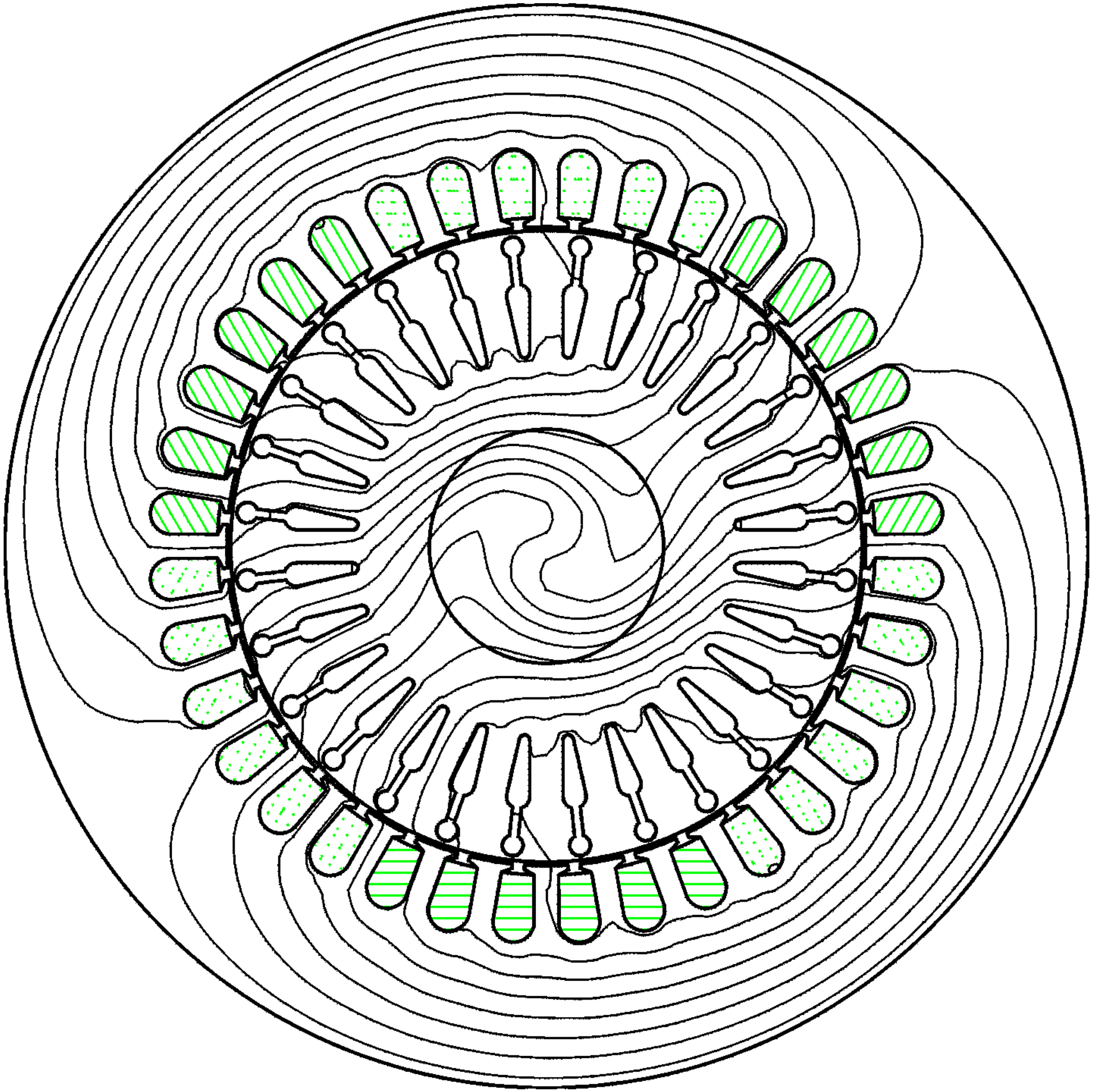
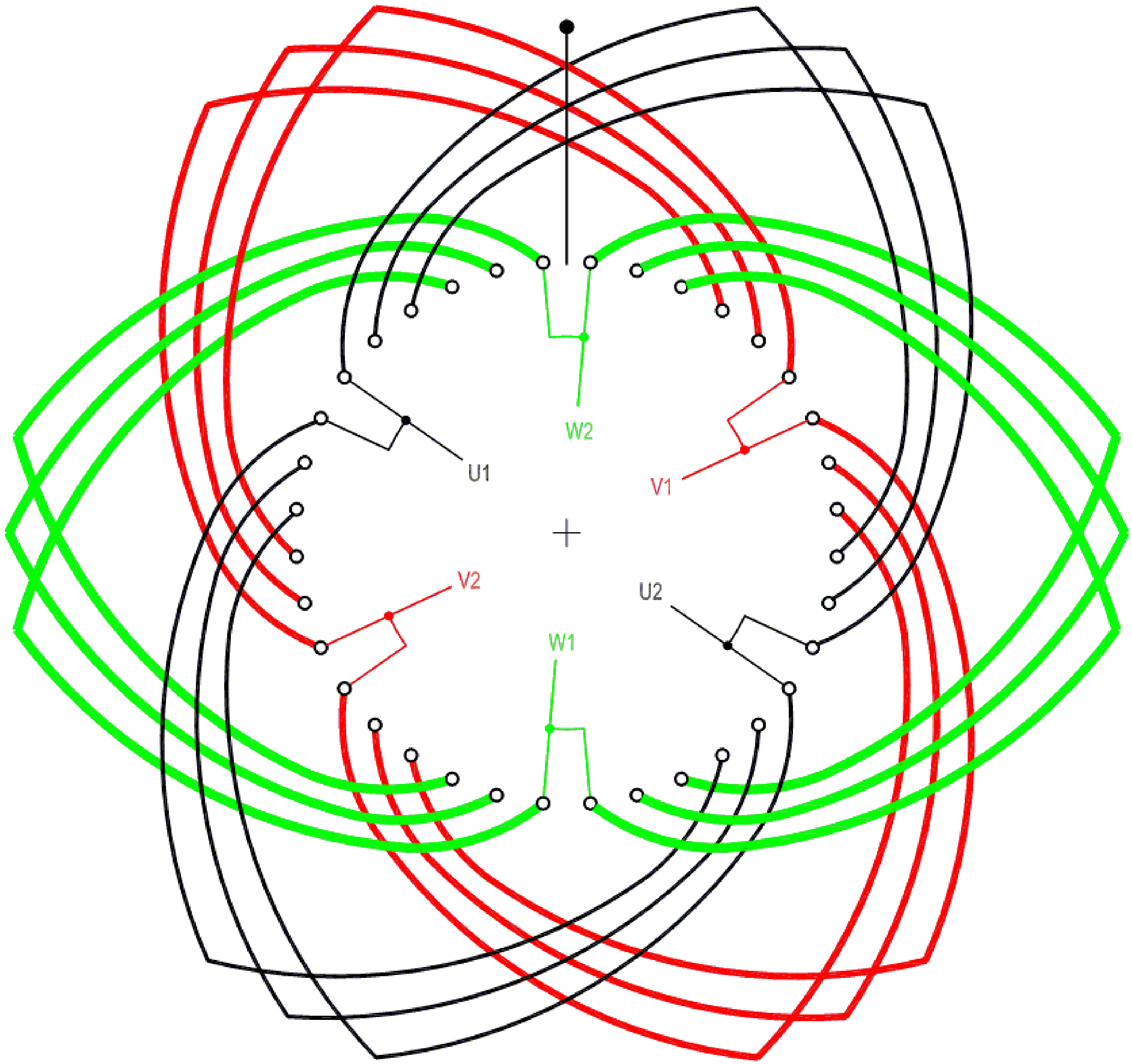
Slot winding or distributed winding



