FACULTY OF ELECTRICAL
ENGINEERING
UNIVERSITY OF WEST BOHEMIA

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

ESF II – project of the University of West Bohemia
reg. no. CZ.02.2.69/0.0/0.0/18_056/0013239

Theory of Electric Machines 2

KEV/TS2

Karel Hruska / r20201116

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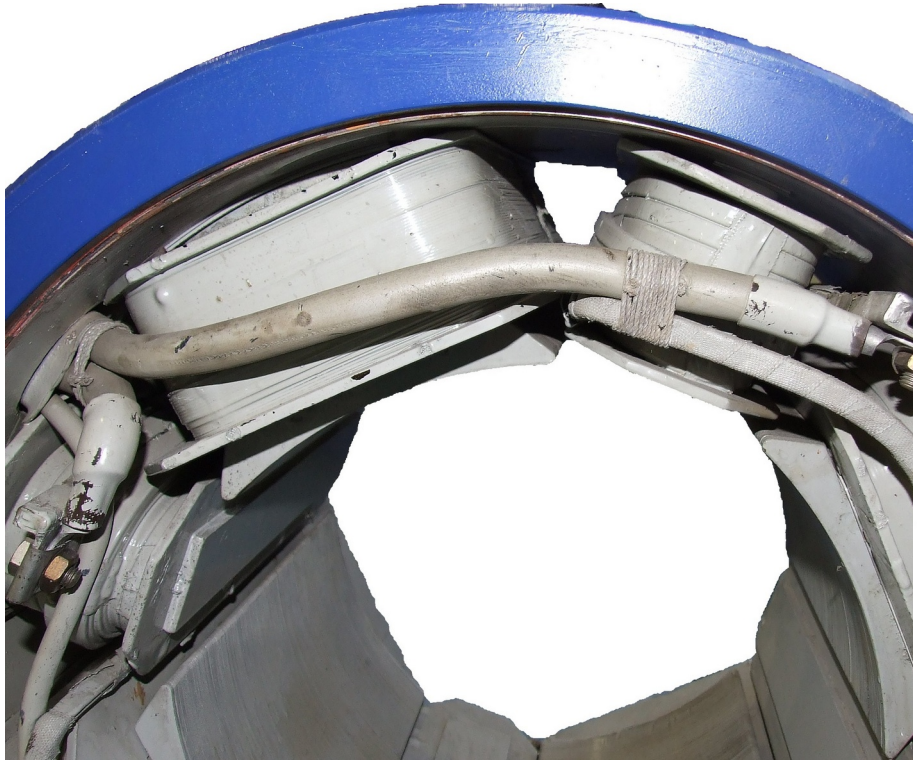
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Winding of Electric Machines

Winding of Electric Machines

- Winding is an ordered system of conductors seving for excitation of magnetic field
- Fundamental categorization:
  - Concentrated
  - Distributed
    - Drum-shaped
    - Planar
- The design of the winding is in detail tought in KEV/VELS

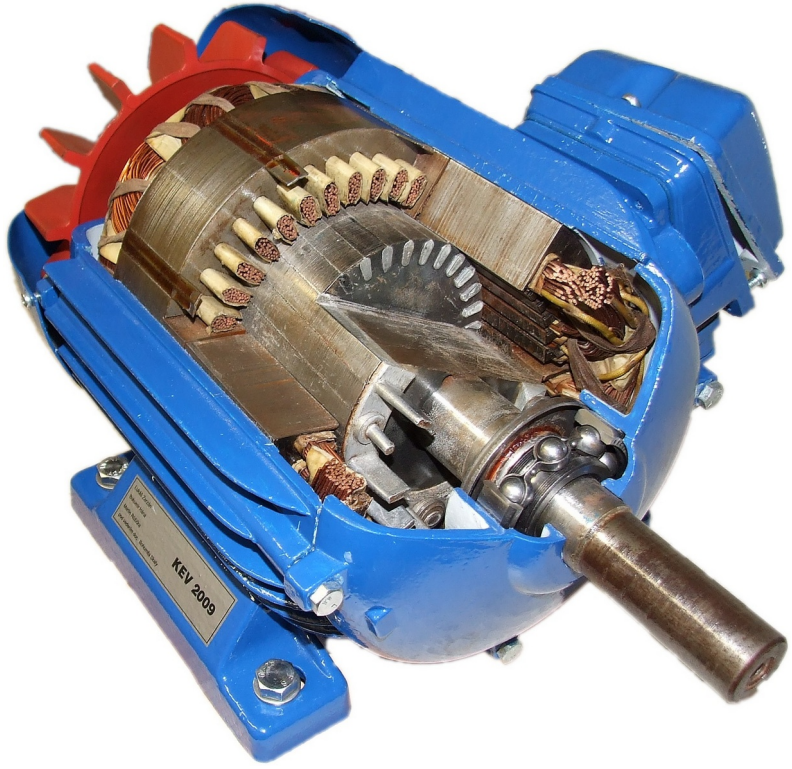
Winding of Electric Machines



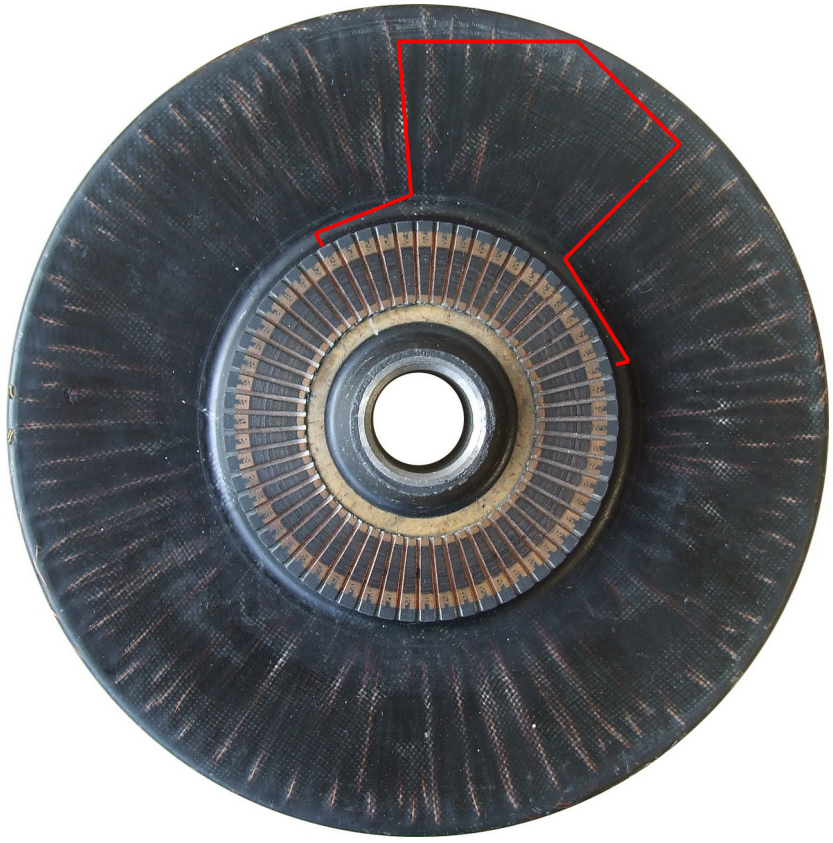


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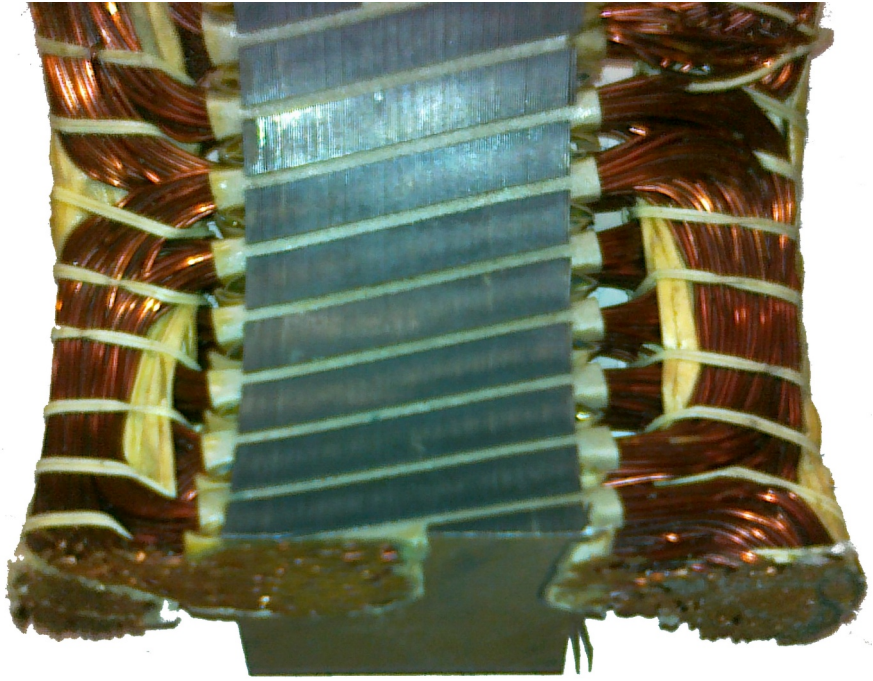
Winding of Electric Machines

- „Armature winding“:
  - Winding of rotors of direct current machines
  - Winding of stators of alternating current machines
    - In case of induction machines the armature is the rotor, too (eve here the voltage is being induced ;-))
- Typically placed in slots
  - But there are also slotless variants
- In case of DC machines it is formed by coils connected through commutator
- In case of AC machines the coils are connected into so-called groups
- In suitable connection they together form phase winding

Winding of Electric Machines

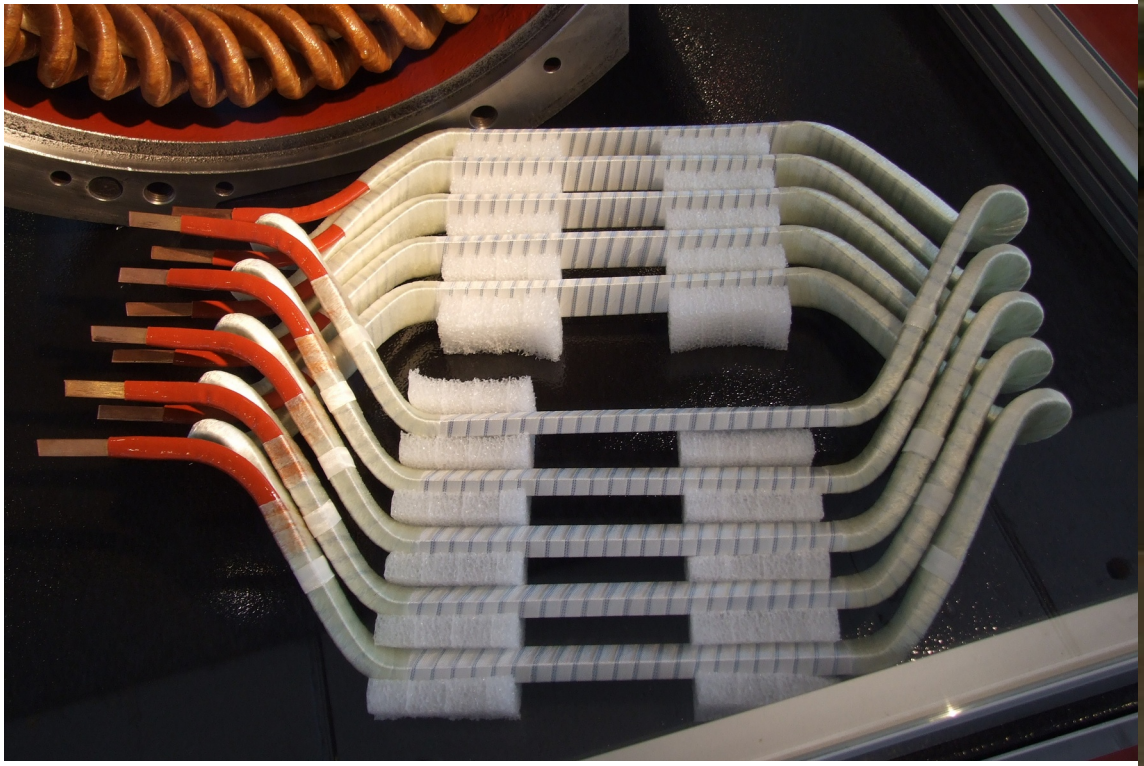
- The resulting look of the winding depends on used technology
- Low power machines (up to tens of kilowatts)
  - The winding is made of a wire with round cross-section
  - Often concentric, single-layered
- Medium and large power machine (hundreds of kilowatts and more)
  - The winding is made of rectangular-shaped conductor
  - Pre-formed coild are put into stator slots
- In case of permanent magnet machines the tooth winding is often used (PMSM, BLDC)

