\bar{i}_\mathrm{s} \xrightarrow{K} \bar{i}_\mathrm{slot}$$

This relationships is missing just the number of series conductor per slot. So

$$\bar{i}_\mathrm{slot} = n_\mathrm{cs} K \, \bar{i}_s$$

2.3 Sinusoidal dq control

For synchronous machines, this is the typical control implemented. A reference current, which comes from the speed loop, is imposed. Usually the control is executed in the dq-reference frame, therefore we start from

$$\boldsymbol{i}^r = i_d + \mathrm{j} i_q = |\boldsymbol{i}| \, \mathrm{e}^{\mathrm{j}\alpha_\mathrm{i}^\mathrm{e}}$$

Then we transform it in the $\alpha\beta$-reference frame and finally we get the phase currents:[2]

$$\bar{i}_\mathrm{s} = U_s^{ab\cdots m} \boldsymbol{i}^s = U_s^{ab\cdots m} U_r^s \, \boldsymbol{i}^r = U_r^{ab\cdots m} \, \boldsymbol{i}^r$$

From here, the slot currents are simply

$$\bar{i}_\mathrm{slot} = n_\mathrm{cs} K \, \bar{i}_\mathrm{s} = n_\mathrm{cs} K \, U_r^{ab\cdots m} \, \boldsymbol{i}^r$$

[1] The adopted convention is the following

$$T\text{ransformation}_\text{from}^\text{to} \qquad U\text{antitransformation}_\text{from}^\text{to}$$

[2] In the code the transformations made available are `dq2ab` and `U`, which is the one from $\alpha\beta$ to $abc\cdots m$.

2.4 Trapezoidal control

This control is typical of BLDC drives. In the trapezoidal control the currents would ideally assume just three values:

$$\{+I_{\mathrm{DC}}, 0, -I_{\mathrm{DC}}\}$$

while the current absorbed from the DC-bus is constant. Only two phases are active simultaneously, while the third one is kept off. Taking half the DC-bus voltage as the reference, the voltages assume just three values too:

$$\{+V_{\mathrm{DC}}/2, 0, -V_{\mathrm{DC}}/2\}$$

The complete number of possible states is the double $(+/-)$ of all the grouping of the phases (m) by two:

$$\#\text{ of states} = 2\binom{m}{2} = m\,(m-1)$$

Consider a three-phase machine for instance. The supply states can be

state 6	$+$	$-$	0
state 1	$+$	0	$-$
state 2	0	$+$	$-$
state 3	$-$	$+$	0
state 4	$-$	0	$+$
state 5	0	$-$	$+$