Two-pole, three-phase cage induction motor

Slot winding for an electrical machine



Slot winding for an electrical machine

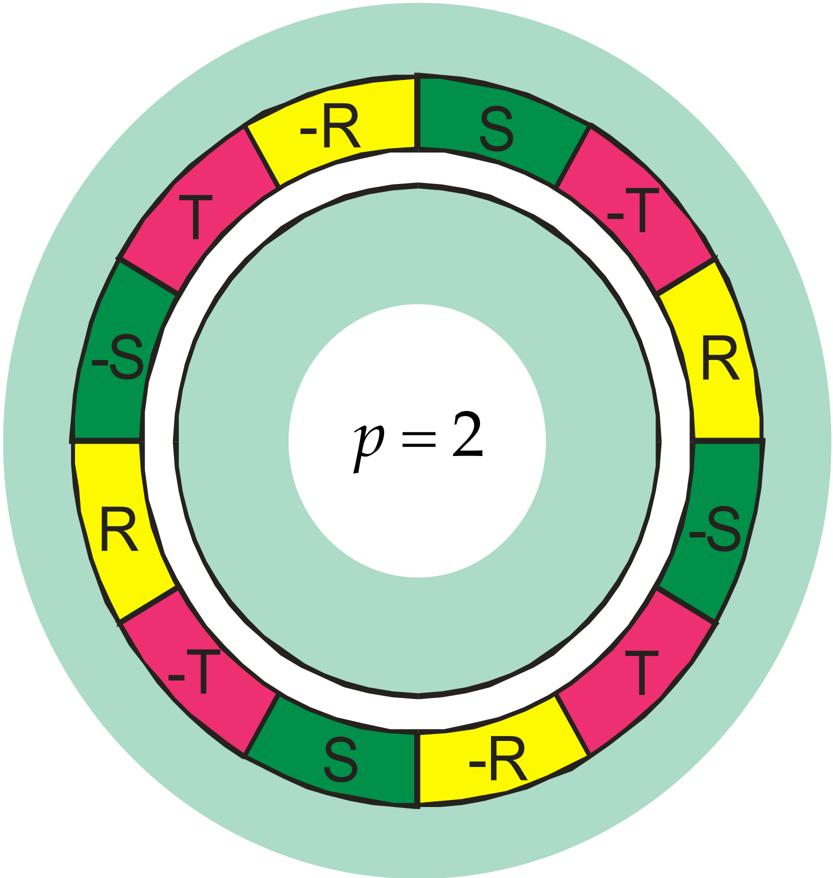
The winding has to be distributed on the poles and phases. The air-gap periphery is divide into **2*p* poles**. The pole pitch is

$$\tau_\mathrm{p} = \frac{\pi D_\mathrm{i}}{2p} \qquad \text{(In meters)}$$

where p is the number of pole pairs and D_i is the air-gap diameter.

The pole pitch is further divided into m phase belts

$$\tau_\mathrm{pb} = \frac{\tau_\mathrm{p}}{m} = \frac{\pi D_\mathrm{i}}{2pm} \qquad \text{(In meters)}$$



Phase belts of a three-phase, four-pole winding

Slot winding for an electrical machine

The average number of slots per phase belt is

$$q = \frac{Q}{2pm}$$

where Q is the number of slots.

q is called the number of slots per pole and phase.

If q is an integer, all the phase belts have an equal, integer number of slots and the winding is called an <u>integral slot winding.</u>

In some cases, q is a fractional number

$$q = \frac{Q}{2pm} = \frac{z}{n}$$

where z and n are integers. In this case, the winding is called a <u>fractional slot winding</u> and the number of slots differs from one phase belt to another.

Slot winding for an electrical machine

The fundamental flux-density wave in the air gap

$$b_p(\phi, t) = \hat{b}_p \cos(p\phi - \omega t)$$

should induce a balanced m-phase voltage in the winding. The phase shift between the voltages of phase windings should be

$$\alpha_{\mathrm{ph}} = \frac{2\pi}{m}$$

and the amplitudes of the phase-winding voltages should be equal.

Θ (*F_m*) Current linkages	→	***B*** Magnetic flux density	→	*e* *emf* induced in coil

Electromotive force on a coil side

Using electrical radians, the fundamental flux-density wave becomes

$$b_1(t,\gamma) = \hat{b}_1 \cos(\gamma - \omega t)$$

$\hat{b}_1$ peak value of the flux-density distribution,
γ circumferential coordinate,
ω angular frequency and
t time.

Time variation of flux linkage induces a total electromotive force in a coil. Considering the flux in the yoke, the emf can be written per coil side

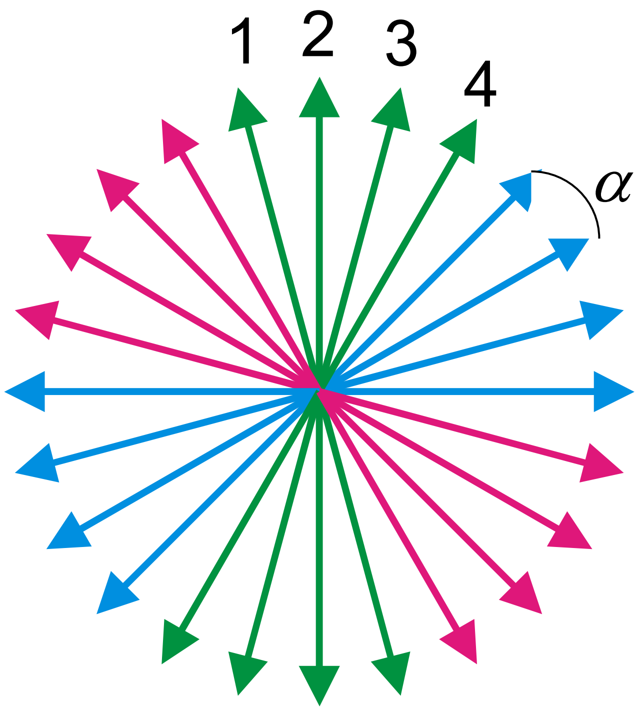
$$e_\mathrm{n}(\gamma) = -\frac{\mathrm{d}\psi_\mathrm{n}}{\mathrm{d}t} = \frac{1}{\pi}\omega N_\mathrm{coil}\,\tau_\mathrm{p} l_\mathrm{i}\,\hat{b}_1 \cos(\gamma - \omega t)$$

Pole pitch

Length of stator stack

Slot star

Presenting the electromotive forces of coil sides as phasors and plotting the phasors of one pole pair, a slot star is obtained.