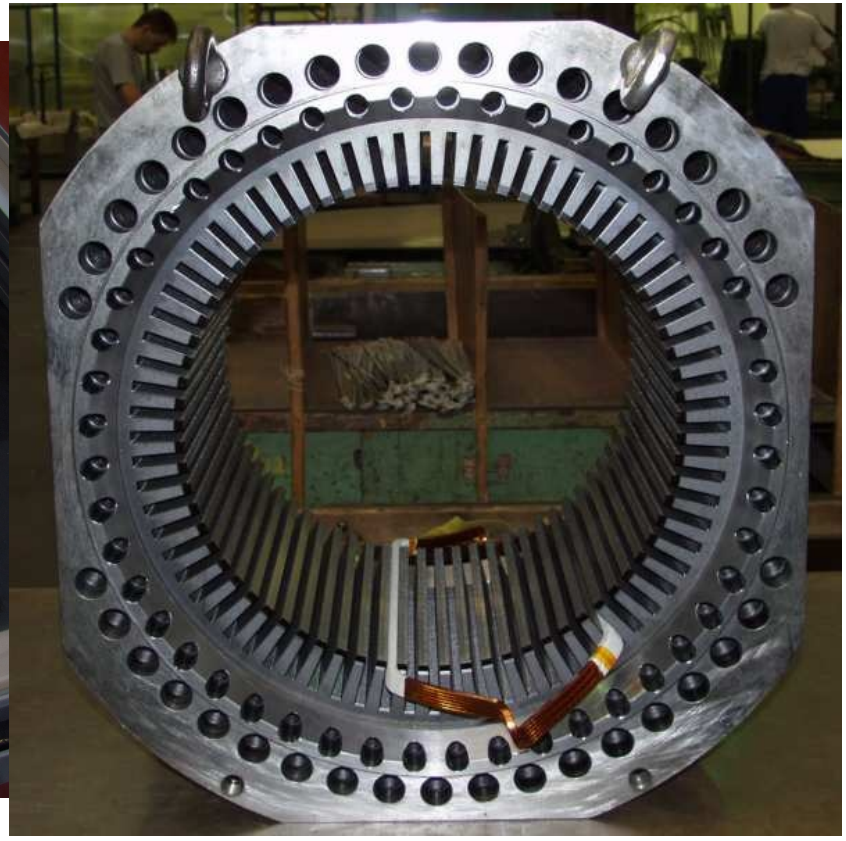
Winding of Electric Machines





Winding of Electric Machines



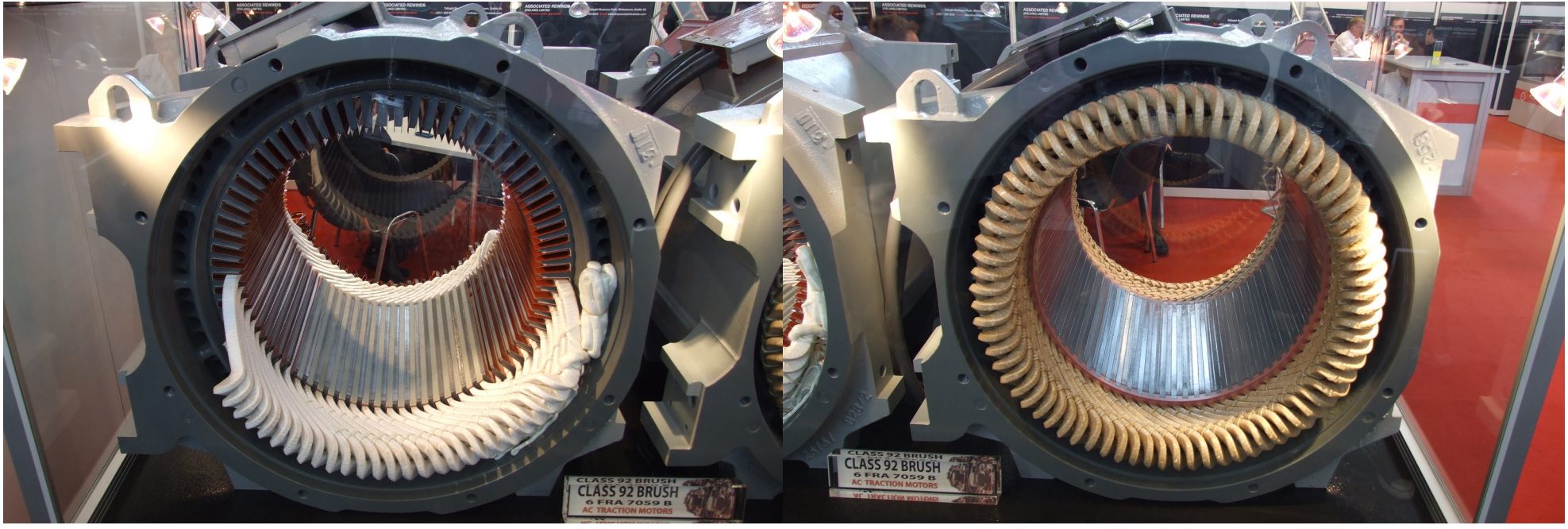


Winding of Electric Machines

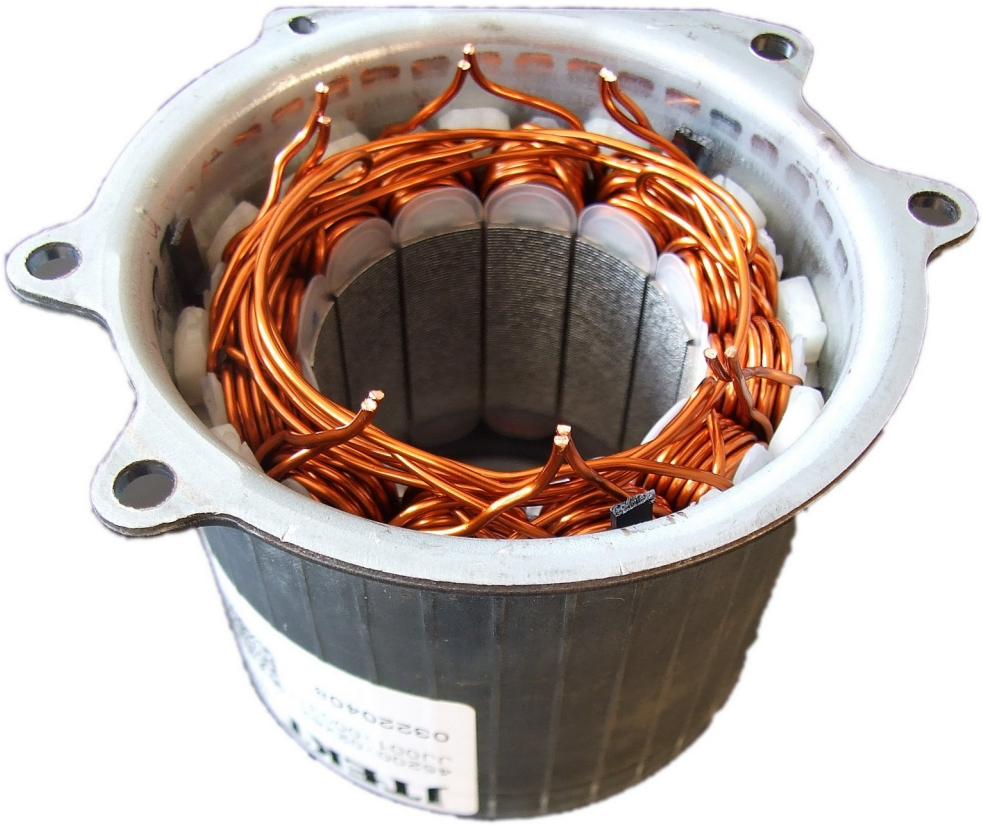


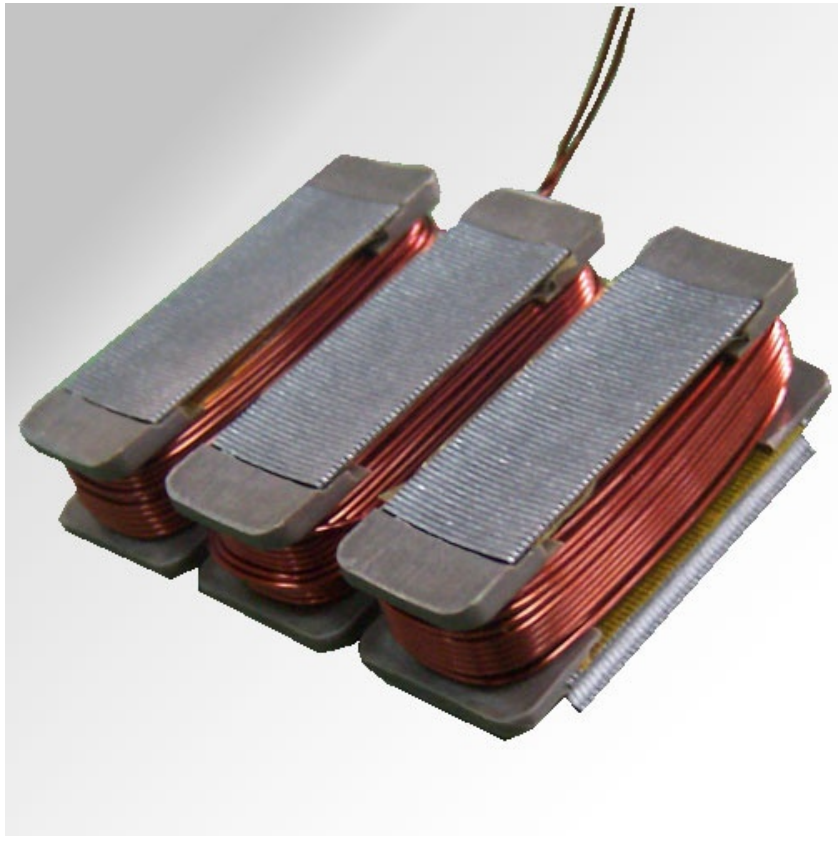


Winding of Electric Machines



Winding of Electric Machines





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Winding Factors and their Relation to Higher Order Harmonic Components

Winding Factors and their Relation to Higher Harmonic Components

- The winding factor recognizes “efficiency factor” of designed winding
- It may be determined geometrically from:
  - The star of slots
  - Tingley’s schema
  - Construction of total induced voltage
- Analytically as a multiplication of winding pitch factor and winding distribution factor
- It varies for higher order harmonic components depending on their order
- Depending n technology they may be supplemented by additional factors, e.g. skewing factor (in case of skewed slots) etc.
- In foreign literature (e.g. German) they are calculated by different approach

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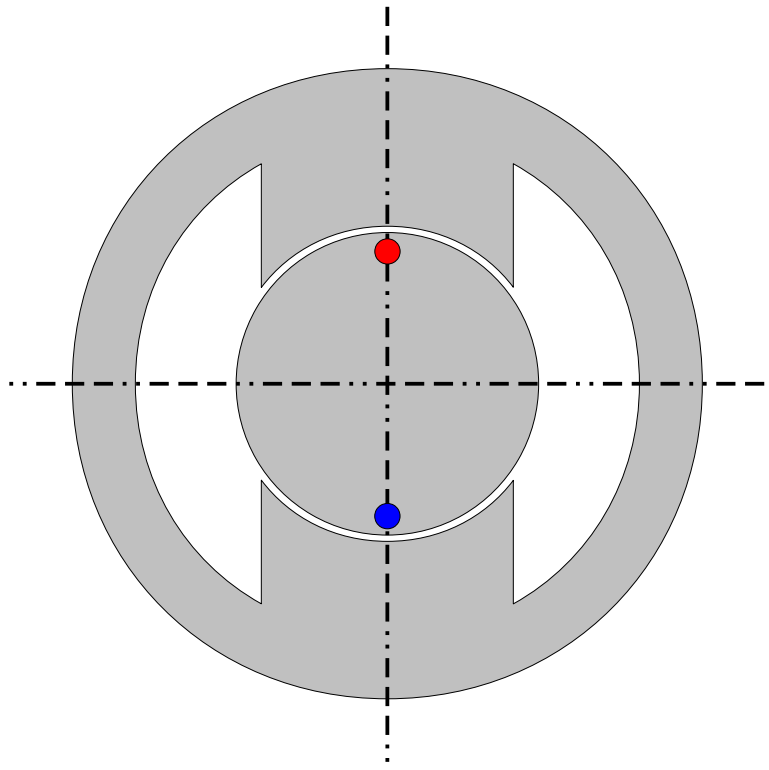
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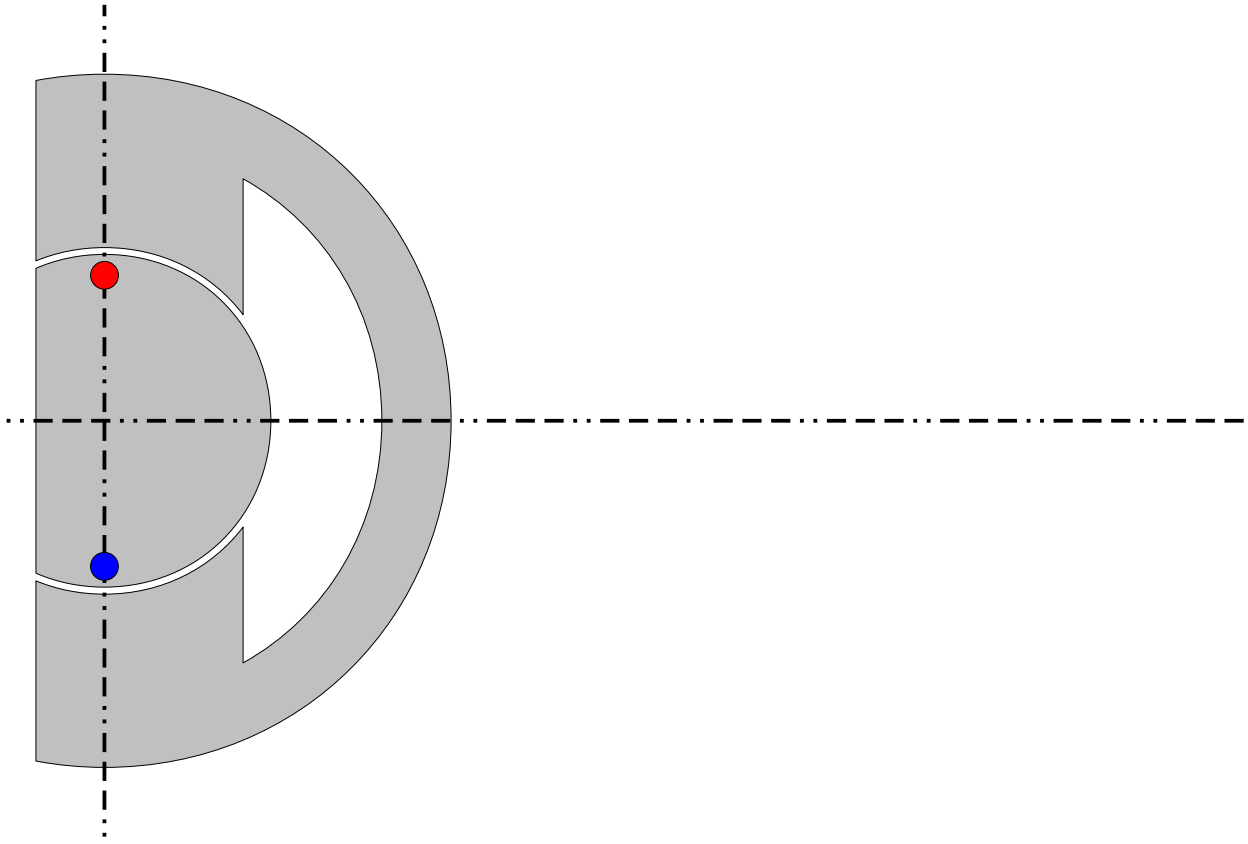
Winding Pitch Factor

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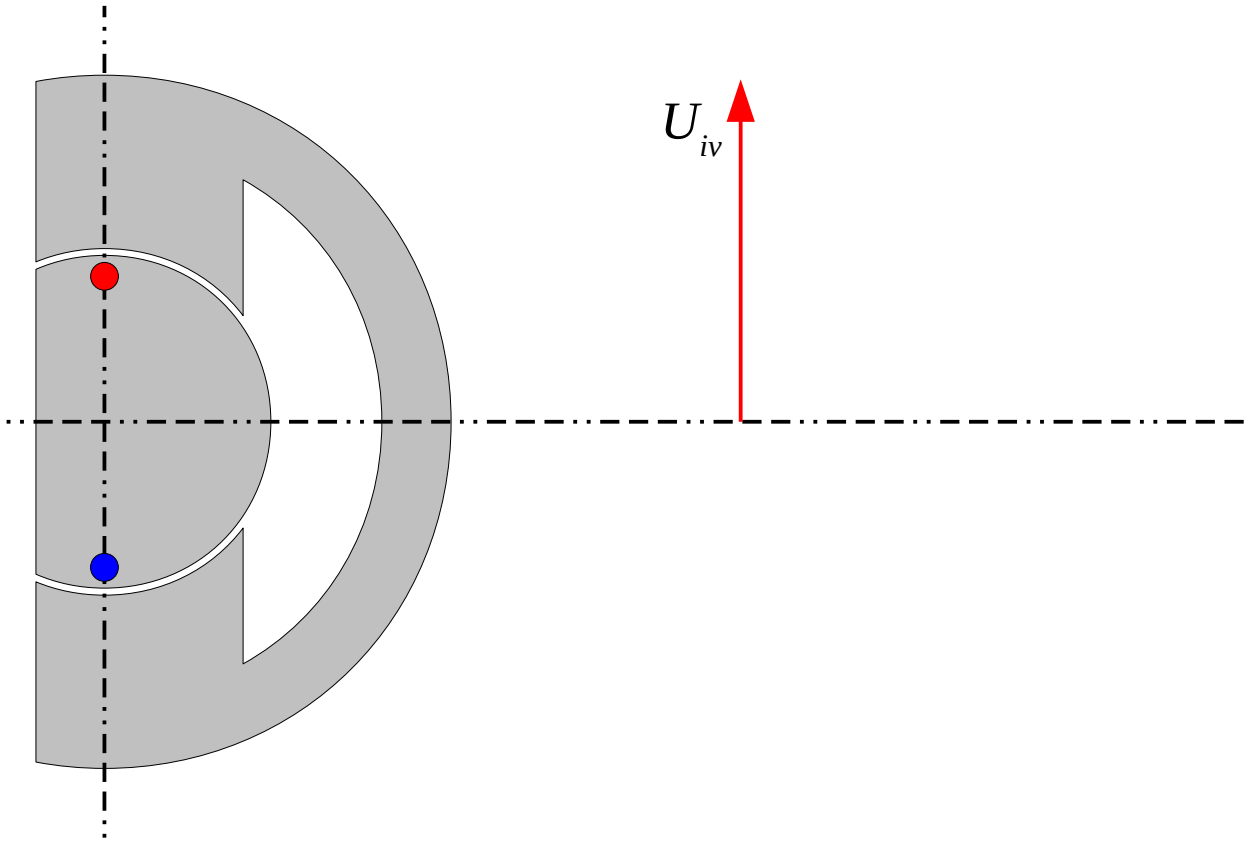
- It is derived from the presumption that the induced voltage in a coil side may be represented by one phasor
- Ideal solution – connection of two coil sides, whose pitch is equal to the pole pitch
- In this case the result is an arithmetic sum of induced voltages



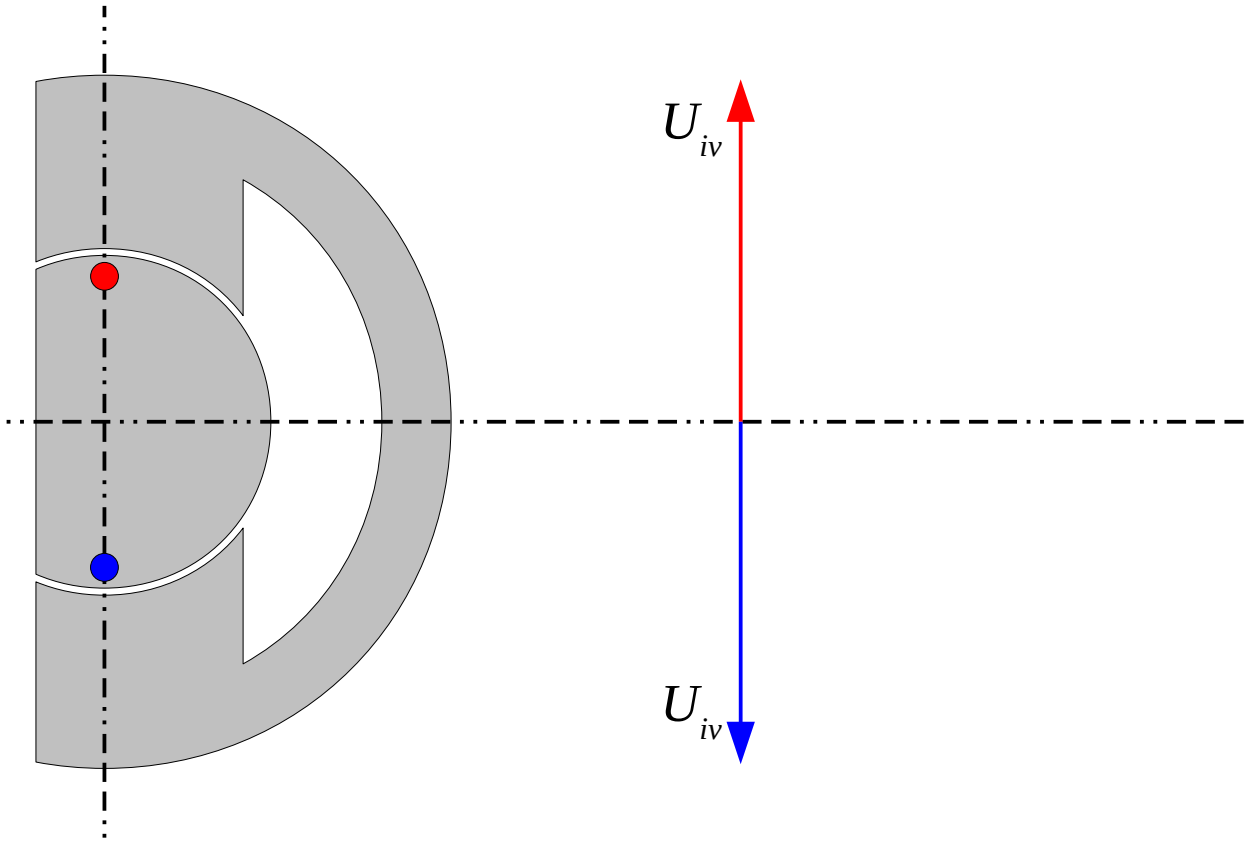
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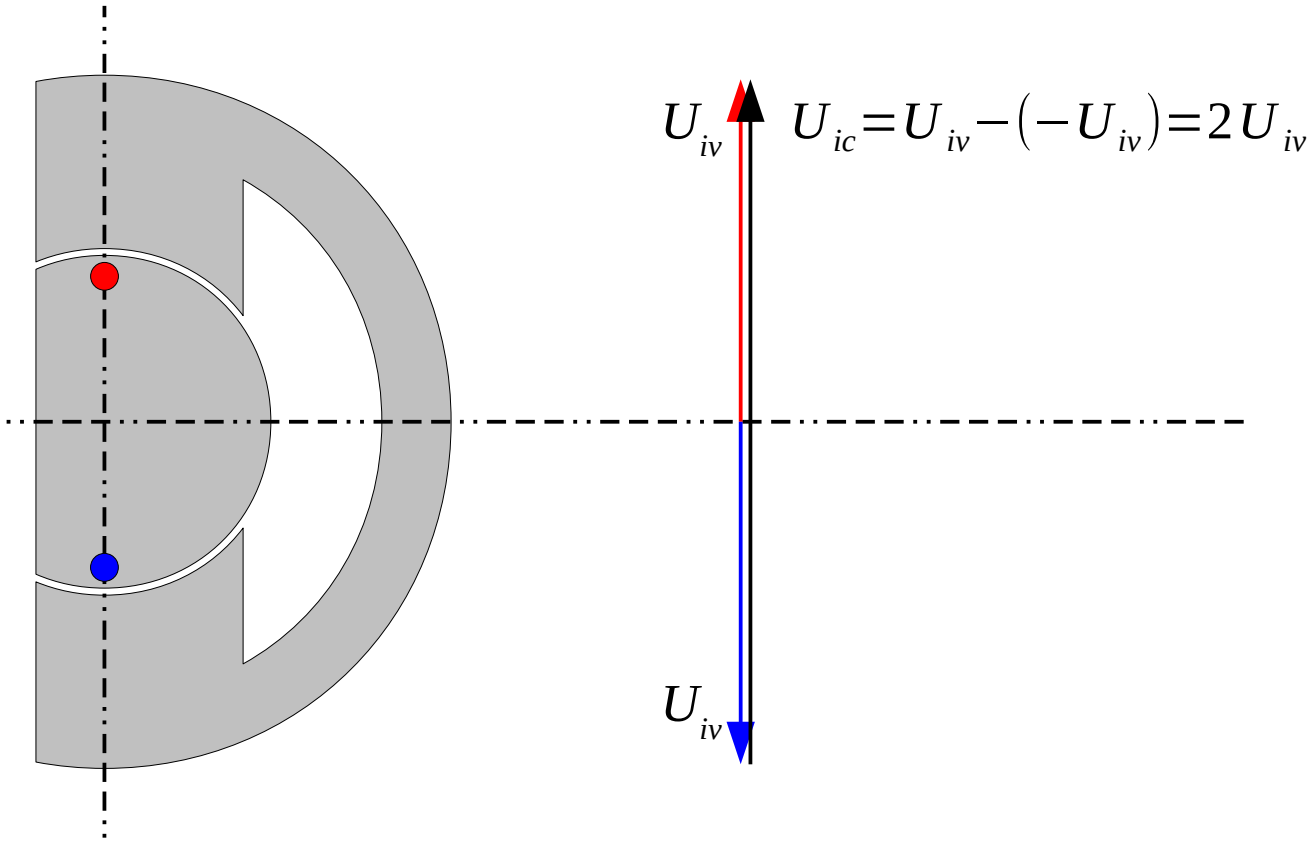
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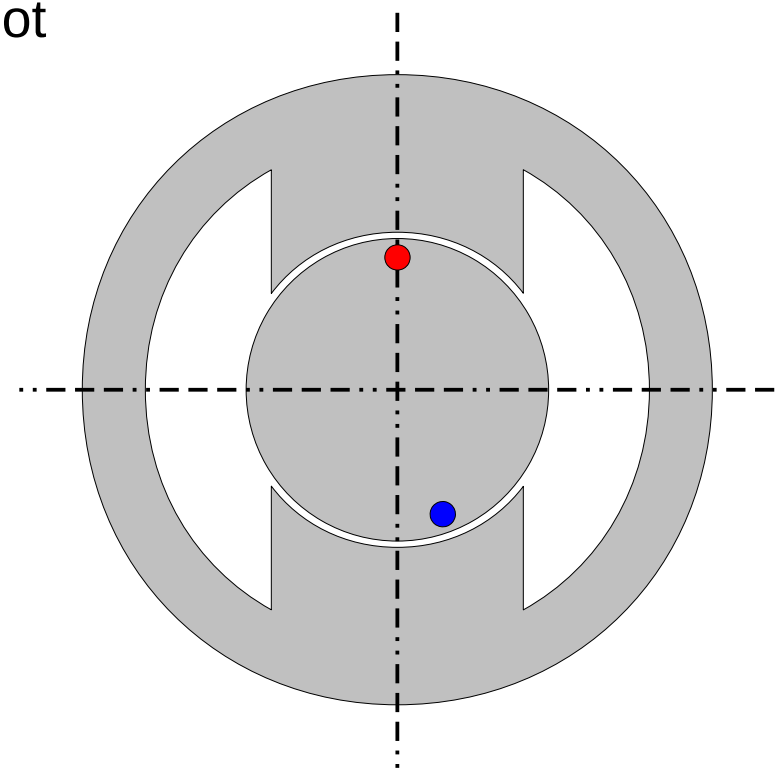


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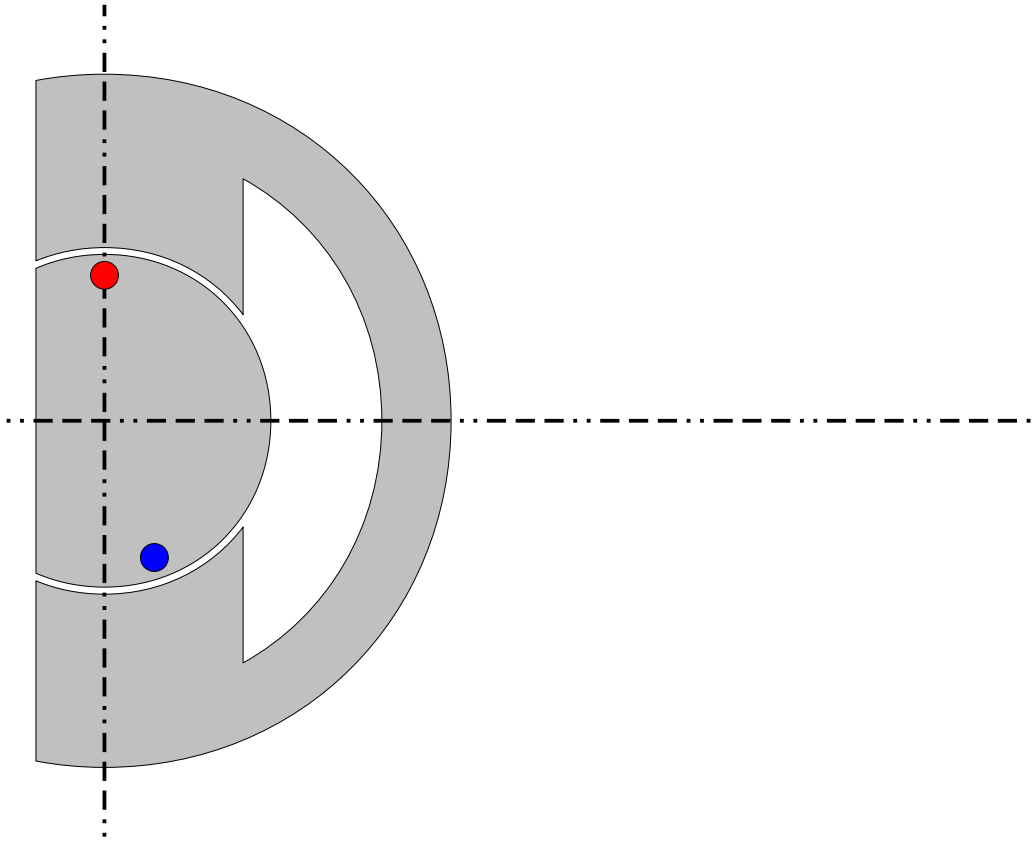


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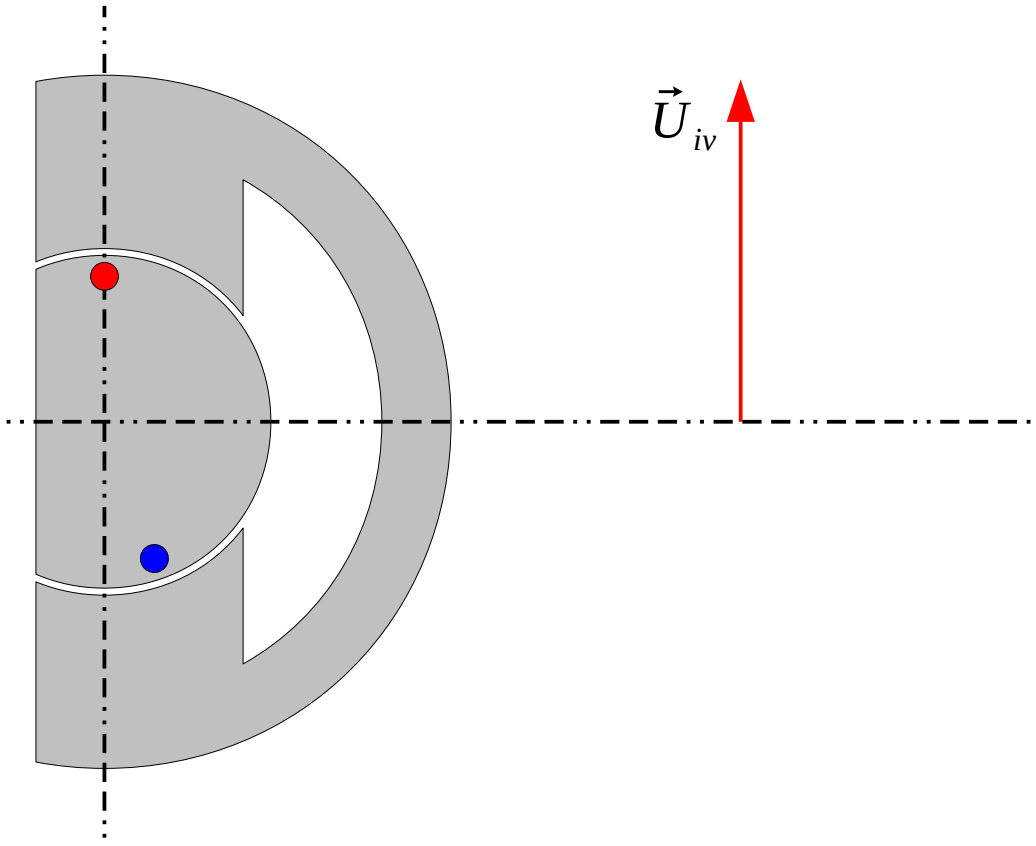
- In a real machine the may not be available a slot in exactly on pole pitch away
  => it is necessary to shorten/extend the coil pitch
- In this case it is not possible to derive the induced voltage as arithmetic sum
  => geometric sum



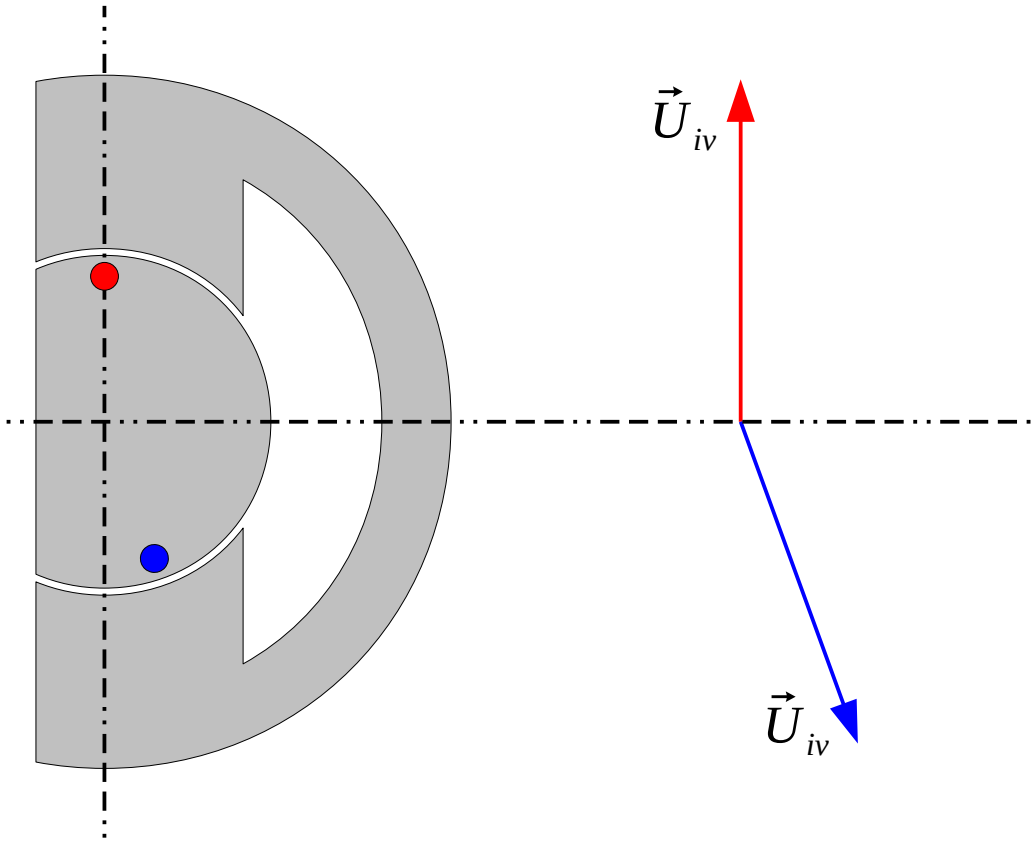
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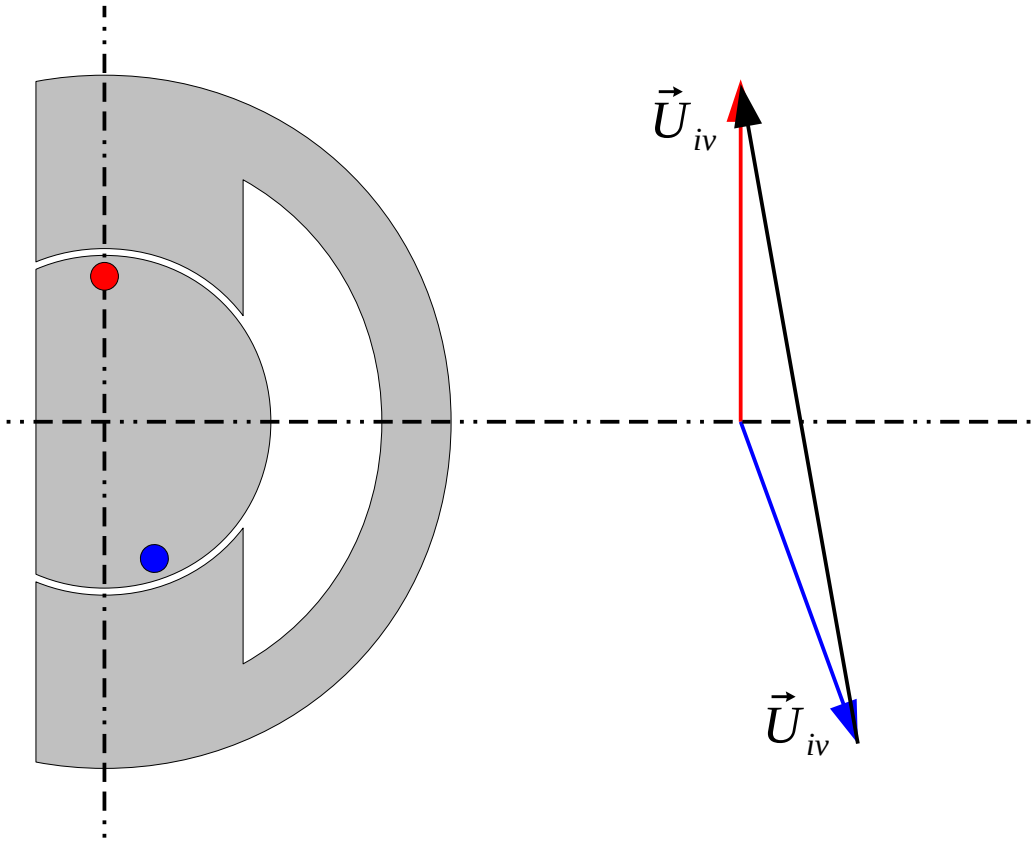
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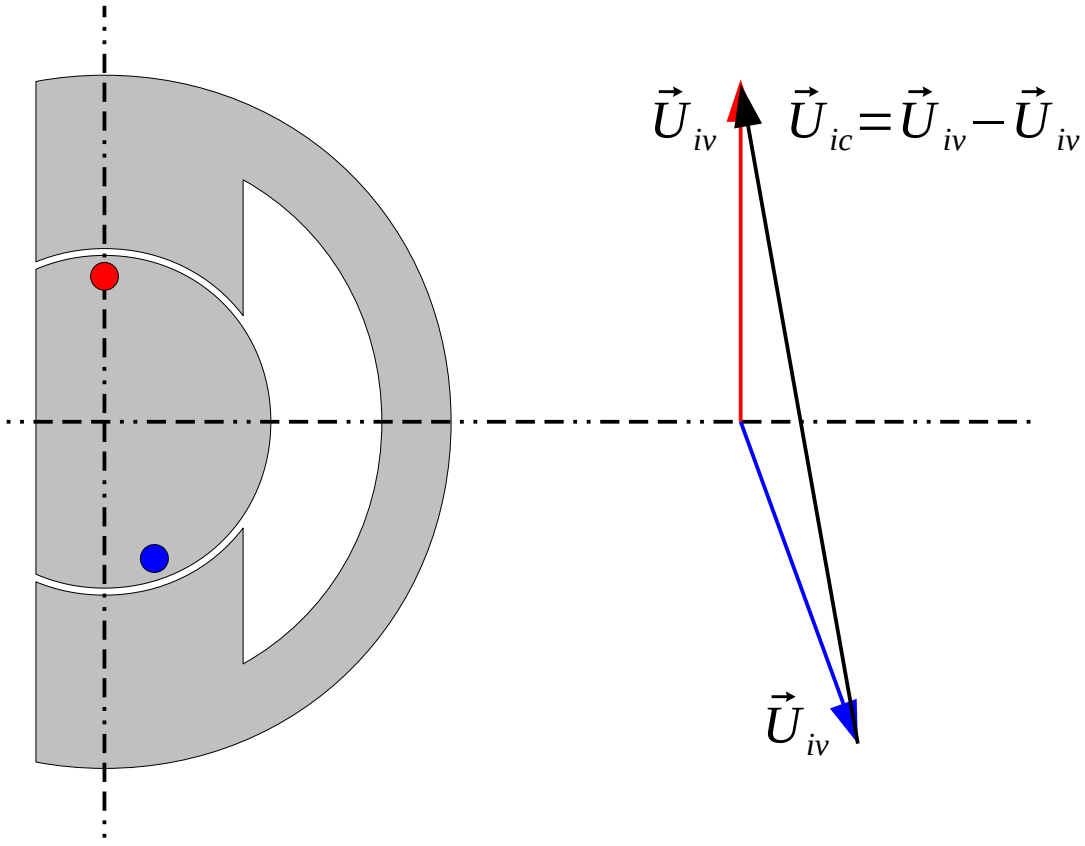
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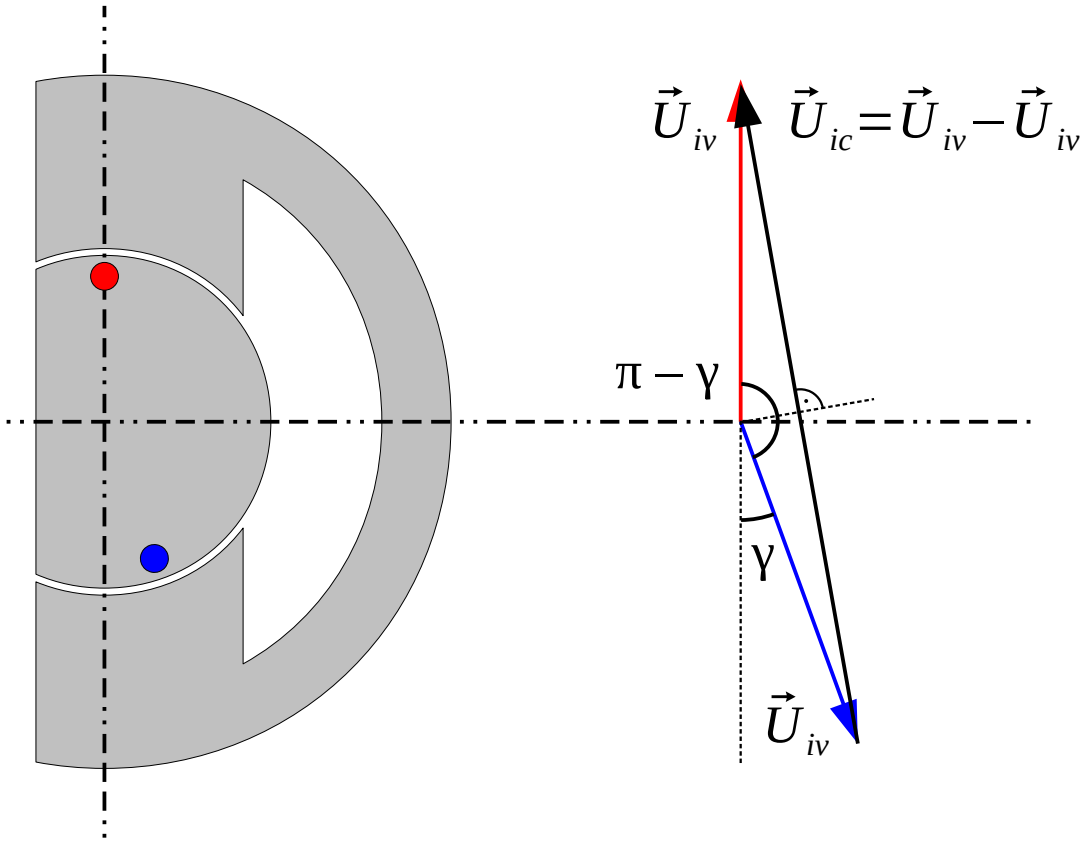
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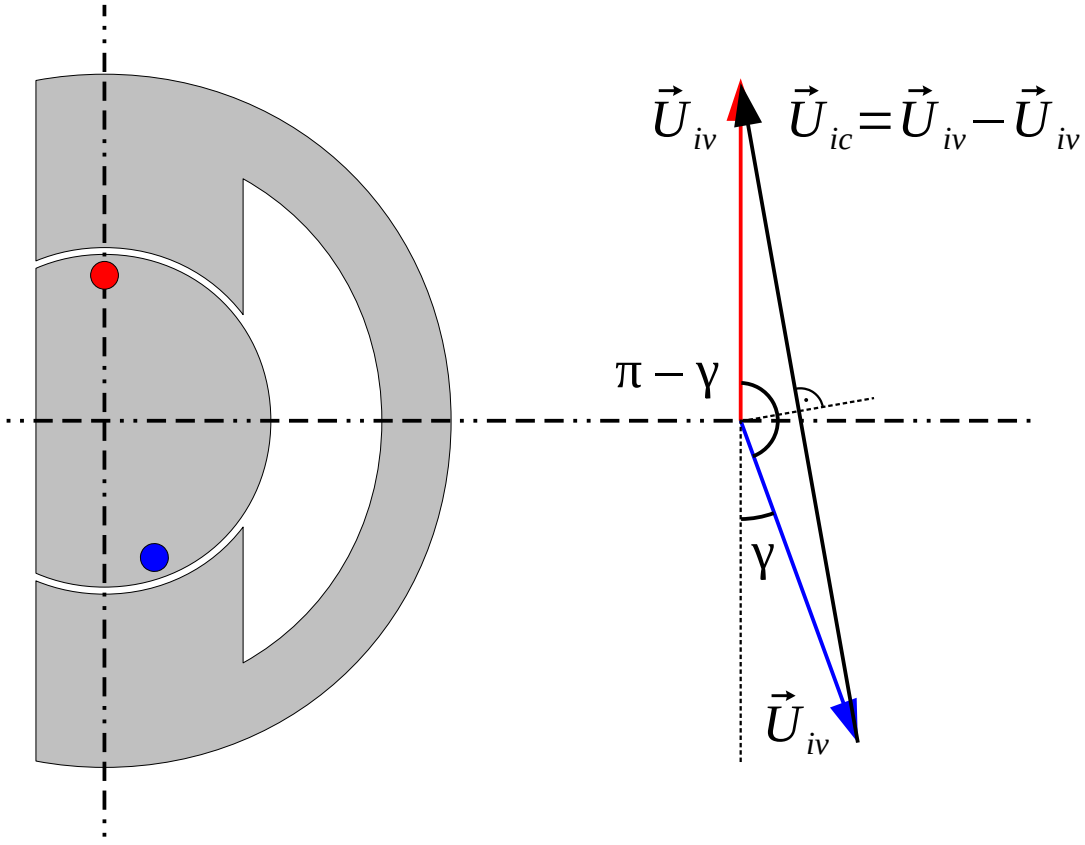
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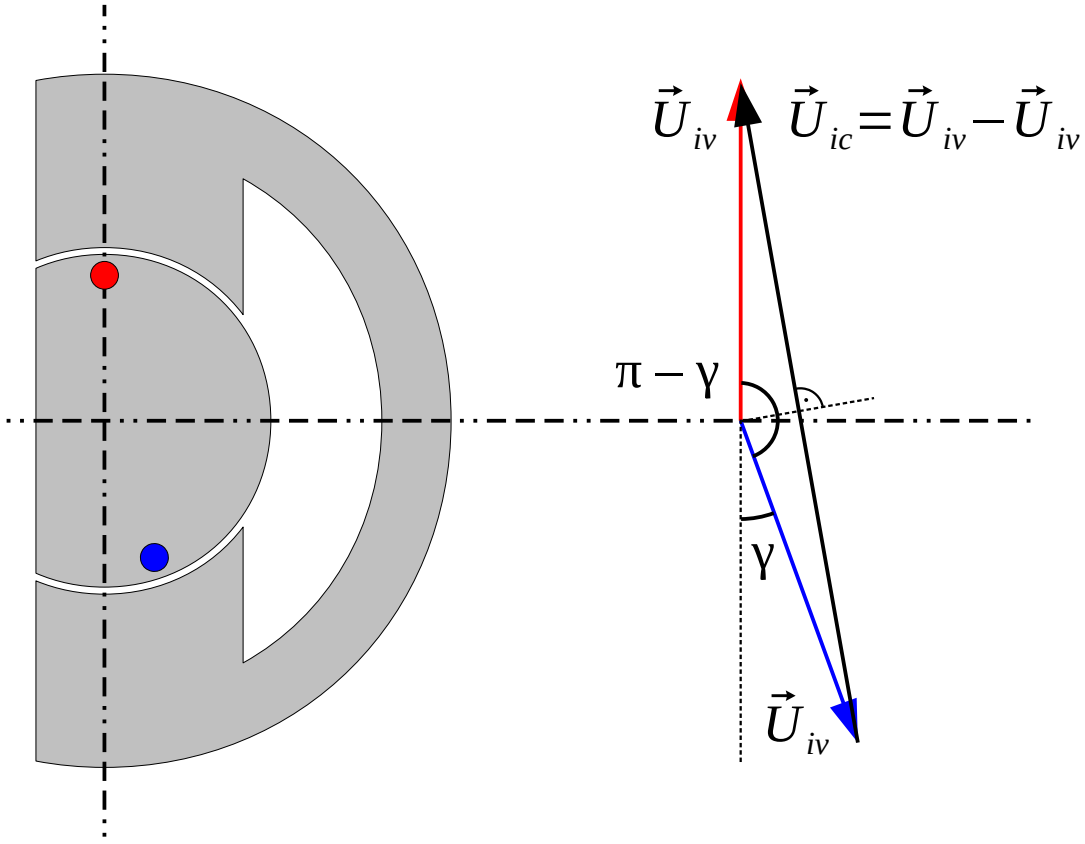
Winding Pitch Factor