The slot star on the left is for an integral slot three-phase winding with $q = 4$.

The phase shift between the voltage phasors is $\alpha = 2\pi/24$.

The natural choice of phases to which the 24 slots belong to is indicated by the colours.

Phasor presentation of fields and voltages

If we can consider the electrical machine as a linear, time-invariant system and the supply voltage is sinusoidal, the magnetic field, currents and voltages of the machine can be expressed using phasor quantities. In the 2D case, the vector potential and current density are

$$\begin{cases} \boldsymbol{A} = \mathrm{Re}\left\{\underline{A}(x,y)\mathrm{e}^{\mathrm{j}\omega t}\right\}\mathbf{e}_z = \mathrm{Re}\left\{\left[A_\mathrm{R}\left(x,y\right)+\mathrm{j}A_\mathrm{I}\left(x,y\right)\right]e^{\mathrm{j}\omega t}\right\}\mathbf{e}_z \\ \boldsymbol{J} = \mathrm{Re}\left\{\underline{J}(x,y)\mathrm{e}^{\mathrm{j}\omega t}\right\}\mathbf{e}_z = \mathrm{Re}\left\{\left[J_\mathrm{R}\left(x,y\right)+\mathrm{j}\,J_\mathrm{I}\left(x,y\right)\right]e^{\mathrm{j}\omega t}\right\}\mathbf{e}_z \end{cases}$$

The phasors are solved from the combined field and circuit equations

$$\nabla\times\left(\nu_\mathrm{eff}\nabla\times\underline{\boldsymbol{A}}\right)+\mathrm{j}\omega\sigma\underline{\boldsymbol{A}}+\sigma\underline{\phi}=\underline{0}$$

$$\underline{u}=\int_a^b -\nabla\underline{\phi}\cdot\mathrm{d}\boldsymbol{l}=\int_a^b\left(\frac{1}{\sigma}\underline{\boldsymbol{J}}+\mathrm{j}\omega\underline{\boldsymbol{A}}\right)\cdot\mathrm{d}\boldsymbol{l}$$

Phasor presentation of fields and voltages II

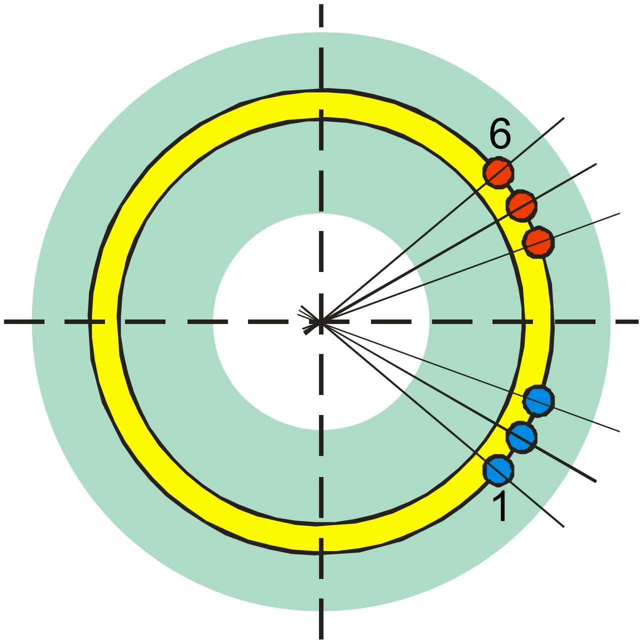
If an idealised conductor of a winding can be considered to be infinitely thin but have a finite resistance, the circuit equation for the winding can be transformed to the form

$$\underline{U} = \int_a^b \left(\frac{1}{\sigma} \underline{\boldsymbol{J}} + \mathrm{j}\omega \underline{\boldsymbol{A}} \right) \cdot \mathrm{d}\boldsymbol{l} = R\underline{I} + \mathrm{j}\omega \int_a^b \underline{\boldsymbol{A}} \cdot \mathrm{d}\boldsymbol{l}$$

The first term is a resistive voltage drop in the conductor, the second term is the electromotive force induced in the conductor.

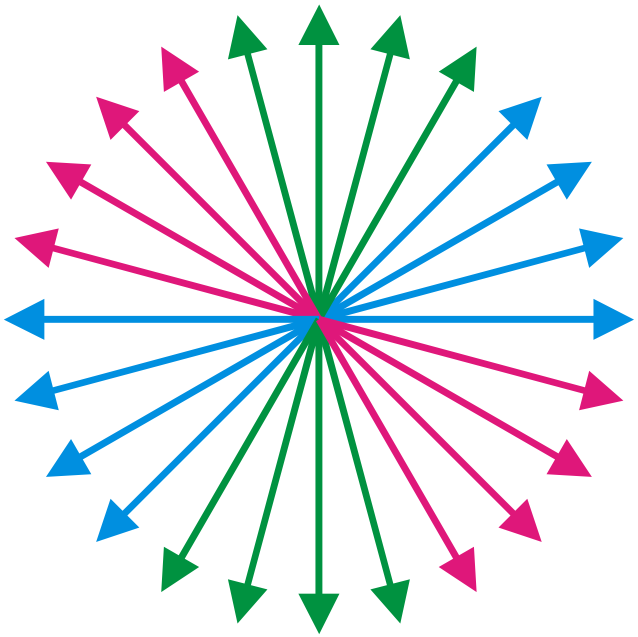
Using this formulation in 2D to calculate the electromotive force induced in the coil group shown in the figure, we get the result

$$\underline{e} = \mathrm{j}\omega l \begin{bmatrix} \underline{A}(\phi_4) + \underline{A}(\phi_5) + \underline{A}(\phi_6) \\ -\underline{A}(\phi_1) - \underline{A}(\phi_2) - \underline{A}(\phi_3) \end{bmatrix}$$



Slot star

This equation can be interpreted so that associated with each slot k there is a phasor $\mathrm{j}\omega l\underline{A}(\phi_k)$ (slot phasor) that gives the electromotive force induced in a conductor in that slot.



Example: Let us take a 4-pole machine with 48 stator slots. If we consider the fundamental harmonic only, and represent the slot phasors graphically, we get the figure on the left.

Actually, we have 48 phasors but as the system repeats itself after every pole pair, two phasors are always on each other. The first 24 slots contain a basic winding which is repeated in the next 24 slots.

Slot star II

The angle between two successive slot phasors is

$$\gamma = \frac{2p\pi}{Q_\mathrm{s}}$$

The length of a slot phasor associated with a winding turn is

$$e_\mathrm{s} = \omega l A_p$$

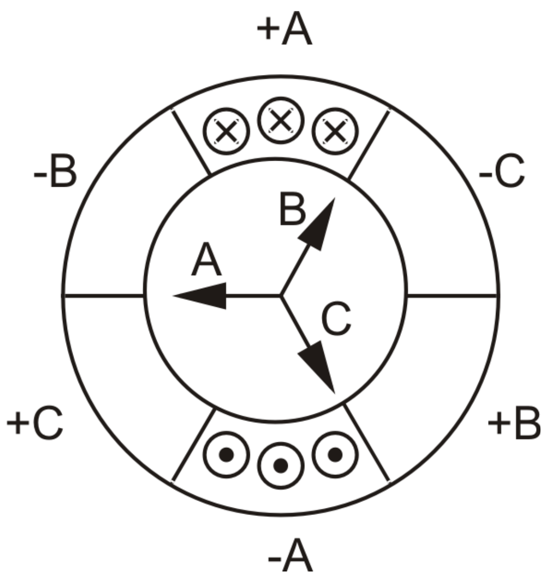
or if we want to use the flux-density amplitude instead of vector-potential amplitude

$$e_\mathrm{s} = \frac{\omega r}{p} l \hat{b}$$

The last equation and the whole concept of a slot star can also be easily derived from the motion induced electromotive forces.

Design of a single layer winding

Number of slots = Q, Number of coils = $Q/2$, as one coil side fills a slot completely.



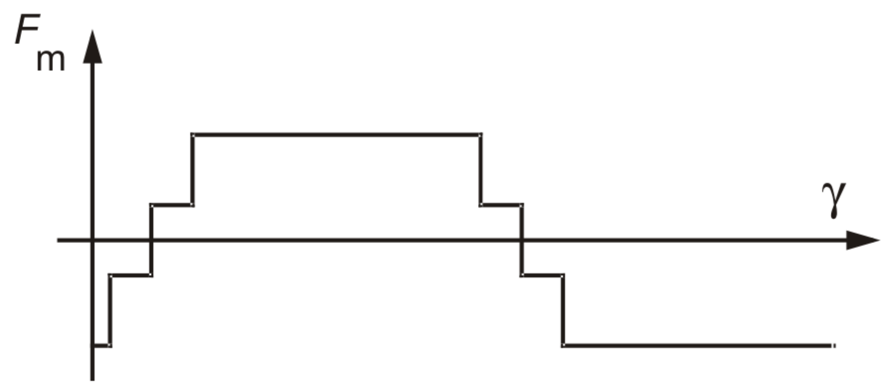
- One of the phase belts is chosen for the positive coil sides of phase A. It is marked + A.
- Moving 120 electrical degrees from + A to the positive direction of rotation of the rotor (clockwise in the figure), phase belt + B is reached.
- An additional 120 electrical degrees brings phase belt + C.
- The negative phase belts are found by moving 180 electrical degrees from the corresponding positive phase belts.

Design of a single layer winding

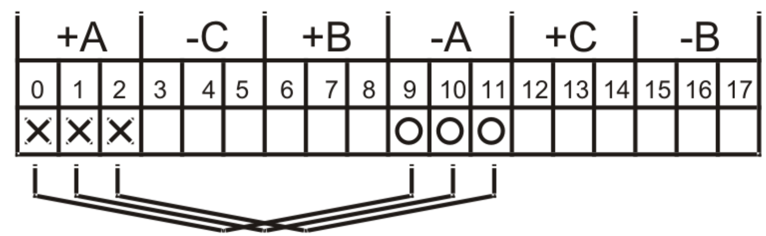
All the coil sides of one phase have currents of equal magnitude. The magnetomotive force of the phase is shown in figure a). It is independent from the exact connection of the positive coil side to the negative ones.

Figures b) and c) show two possible configurations of coils, which give exactly the same magnetomotive force distribution in the air gap.

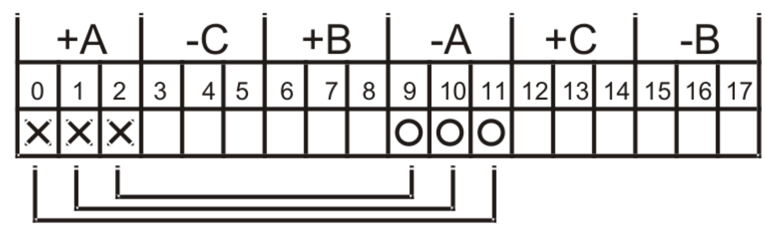
a)



b)



c)