Induced voltage into a coil is:

$$\frac{U_{ic}}{2}=U_{iv}\sin\left(\frac{\pi-\gamma}{2}\right)$$

Winding Pitch Factor

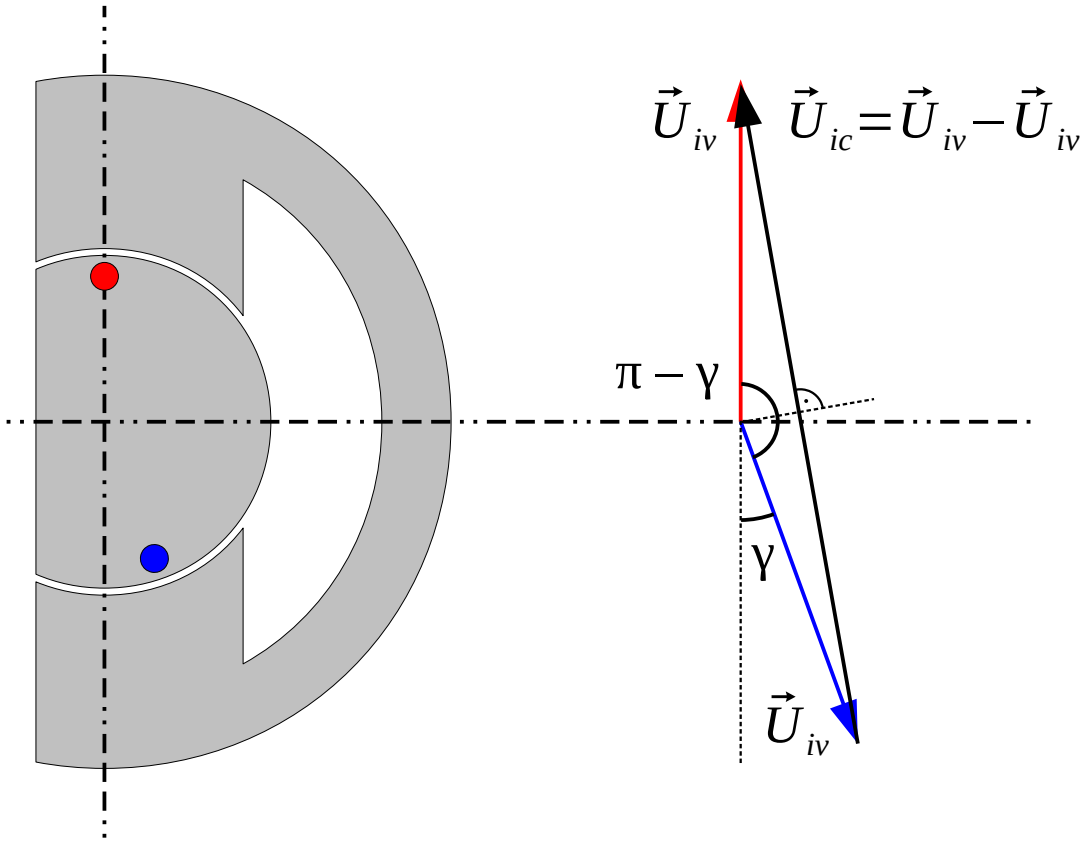


Induced voltage into a coil is:

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Winding Pitch Factor



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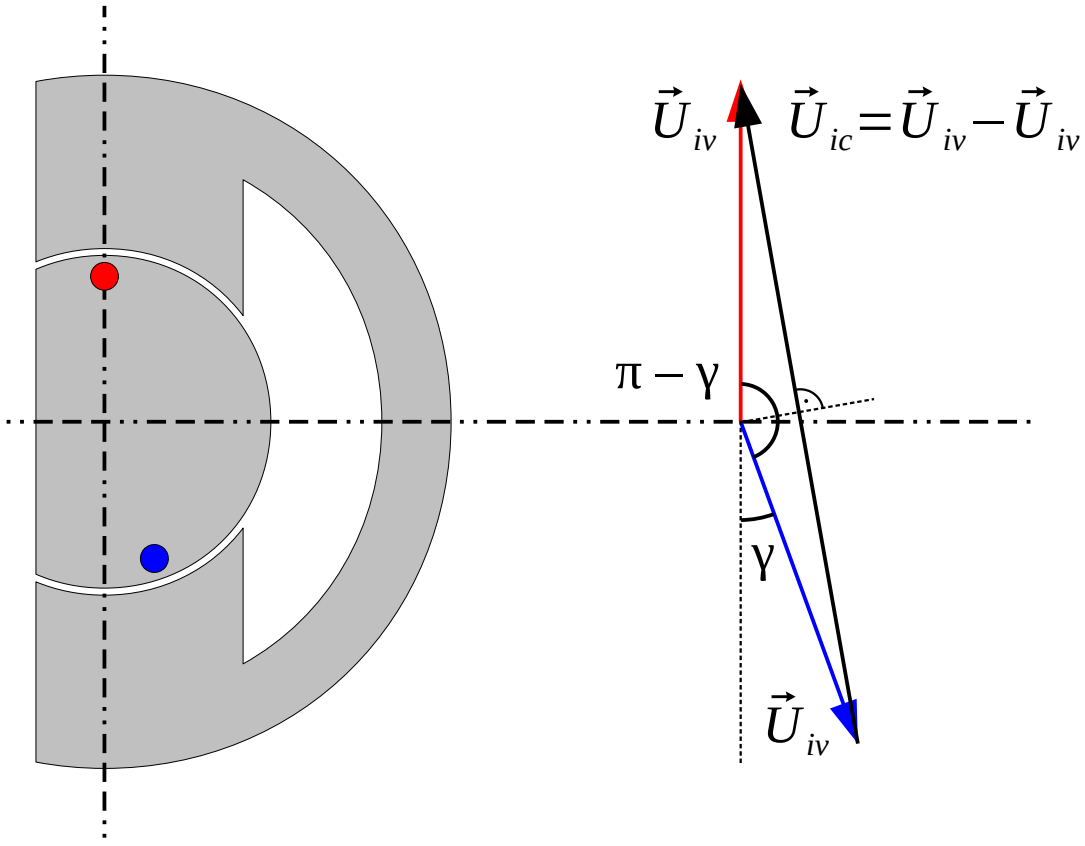
$$\frac{U_{ic}}{2}=U_{iv}\sin\left(\frac{\pi-\gamma}{2}\right)$$

$$U_{ic}=2U_{iv}\sin\left(\frac{\pi-\gamma}{2}\right)$$

The winding pitch factor is given as a ratio of geometric and arithmetic sum:

$$k_y=\frac{U_{icg}}{U_{ica}}=\frac{2U_{iv}\sin\left(\frac{\pi-\gamma}{2}\right)}{2U_{iv}}$$

Winding Pitch Factor



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Winding Pitch Factor

- The obtained ration may be further extended

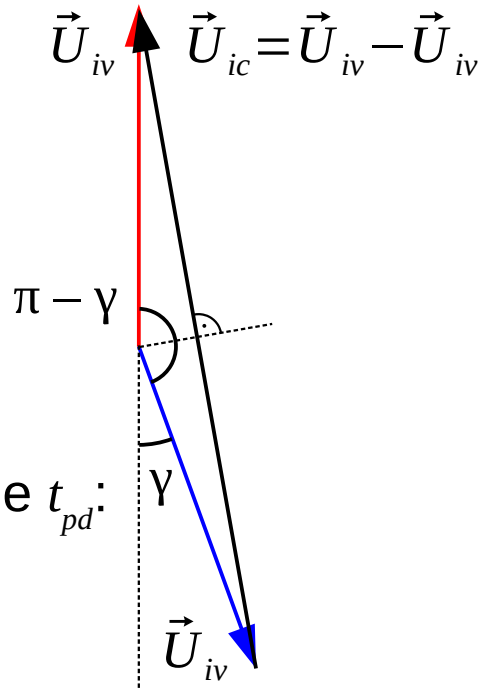
$$k_y = \sin\left(\frac{\pi-\gamma}{2}\cdot\frac{\pi}{\pi}\right) = \sin\left(\frac{\pi-\gamma}{\pi}\cdot\frac{\pi}{2}\right)$$

and introduce the winding pitch shortening factor

$$\beta = \frac{\pi-\gamma}{\pi}$$

- The winding pitch shortening factor may be then easily obtained from the coil pitch y_{1d} and pole pitch of the machine t_{pd}:

$$\beta = \frac{\pi-\gamma}{\pi} = \frac{y_{1d}}{t_{pd}}$$



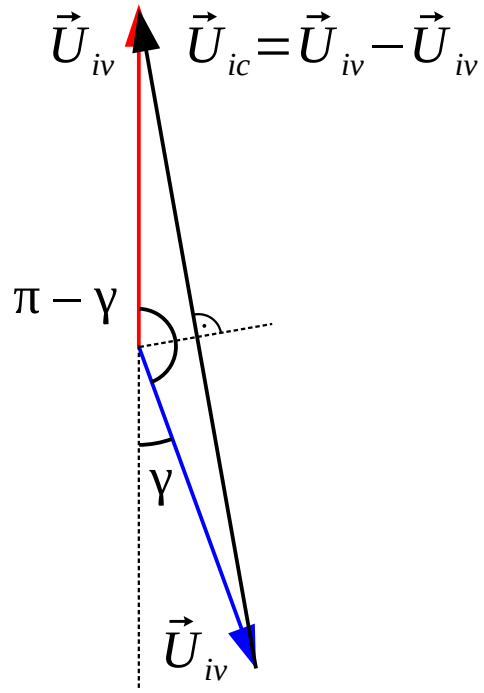
Winding Pitch Factor

- Then the often used form of the winding pitch factor relation is obtained:

$$k_y = \sin\left(\beta \frac{\pi}{2}\right) \qquad \text{or} \qquad k_y = \sin\left(\frac{y_{1d}}{t_{pd}} \cdot \frac{\pi}{2}\right)$$

where y_{1d} is the coil pitch

and t_{pd} is the pole pitch, both calculated in amount of slots



Winding Pitch Factor

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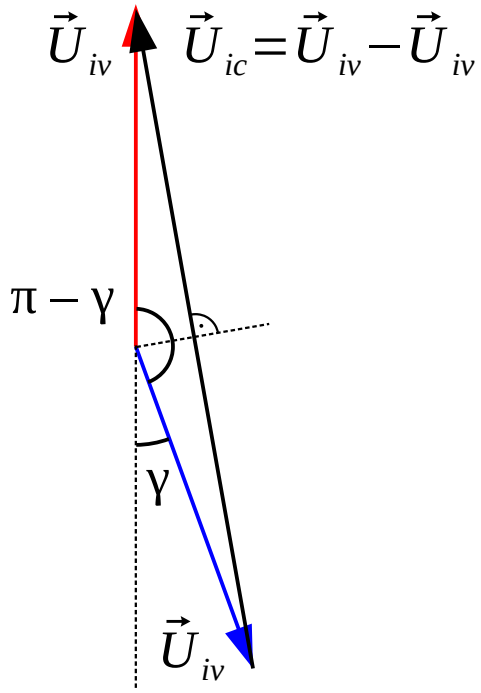
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where y_{1d} is the coil pitch

and t_{pd} is the pole pitch, both calculated in amount of slots

- For higher order harmonic component it is ν-times higher:

$$k_{y\nu} = \sin\left(\nu \beta \frac{\pi}{2}\right)$$

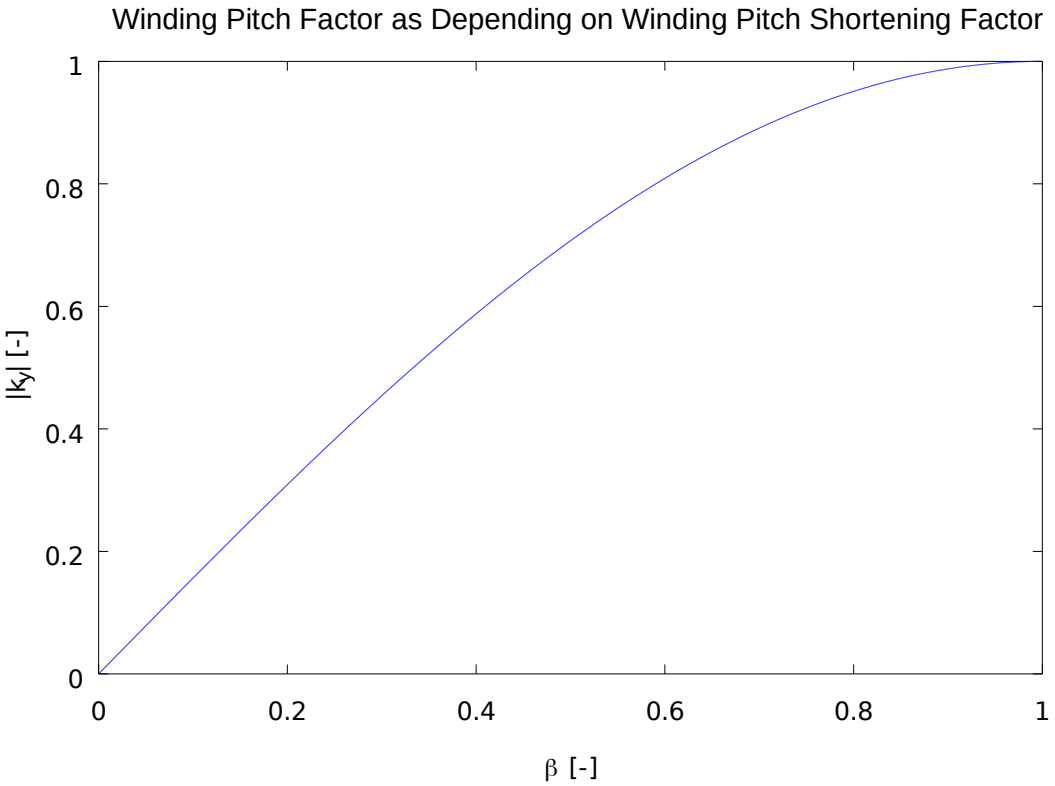


Winding Pitch Factor

- Thus, except dependency on winding pitch shortening factor the winding pitch factor depends also on the order of harmonic component for which it is solved
- For any harmonic component it is possible to draw a dependency of

$$k_{y\nu} = f(\nu, \beta)$$

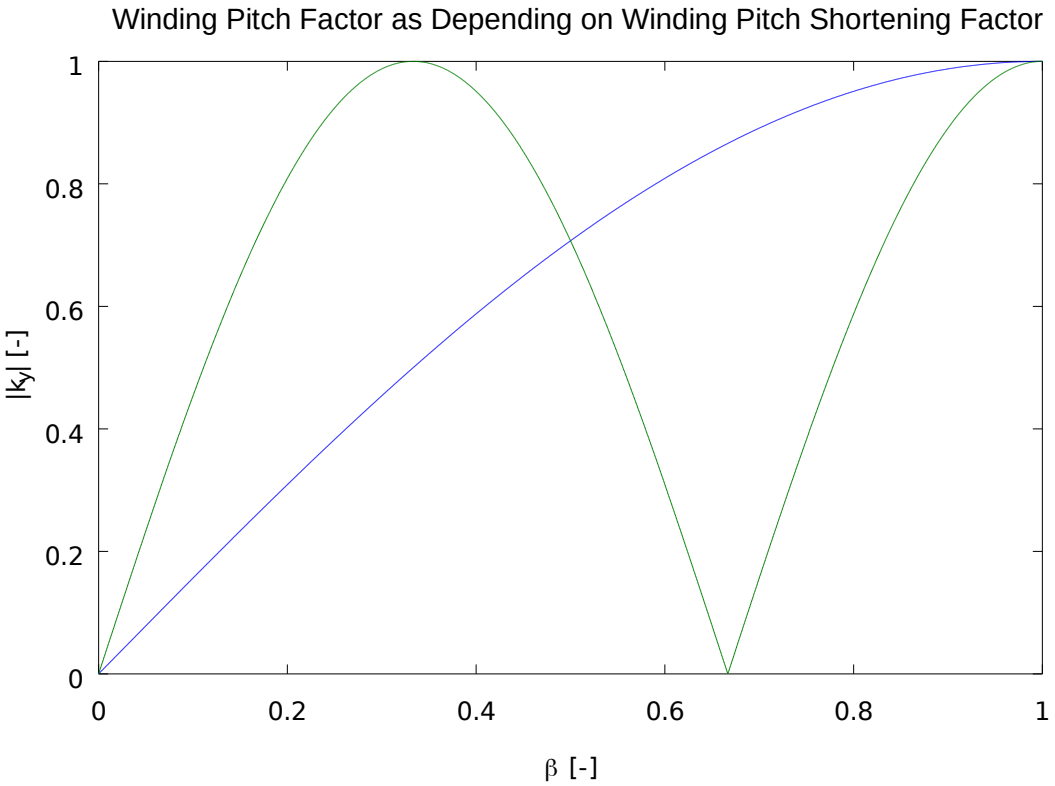
Winding Pitch Factor



$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1$$

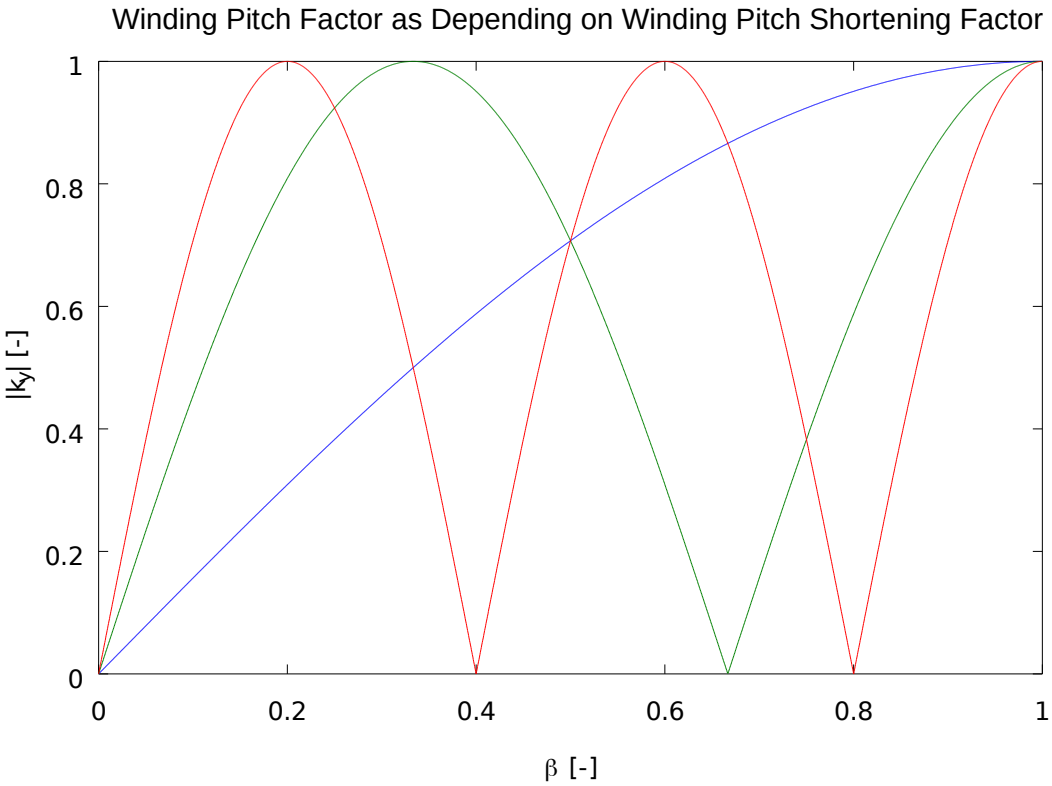
Winding Pitch Factor



$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3$$

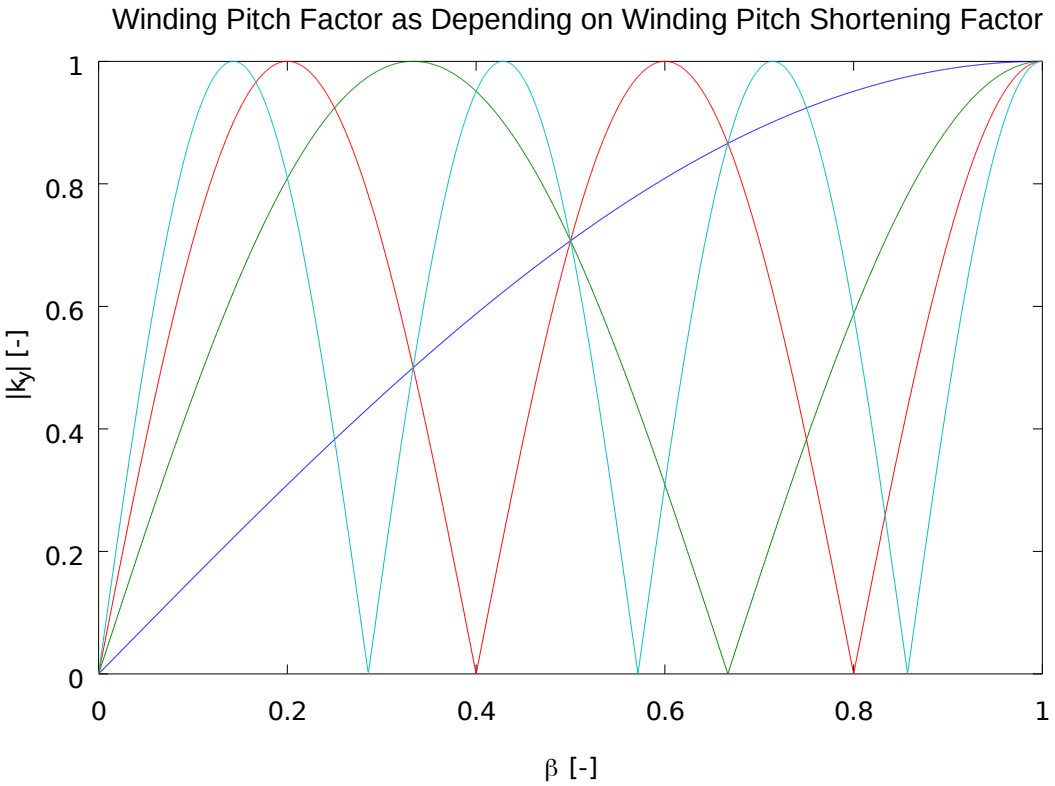
Winding Pitch Factor



$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3, 5$$

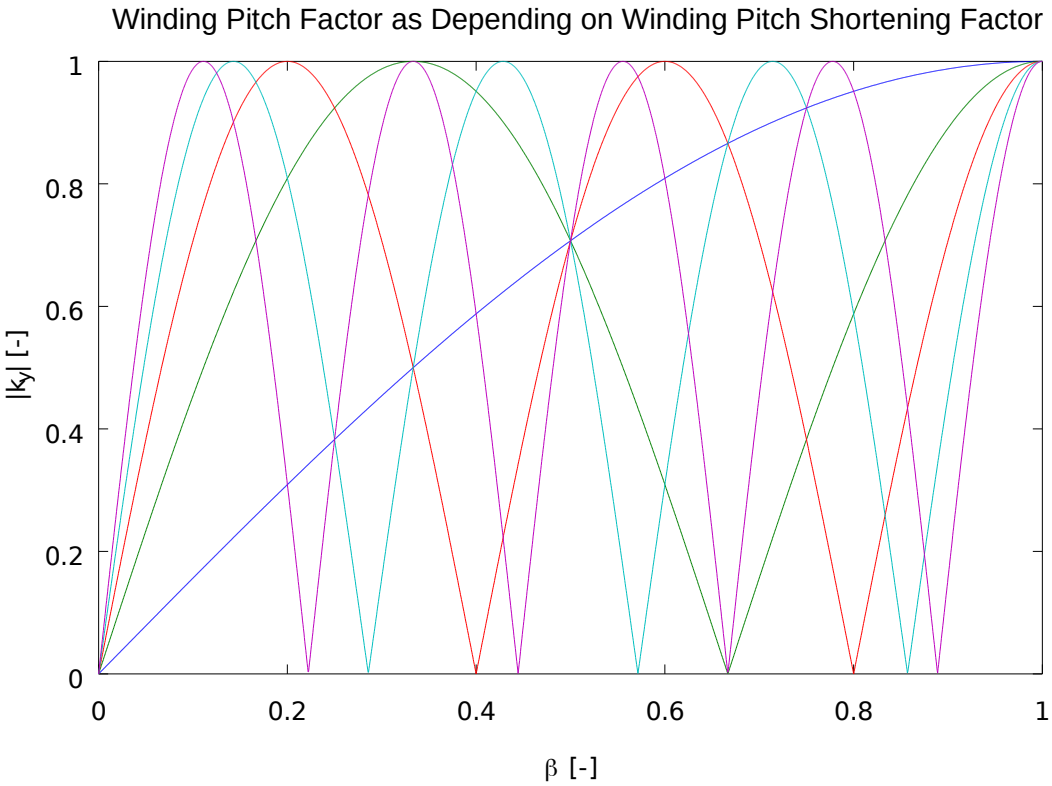
Winding Pitch Factor



$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3, 5, 7$$

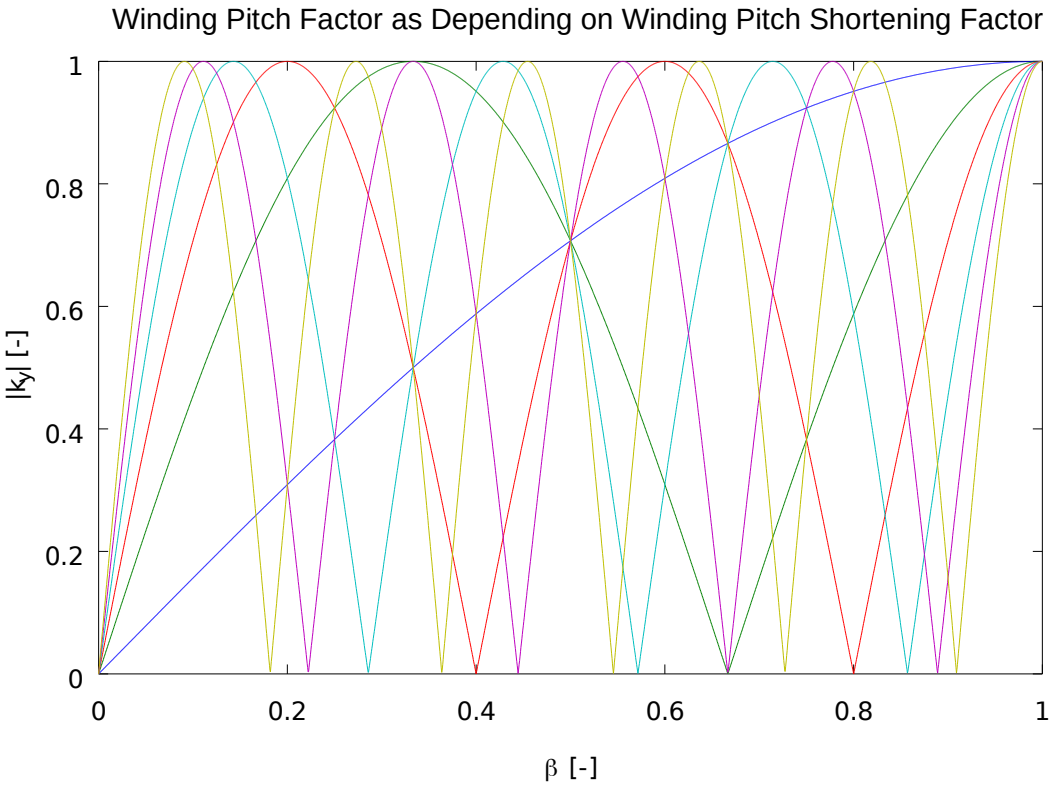
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$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3, 5, 7, 9$$

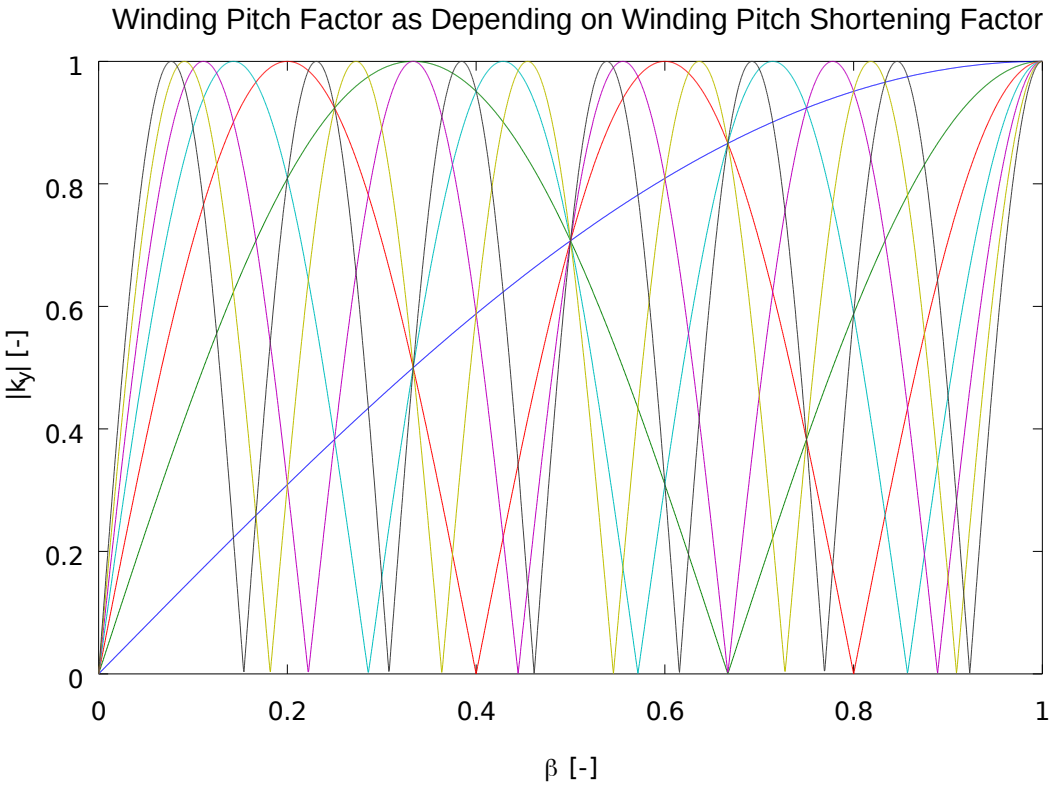
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$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3, 5, 7, 9, 11$$