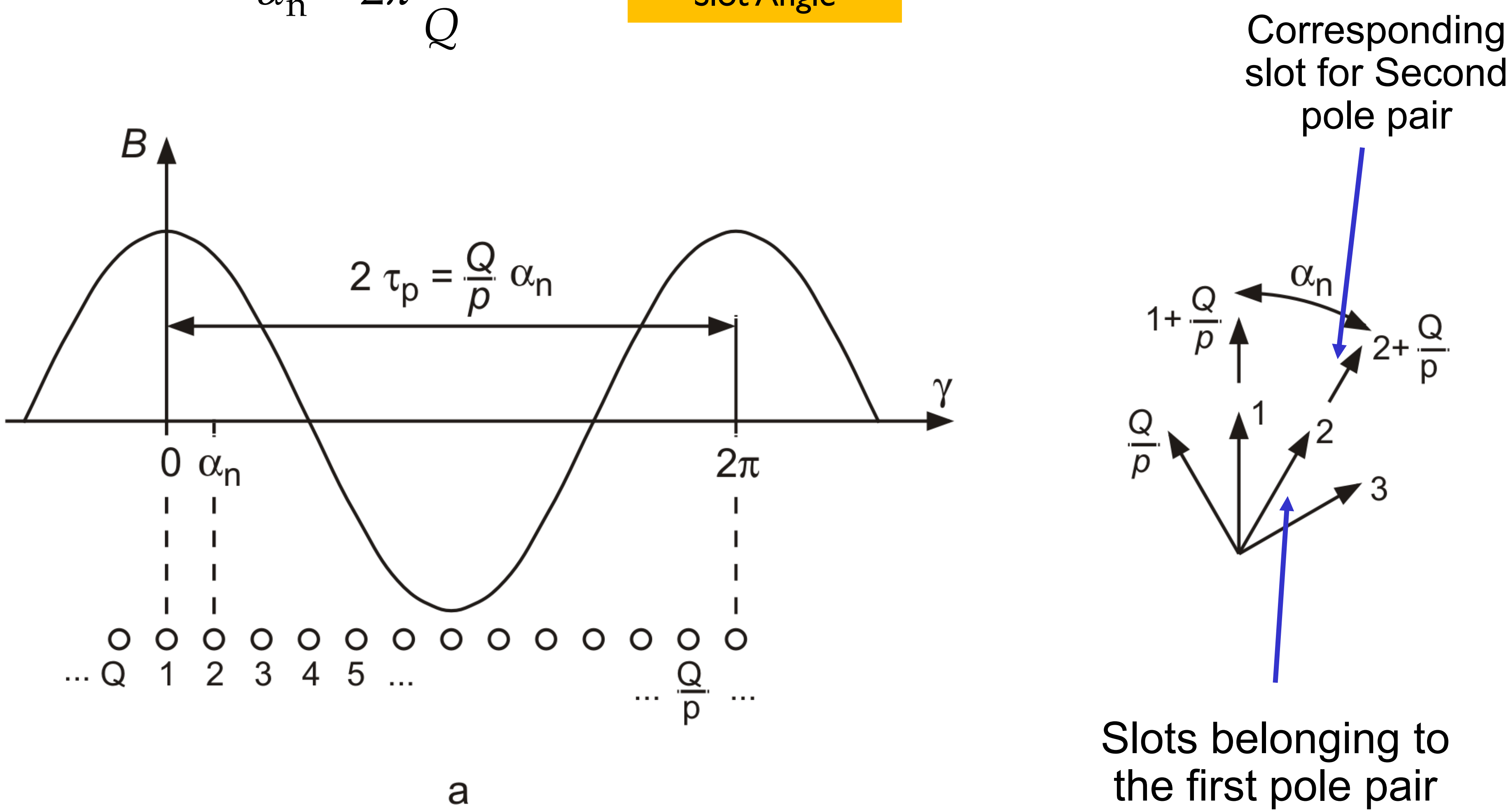


Slot star for an integral slot winding

Integral slot winding => all the phase belts are similar

$$\alpha_{\mathrm{n}} = 2\pi \frac{p}{Q}$$

Slot Angle



Slot star for a fractional slot winding

Fractional slot winding => The number of slots and configuration of slot phasors changes from one phase belt to phase belt.

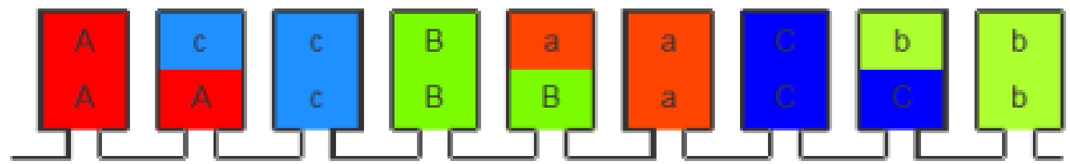
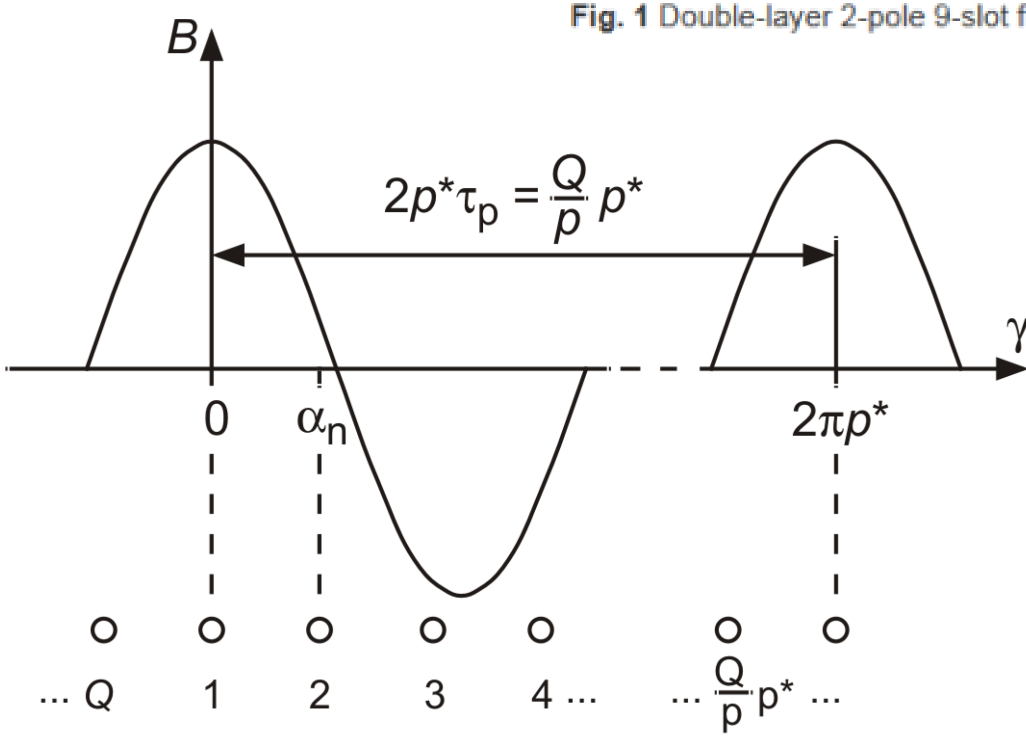
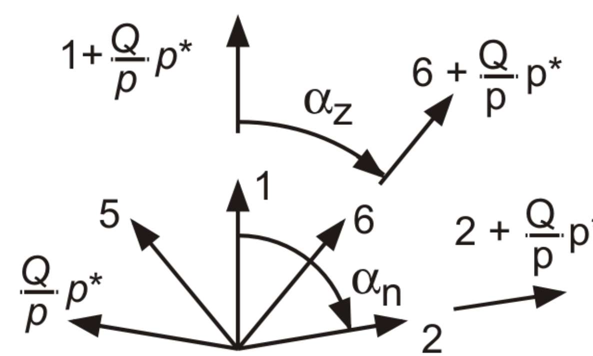


Fig. 1 Double-layer 2-pole 9-slot fractional slot winding with a winding factor of 0.945.



a

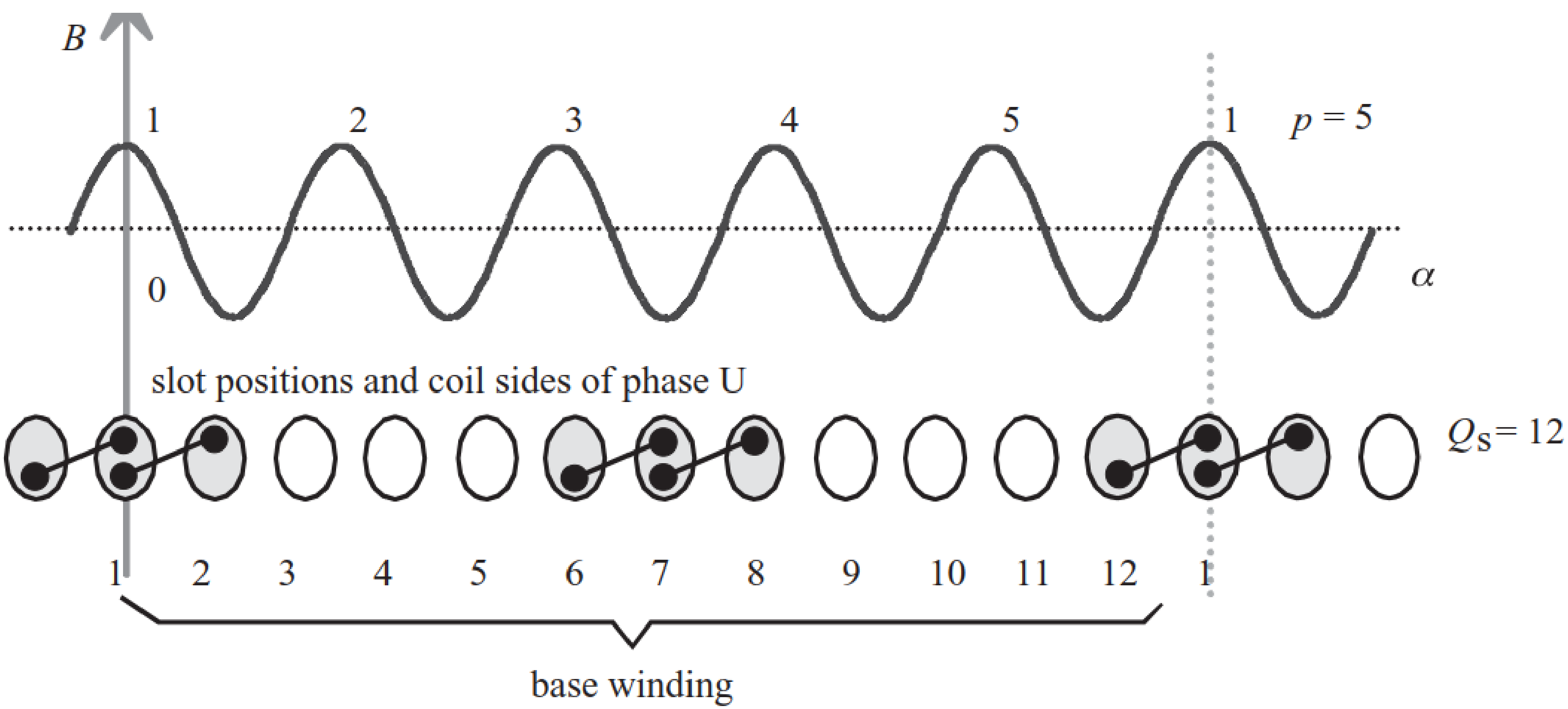


b

Slot star for a fractional slot winding

Fractional slot winding

$$\frac{Q}{3(2p)}, \mathrm{Q} = 12, p = 5$$



Symmetry conditions

Each phase has an integral number of coils

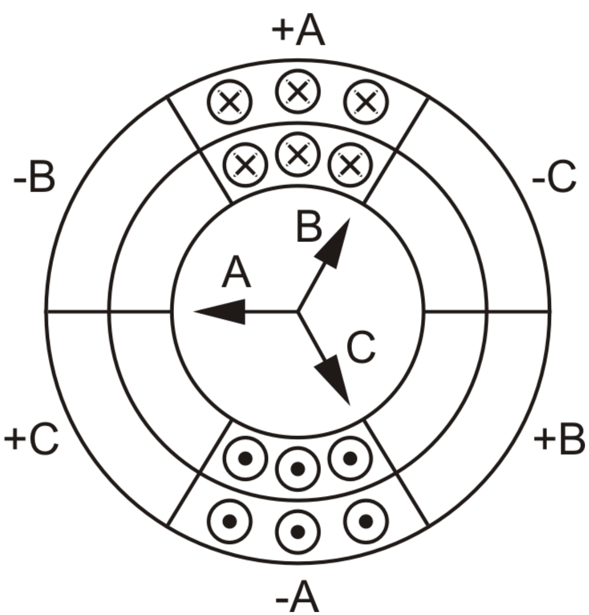
$$\frac{Q}{2m} = pq = \text{integer} \quad (\text{single layer winding})$$

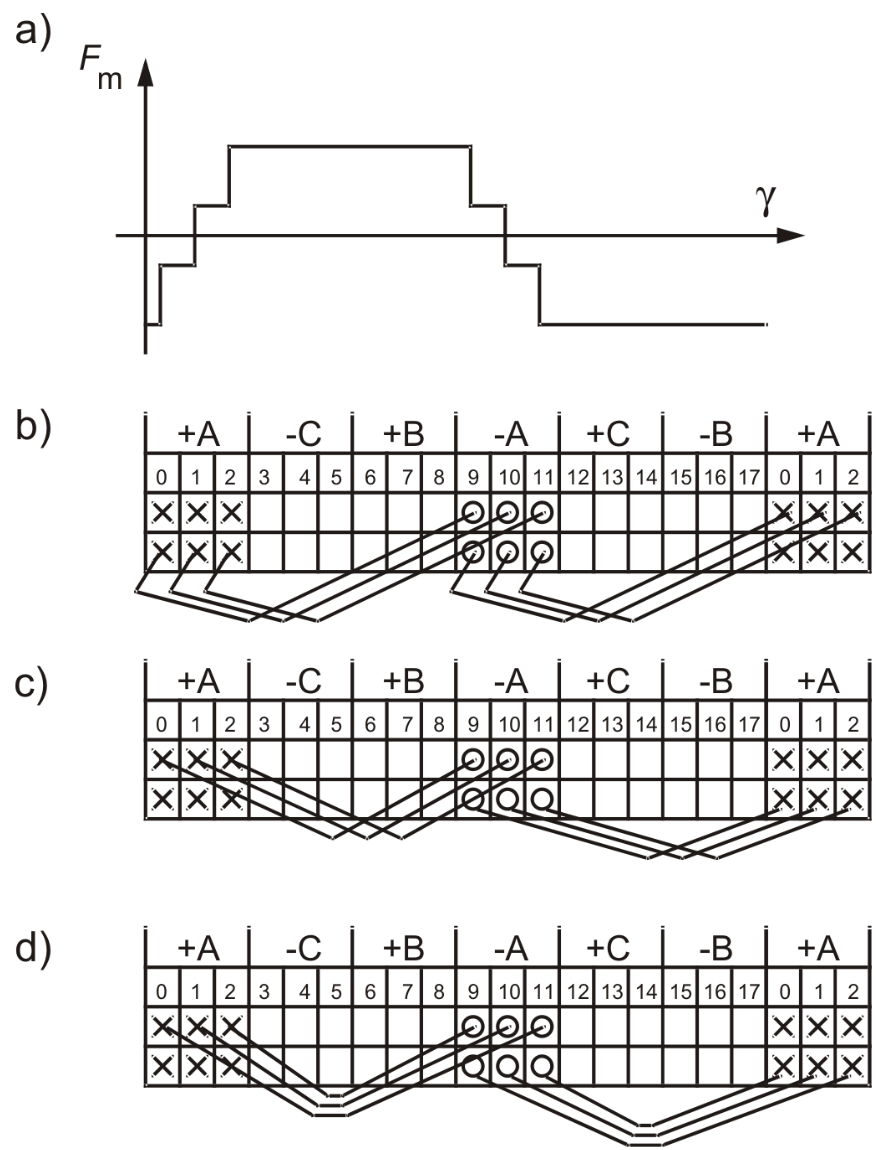
$$\frac{Q}{m} = 2pq = \text{integer} \quad (\text{double layer winding})$$