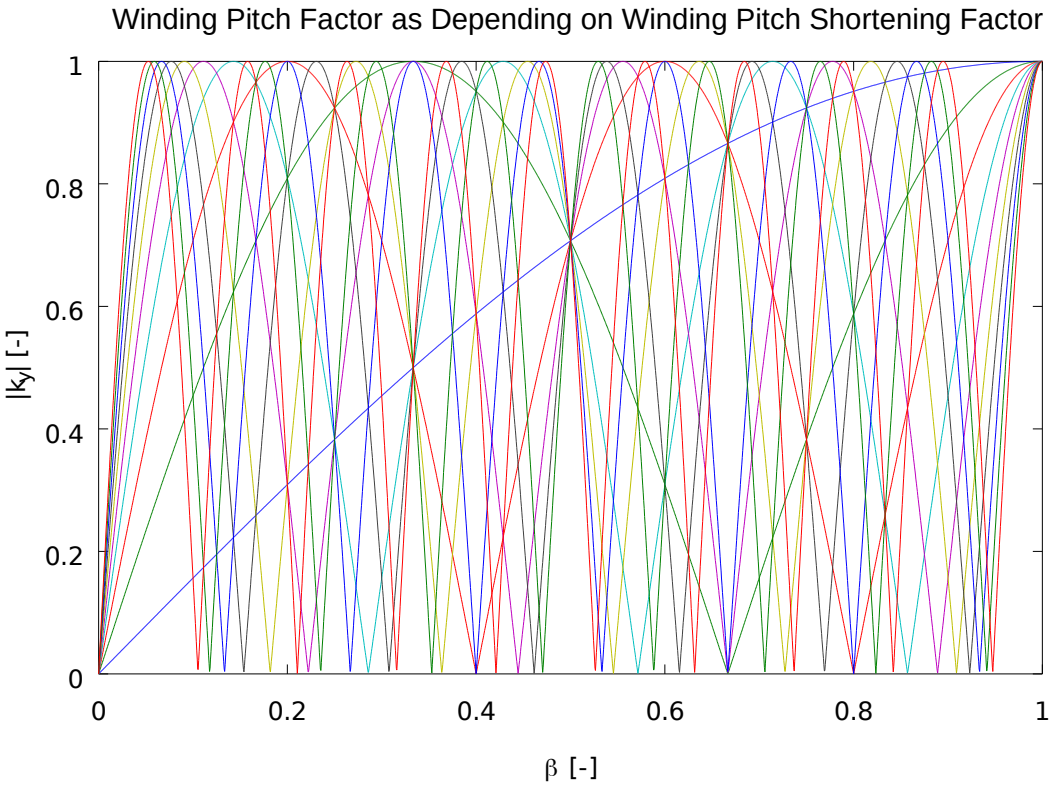
Winding Pitch Factor



$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3, 5, 7, 9, 11, 13$$

Winding Pitch Factor



$$k_y = \left| \sin\left(\nu \beta \frac{\pi}{2} \right) \right|$$

$$\nu = 1, 3, 5, 7, 9, 11, 13 \ldots$$

Winding Pitch Factor

- Thus, except dependency on winding pitch shortening factor the winding pitch factor depends also on the order of harmonic component for which it is solved
- For any harmonic component it is possible to draw a dependency of

$$k_{y\nu} = f(\nu, \beta)$$

- For certain winding pitch shortening factors the winding pitch factors are equal to zero
- The most important winding pitch factors are for low harmonic components (they have greatest magnitude)

Winding Pitch Factor

- To have possibly highest decrease of low order harmonic components, an optimal winding pitch factor value is used
- Presumptions:
  - For three phase machines the 3^{rd} harmonic component disappears from the phase-to-phase voltage
    => it is not considered
  - As most important orders remain 5^{th} and 7^{th} harmonic component

Winding Pitch Factor

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- Presumptions:
  - For three phase machines the 3rd harmonic component disappears from the phase-to-phase voltage
    => it is not considered
  - As most important orders remain 5th and 7th harmonic component
- Thus we seek equality of:

$$k_{y5} = k_{y7}$$

Winding Pitch Factor

$$k_{y5} = k_{y7}$$

Winding Pitch Factor

$$k_{y5} = k_{y7}$$

$$\sin\left(5\beta\frac{\pi}{2}\right) = \sin\left(7\beta\frac{\pi}{2}\right)$$

Winding Pitch Factor

$$k_{y5} = k_{y7}$$

$$\sin\left(5\beta\frac{\pi}{2}\right) = \sin\left(7\beta\frac{\pi}{2}\right)$$

$$\sin\left(5\beta\frac{\pi}{2}\right) - \sin\left(7\beta\frac{\pi}{2}\right) = 0$$

Winding Pitch Factor

$$k_{y5} = k_{y7}$$

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$$\sin\left(5\beta\frac{\pi}{2}\right) - \sin\left(7\beta\frac{\pi}{2}\right) = 0$$

$$\sin x - \sin y = 2\cos\left(\frac{x+y}{2}\right)\sin\left(\frac{x-y}{2}\right)$$

Winding Pitch Factor

$$k_{y5} = k_{y7}$$

$$\sin\left(5\beta\frac{\pi}{2}\right) = \sin\left(7\beta\frac{\pi}{2}\right)$$

$$\sin\left(5\beta\frac{\pi}{2}\right) - \sin\left(7\beta\frac{\pi}{2}\right) = 0$$

$$\sin x - \sin y = 2\cos\left(\frac{x+y}{2}\right)\sin\left(\frac{x-y}{2}\right)$$

$$2\cos\left(\frac{5\beta\frac{\pi}{2} + 7\beta\frac{\pi}{2}}{2}\right)\sin\left(\frac{5\beta\frac{\pi}{2} - 7\beta\frac{\pi}{2}}{2}\right) = 0$$

Winding Pitch Factor

$$k_{y5} = k_{y7}$$

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$$2\cos\left(3\beta\pi\right)\sin\left(\frac{1}{2}\beta\pi\right) = 0$$

Winding Pitch Factor

- The winding pitch factors for 5th and 7th component are equal, when following equation is valid:

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… the solutions are all odd multiplies of 1/6: $\beta=\frac{1}{6};\frac{3}{6};\frac{5}{6};\frac{7}{6};...$

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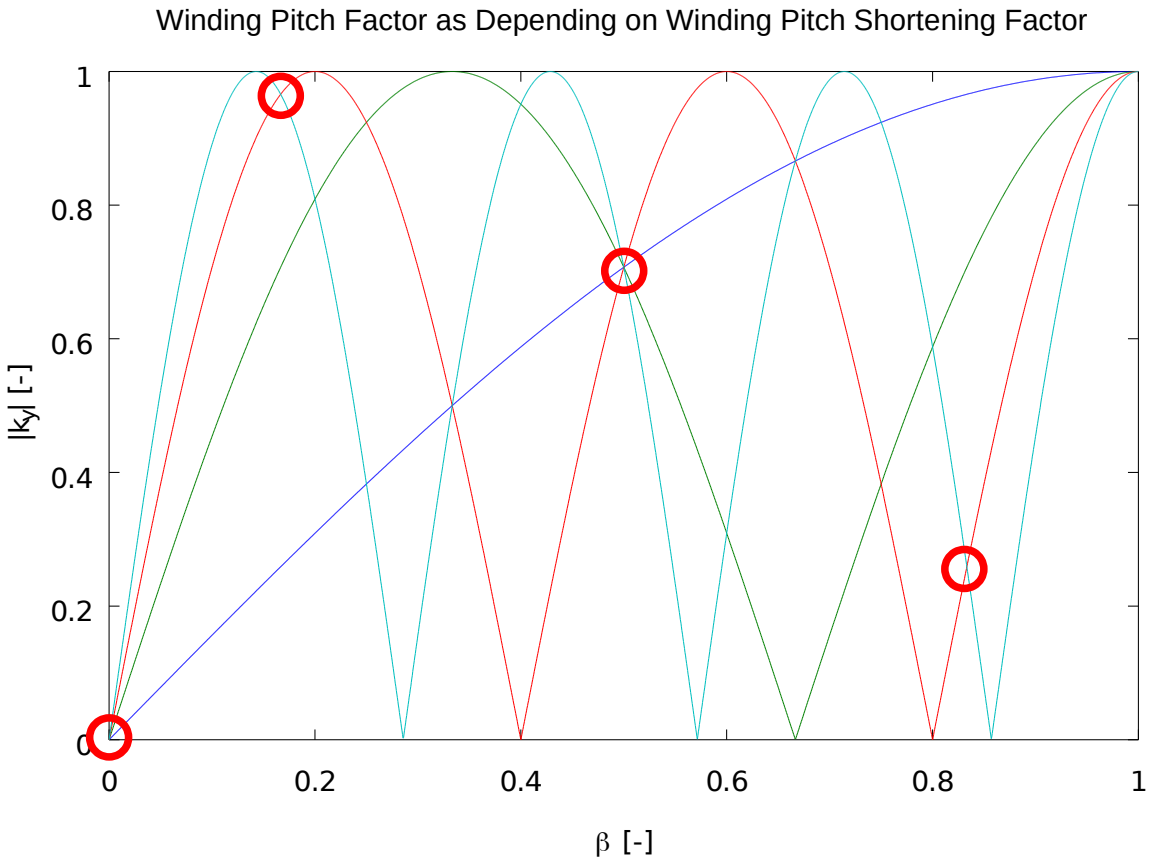
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$$\beta=2k;\quad k\in\mathbb{Z}_0$$

… the solutions are all integer multiplies of 2: $\beta=0;2;...$

Winding Pitch Factor



Winding Pitch Factor

- Considering the value of fundamental harmonic winding pitch factor it is suitable to choose for optimal decrease of 5^{th} and 7^{th} harmonic component winding pitch shortening factor $\beta \simeq \frac{5}{6}$
- For “traditional” AC windings the commonly chosen values of the winding pitch shortening factor are in range of 0,75 – 0,9
- For DC windings the suppression of higher order harmonic components has no reason, thus the coil pitch is always chosen to be possibly closest to the pole pitch (if allowed by manufacture technology)

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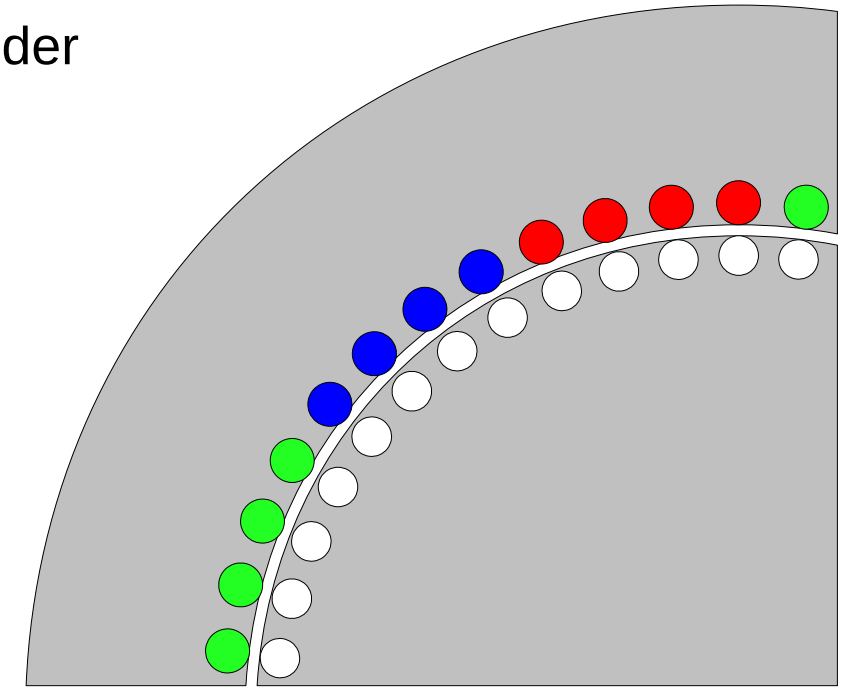
Winding Distribution Factor

Winding Distribution Factor

- Usable only in relation to AC windings – recognizes a degre of usage of periphery of the machine by given phase
- For the purpose of simplification let us consider double-layered winding
- The area of one pole is covered by q slots coinciding with a single phase

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Winding Distribution Factor

- For integer amount of slots per pole and phase q we can write:

$$q = \frac{n}{c}; \qquad c = 1$$

- For a single pole and phase the winding utilizes:

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

slots, where Q is the total amount of slots

$2p$ is the amount of poles of the machine

m is the amount of winding phases

Winding Distribution Factor

- For a fractional amount of slots per pole and phase q we can write:

$$q=\frac{n}{c};\qquad c\in\mathbb{Z}\wedge c\neq 3k;k\in\mathbb{Z}$$

where

$$Q=2pmq=2pm\frac{n}{c}$$

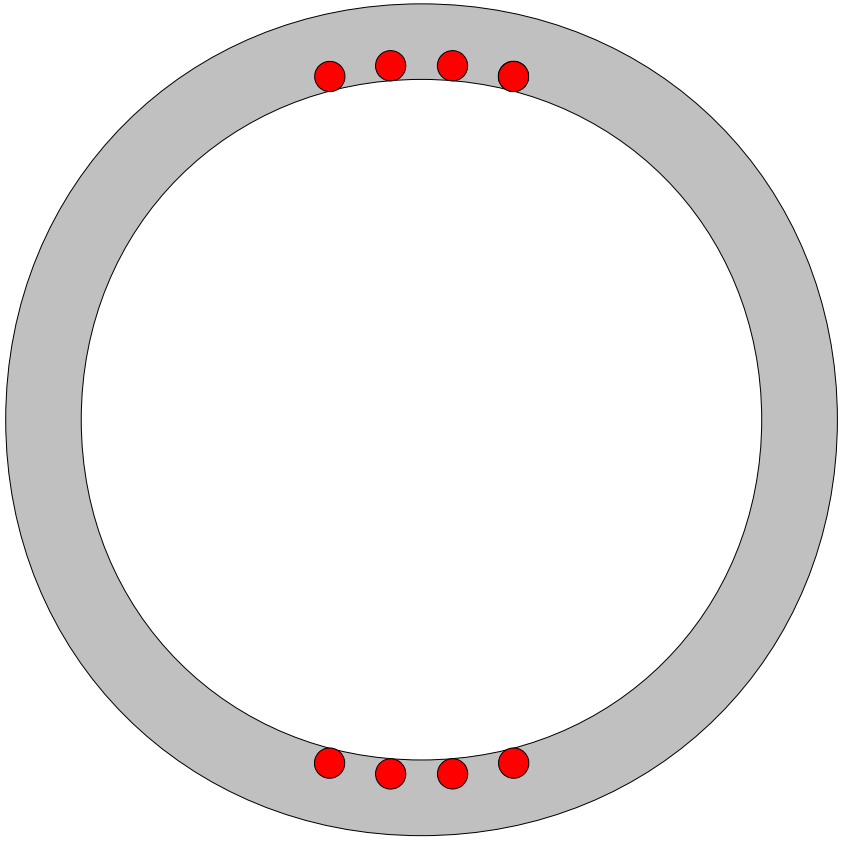
- If the amount of slots is supposed to be an integer number, then $2p$ must be dividable by c
- The amount of slots is then $Q=2pm\frac{n}{c}=kmn$

Winding Distribution Factor

- A fractional winding then has n slots in a phase per each c poles, which repeats k-times along the periphery of the machine
- On the outside the winding the appears similar properties as a winding with $q = n$
- For fractional and integral windings it is possible to calculate the winding distribution factor k_r in the same way

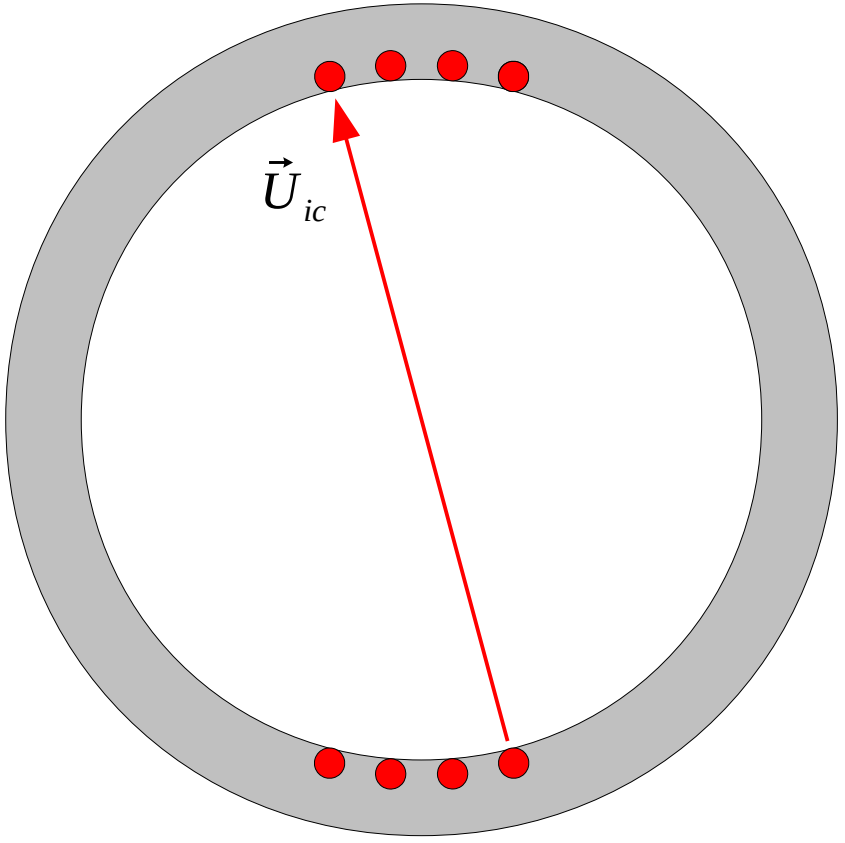
Winding Distribution Factor

- Let us have a group of q coils in series:



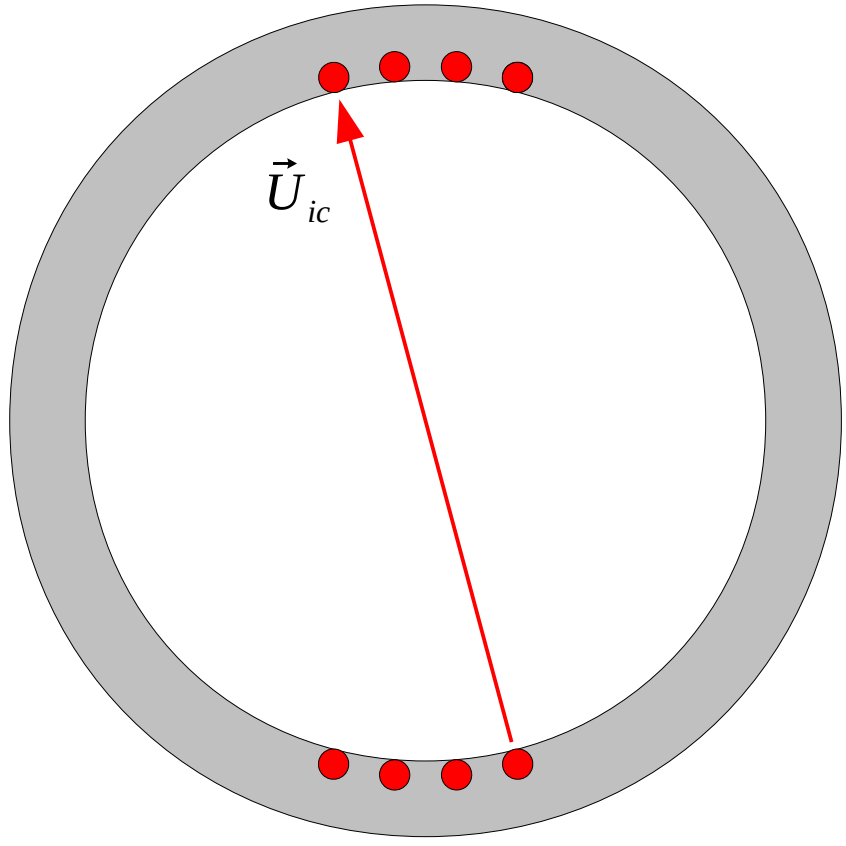
Winding Distribution Factor

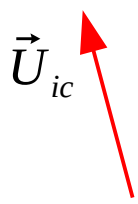
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Winding Distribution Factor

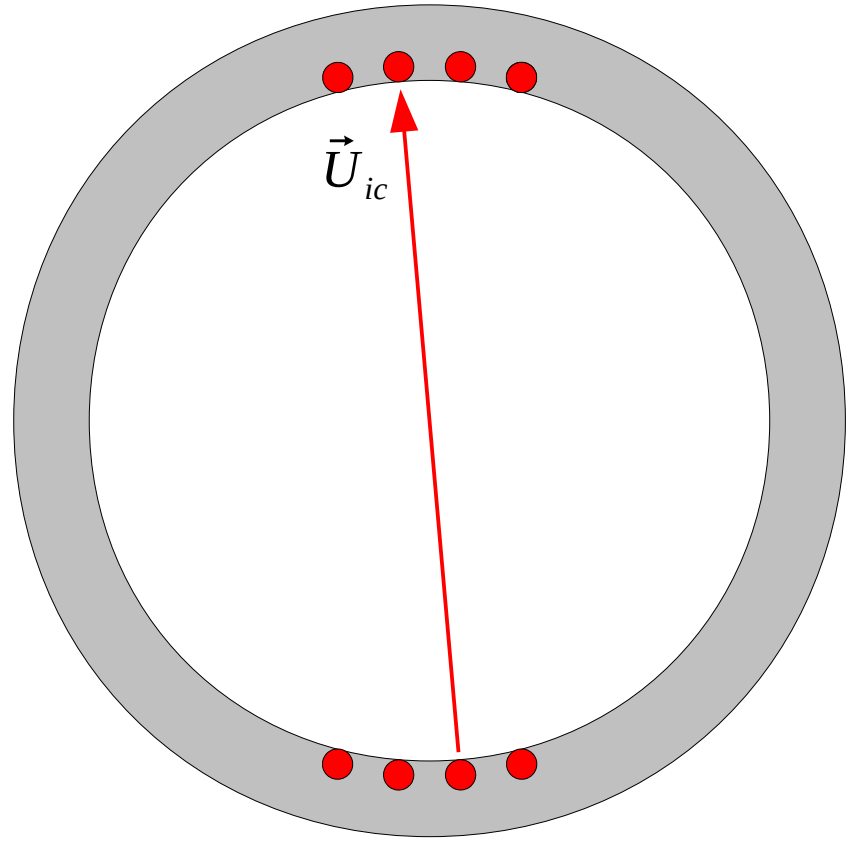
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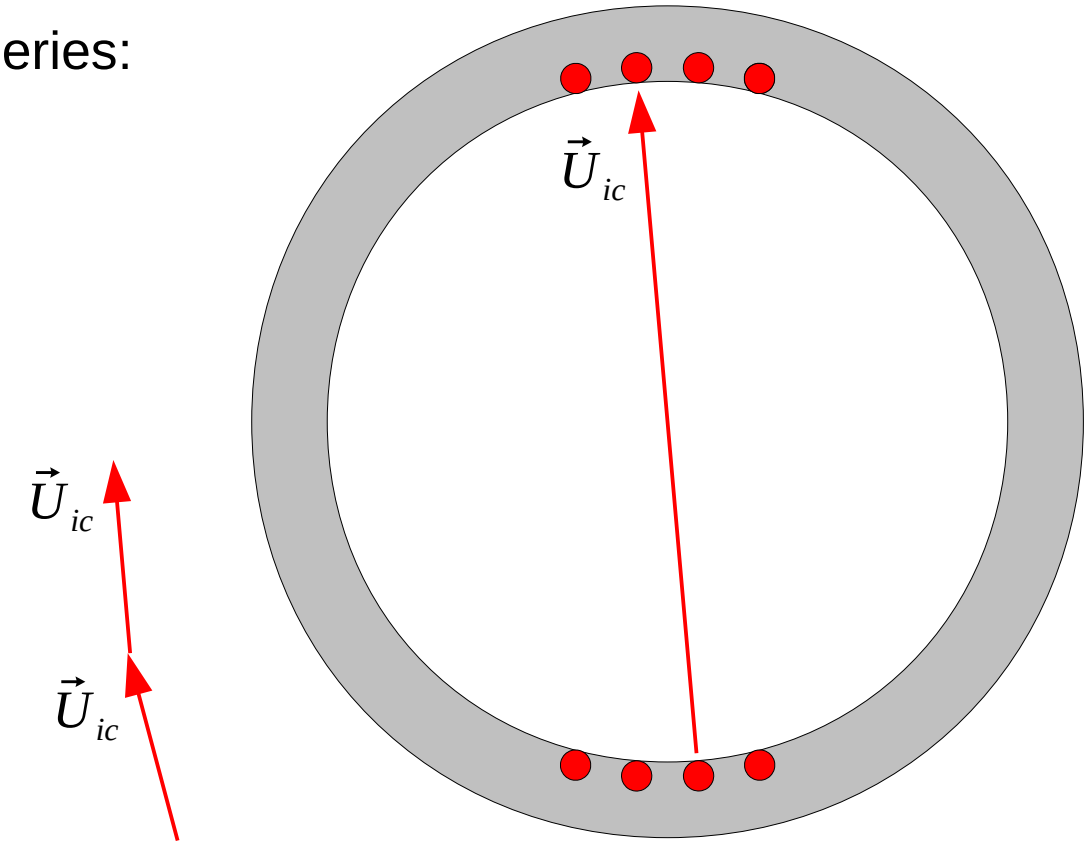
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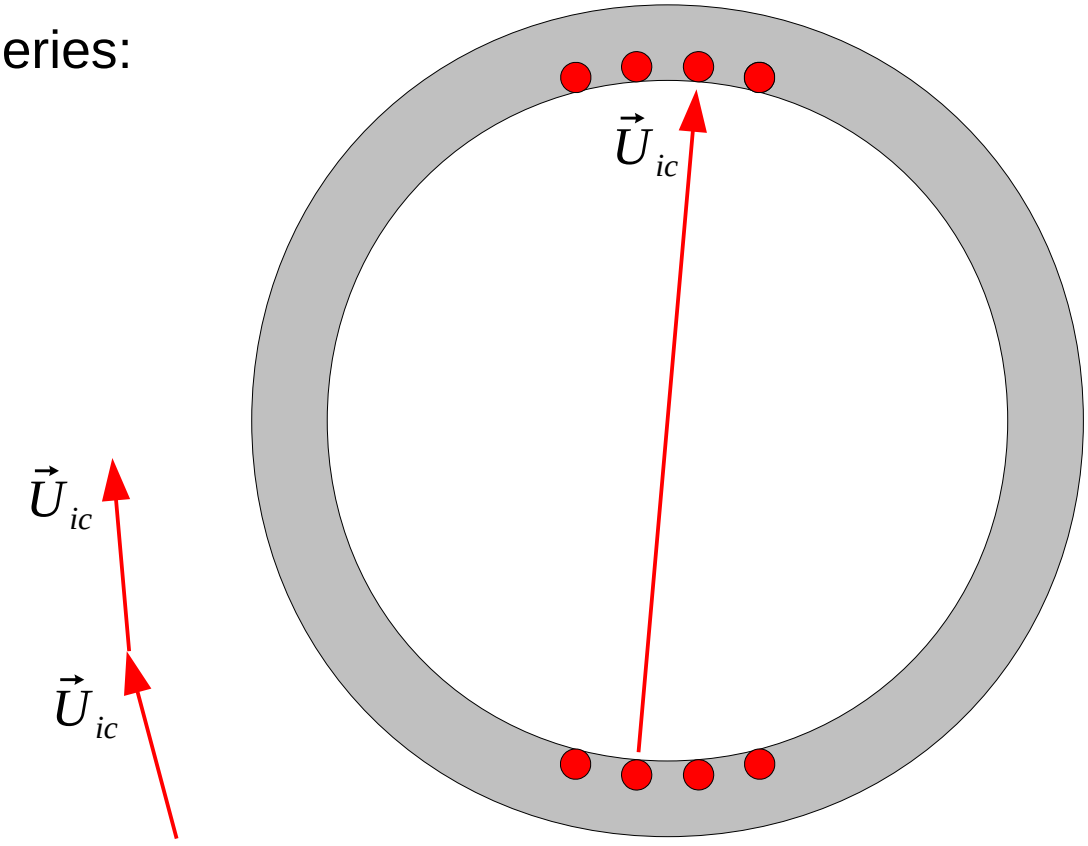
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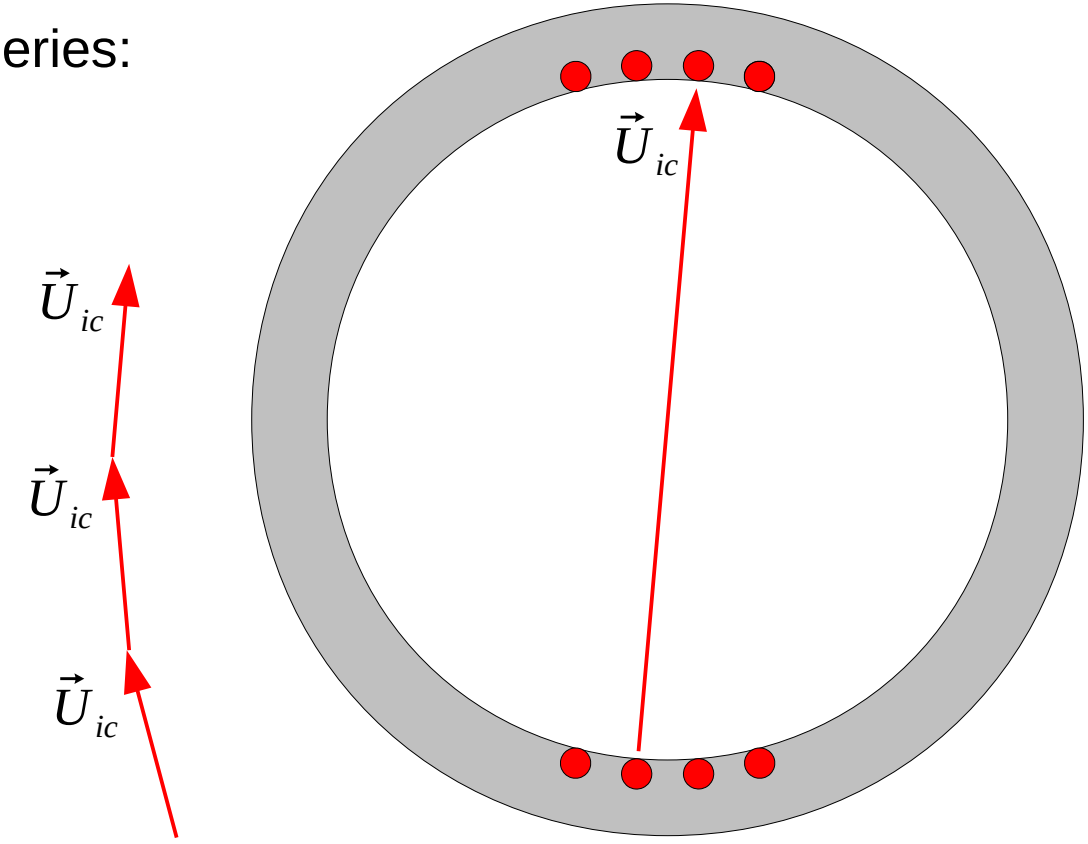
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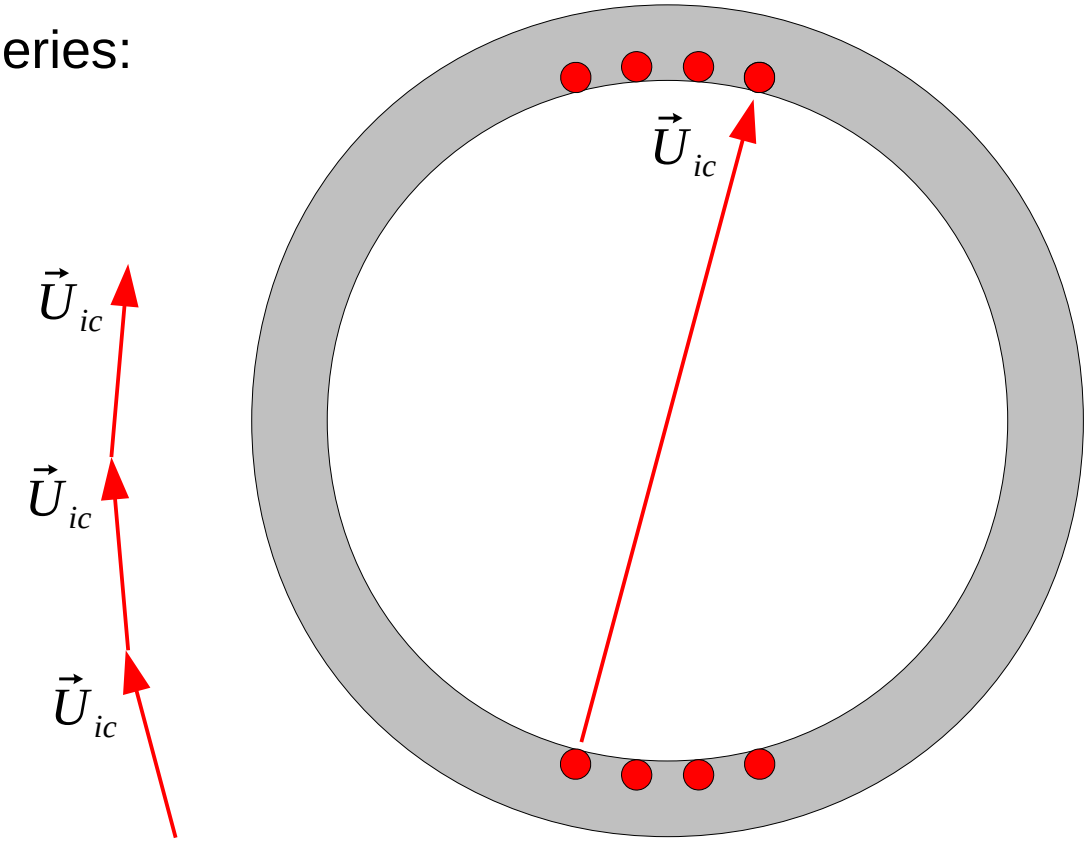
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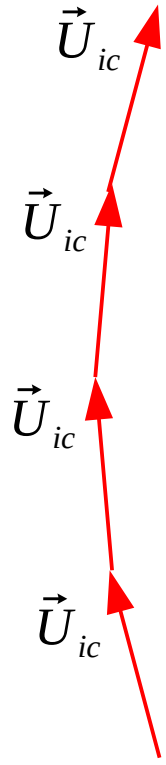
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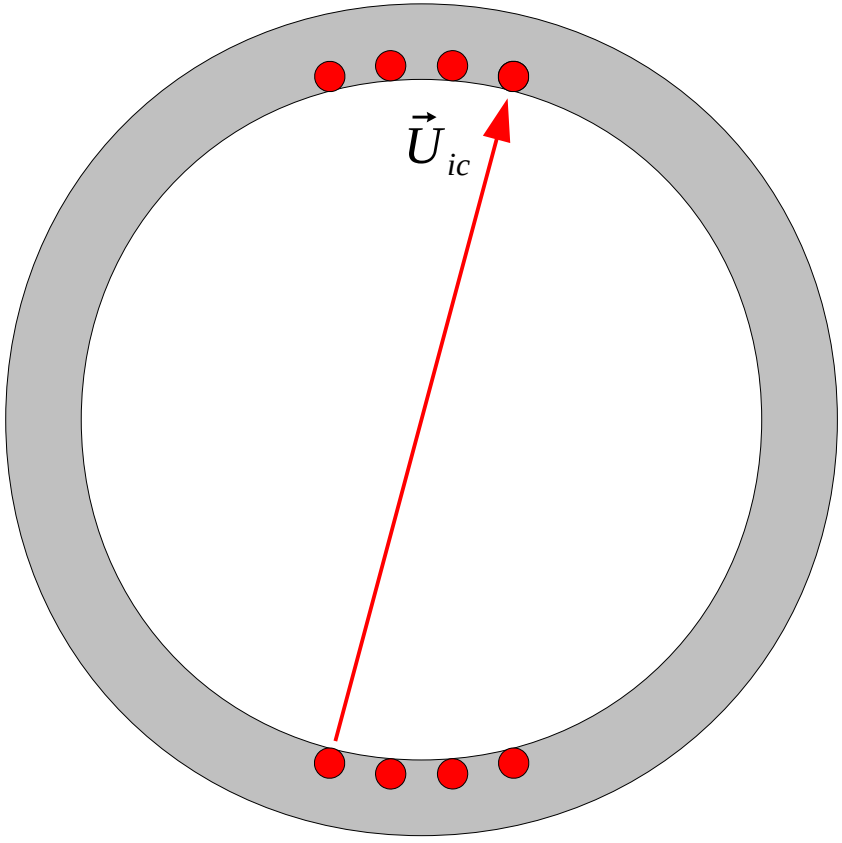
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Winding Distribution Factor