The phase shift angle between induced phase voltages is a multiple of phase shift angles between slot voltages

$$\frac{\alpha_{\mathrm{v}}}{\alpha_{\mathrm{z}}} = \frac{Q}{m\mathrm{t}} = \text{integer}$$

Design of a double layer winding

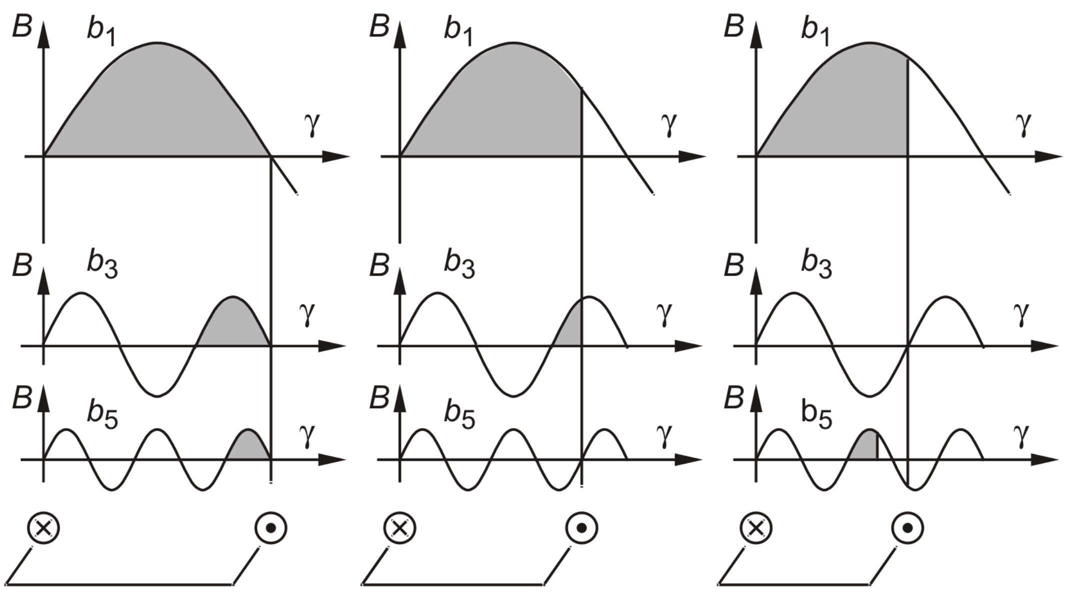




In a double layer winding, there are even more possibilities to put the coils into the slots but all these windings produce equal mmf waves in the air gap.

Chording

Changing the coil pitch may strongly affect the emf induced by a higher harmonic. In this way, the effects of some harmful harmonic component can be eliminated. A winding having non-diagonal coils is called a chorded winding.



Double-layer windings

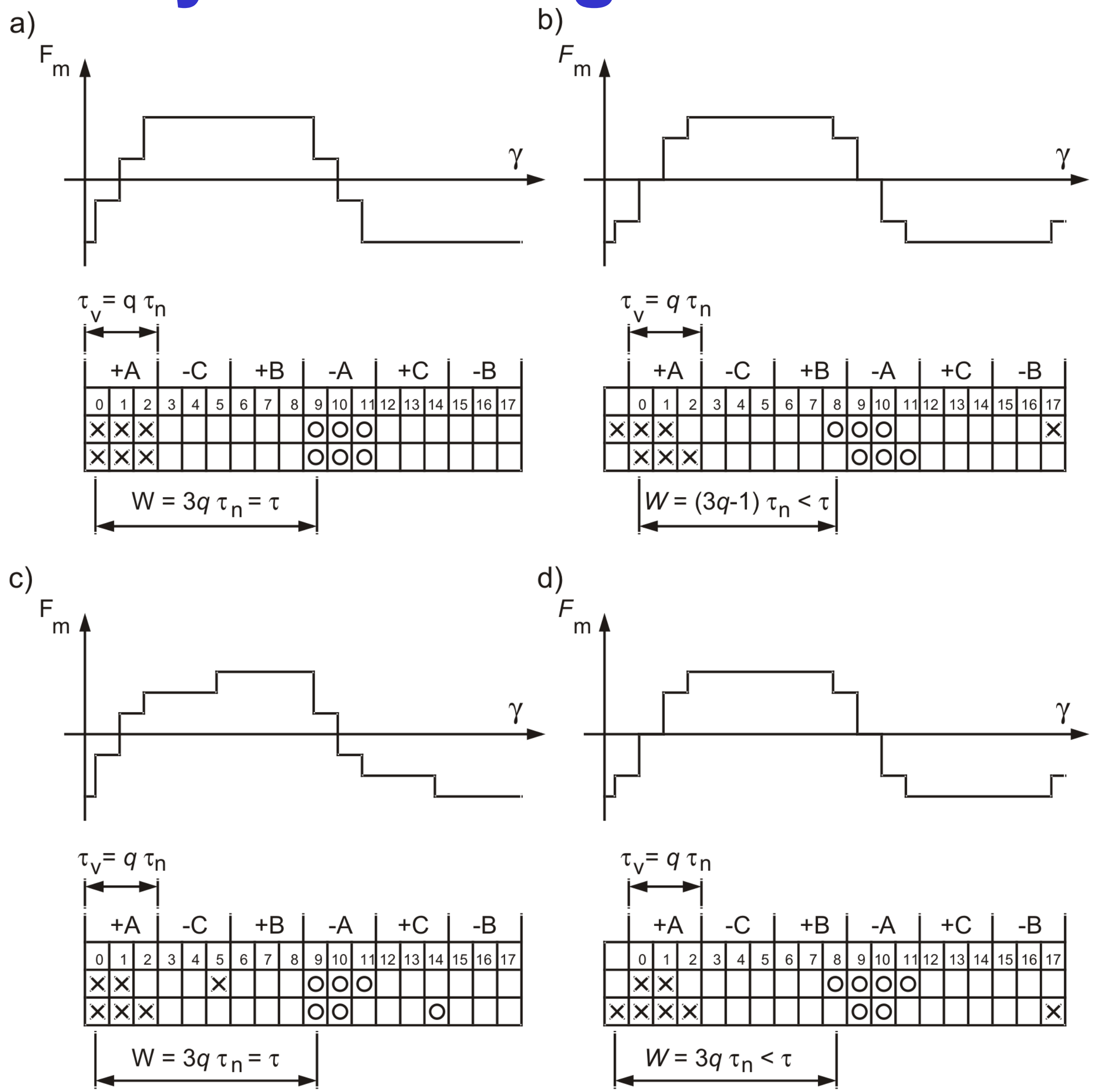
a) Double layer winding with diagonal coils.

b) Typical chorded winding. The coil pitch is reduced by one slot from the the diagonal one.

c) Special winding with diagonal coils.

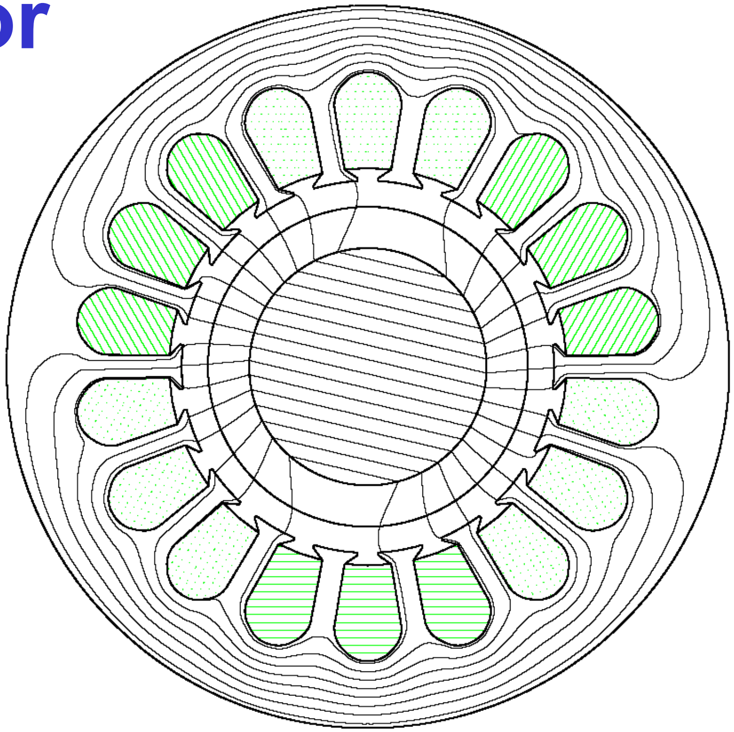
d) Special winding with diagonal coils, probably.

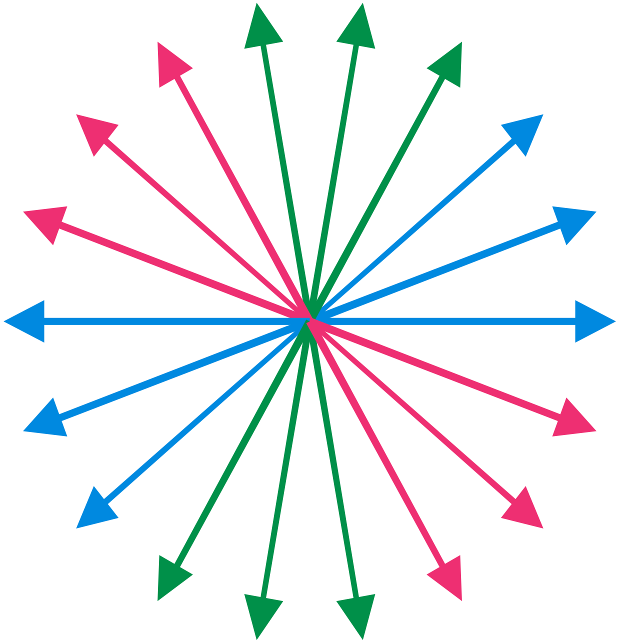
The double-layer configuration gives freedom to place the coils.



Example of winding factor

Problem: High-speed two-pole PM generator with 18 stator slots. The winding is a single layer winding. Calculate the winding factor of the stator winding starting from the slot star.



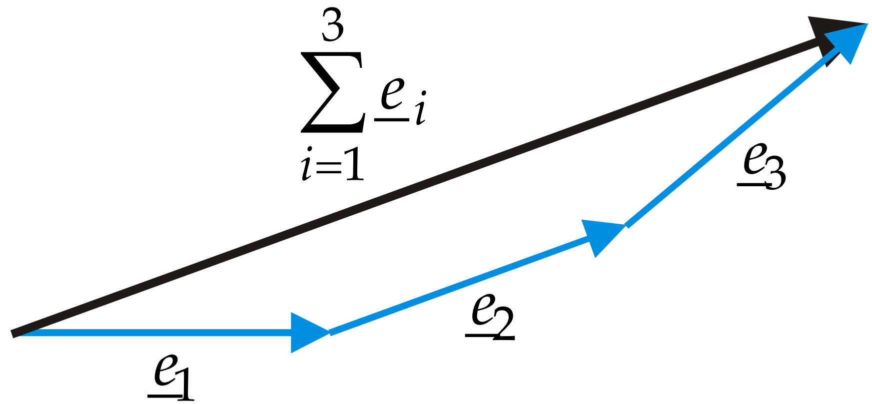


The phase shift between the emf vectors induced in the conductors of adjacent slots is $2\pi/18$. There are 18 vectors (slots). To gain the maximum voltage, the phases are chosen as indicated by the colours in the slot star on the left.

Winding factor

The total emf induced in a phase is obtained by adding the slot-star vectors. The sum of the positive coil sides for phase A is

$$\begin{cases} \underline{e}_1 = e_\mathrm{s} \\ \underline{e}_2 = e_\mathrm{s}\mathrm{e}^{\mathrm{j}\pi/9} \\ \underline{e}_3 = e_\mathrm{s}\mathrm{e}^{\mathrm{j}2\pi/9} \end{cases}$$



The negative coil sides give an equal amplitude but opposite sign. The total emf, obtained as the difference of the two vectors, is twice the vector shown above.

In this case, the winding factor is

$$\xi = \left| \frac{1}{3e_\mathrm{s}} \sum_{i=1}^{3} \underline{e}_i \right| = \frac{1}{3}\left| 1 + \mathrm{e}^{\mathrm{j}\pi/9} + \mathrm{e}^{\mathrm{j}\pi 2/9} \right| \approx 0{,}960$$

Winding factor

More generally, the winding factor can be calculated from equation

$$\xi_\nu = \sin\left(\nu\frac{\pi}{2}\right)\frac{\sin\left(q\nu\frac{\alpha_\mathrm{n}}{2}\right)}{q\sin\left(\nu\frac{\alpha_\mathrm{n}}{2}\right)} = \sin\left(\nu\frac{\pi}{2}\right)\frac{\sin\left(\nu\frac{\pi}{2m}\right)}{q\sin\left(\nu\frac{\pi}{2mq}\right)}$$

Where ν is the order of the harmonic, α_n is the slot pitch angle, q is the number of slots per pole and phase and m is the number of phases. This equation is not valid for a chorded winding.

R.m.s value of induced voltage in the coil for the fundamental harmonic $(\nu = 1)$ is

$$E_p = 4.44\xi_\nu fN\phi$$