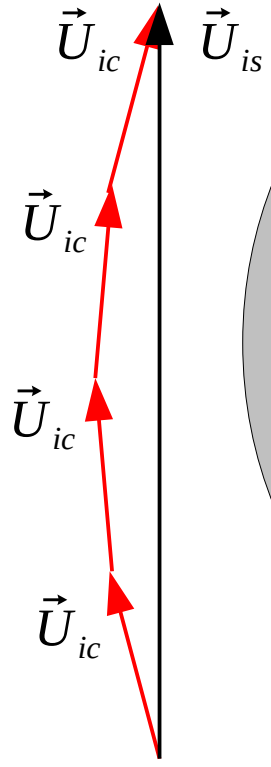
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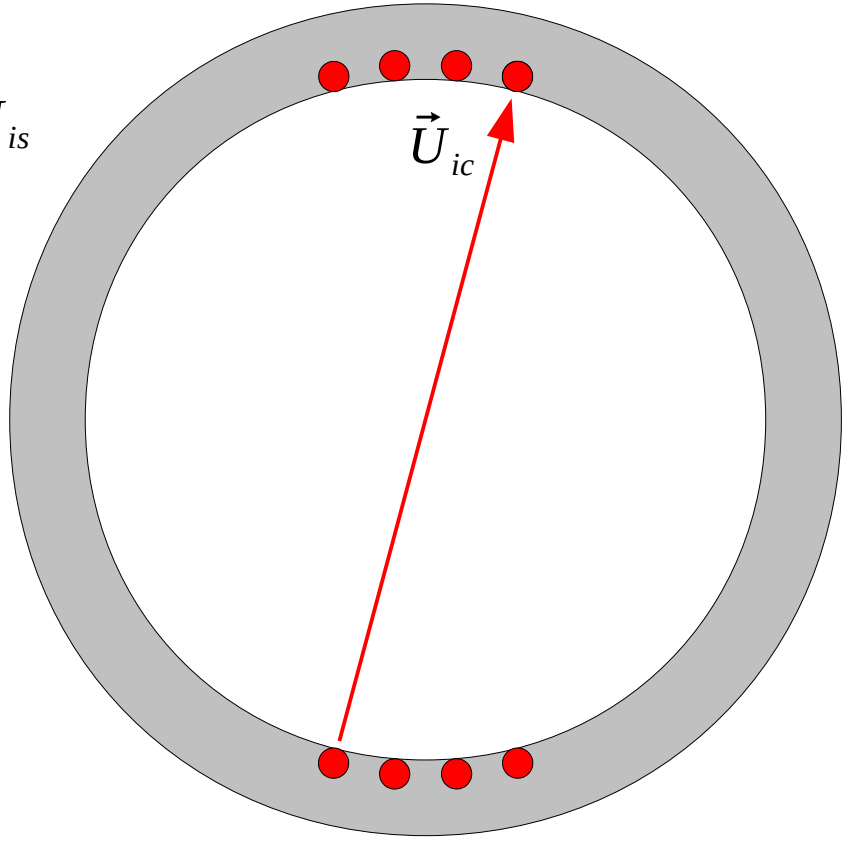




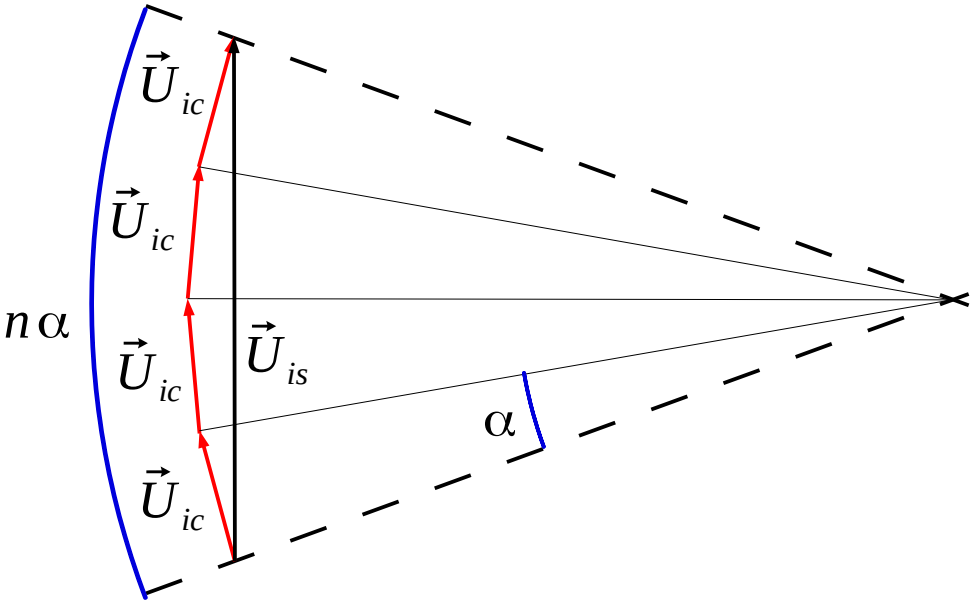
Winding Distribution Factor

- Let us have a group of q coils in series:
- The induced winding in a group of coils in series U_{is} is a geometric sum of induced voltages in all coils U_{ic}
- The winding distribution factor then gives a ratio between geometric and arithmetic sums of induced voltages



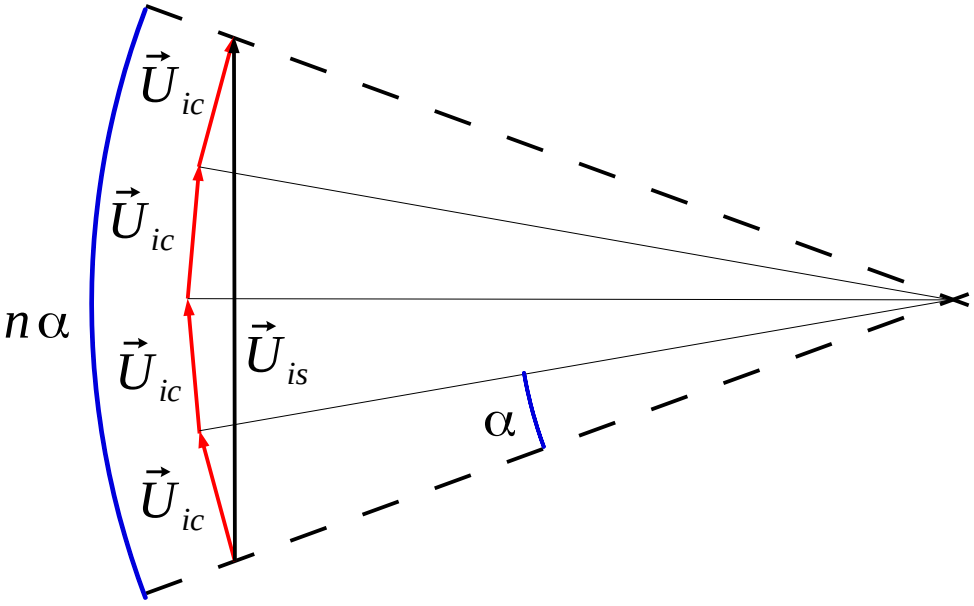


Winding Distribution Factor



$$k_r = \frac{U_{is}}{n U_{ic}}$$

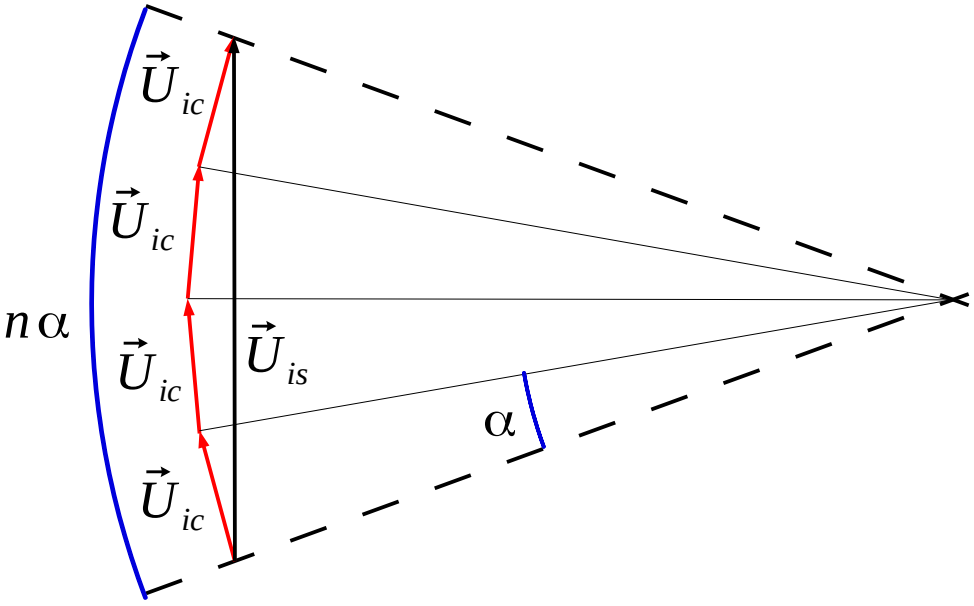
Winding Distribution Factor



$$k_r = \frac{U_{is}}{n U_{ic}}$$

$$\frac{U_{is}}{2} = R \sin\left(\frac{n\alpha}{2}\right)$$

Winding Distribution Factor

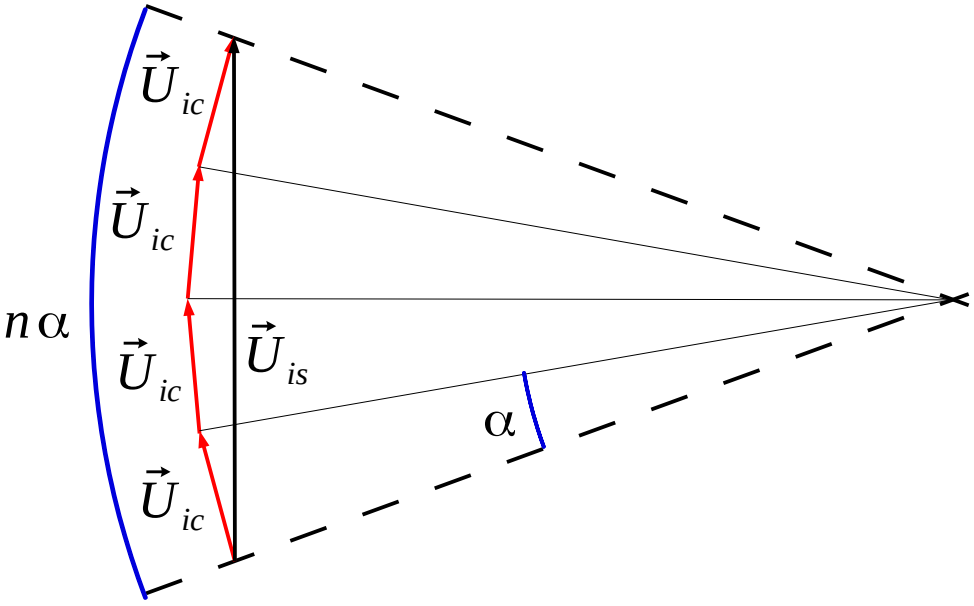


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Winding Distribution Factor



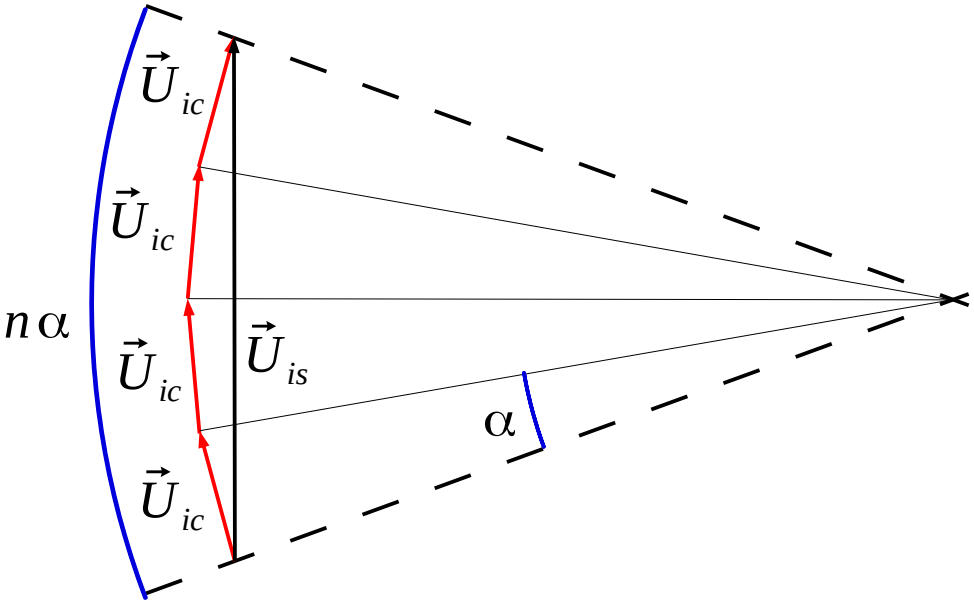
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$$\frac{U_{is}}{2} = R \sin\left(\frac{n\alpha}{2}\right)$$

$$\frac{U_{ic}}{2} = R \sin\left(\frac{\alpha}{2}\right)$$

$$k_r = \frac{\sin\left(\frac{n\alpha}{2}\right)}{n \sin\left(\frac{\alpha}{2}\right)}$$

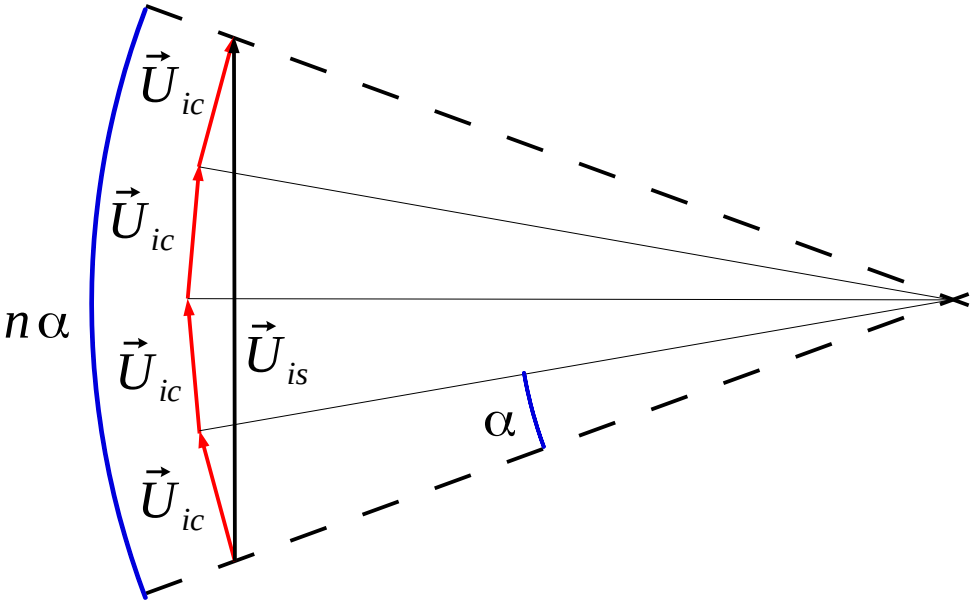
Winding Distribution Factor



$$k_r = \frac{\sin\left(\frac{n\alpha}{2}\right)}{n\sin\left(\frac{\alpha}{2}\right)}$$

… the angle α is the electric angle between adjacent front coil sides

Winding Distribution Factor

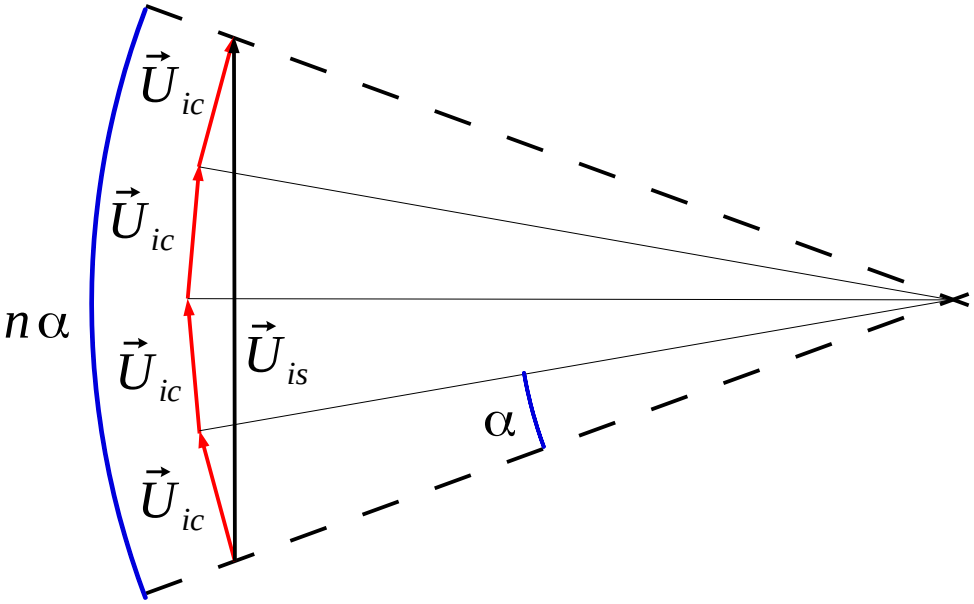


$$k_r = \frac{\sin\left(\frac{n\alpha}{2}\right)}{n\sin\left(\frac{\alpha}{2}\right)}$$

$$\alpha = \frac{2\pi}{2mn}$$

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Winding Distribution Factor



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Winding Distribution Factor

- Similarly as in case of the winding pitch factor, in case of winding distribution factor the angles are ν-times higher:

$$k_{r\nu} = \frac{\sin\left(\nu \frac{\pi}{2m}\right)}{n \sin\left(\nu \frac{\pi}{2mn}\right)}$$

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$$k_{r\nu} = \frac{\sin\left(\nu \frac{\pi}{2m}\right)}{n \sin\left(\nu \frac{\pi}{2mn}\right)}$$

- For $m = 3$ phase windings and fundamental harmonic component the following form is often used

$$k_r = \frac{\sin\left(30°\right)}{n \sin\left(\frac{30°}{n}\right)}$$

Winding Distribution Factor

- Similarly as in case of the winding pitch factor, in case of winding distribution factor the angles are ν-times higher:

$$k_{r\nu} = \frac{\sin\left(\nu \frac{\pi}{2m}\right)}{n \sin\left(\nu \frac{\pi}{2mn}\right)}$$

- In older literature, the q is denoted as a ratio $q = \frac{q_0}{c}$, then the result is

$$k_{r\nu} = \frac{\sin\left(\nu \frac{\pi}{2m}\right)}{q_0 \sin\left(\nu \frac{\pi}{2mq_0}\right)}$$

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Winding Factor

Winding Factor

- In general, the winding factor for ν-th harmonic component is:

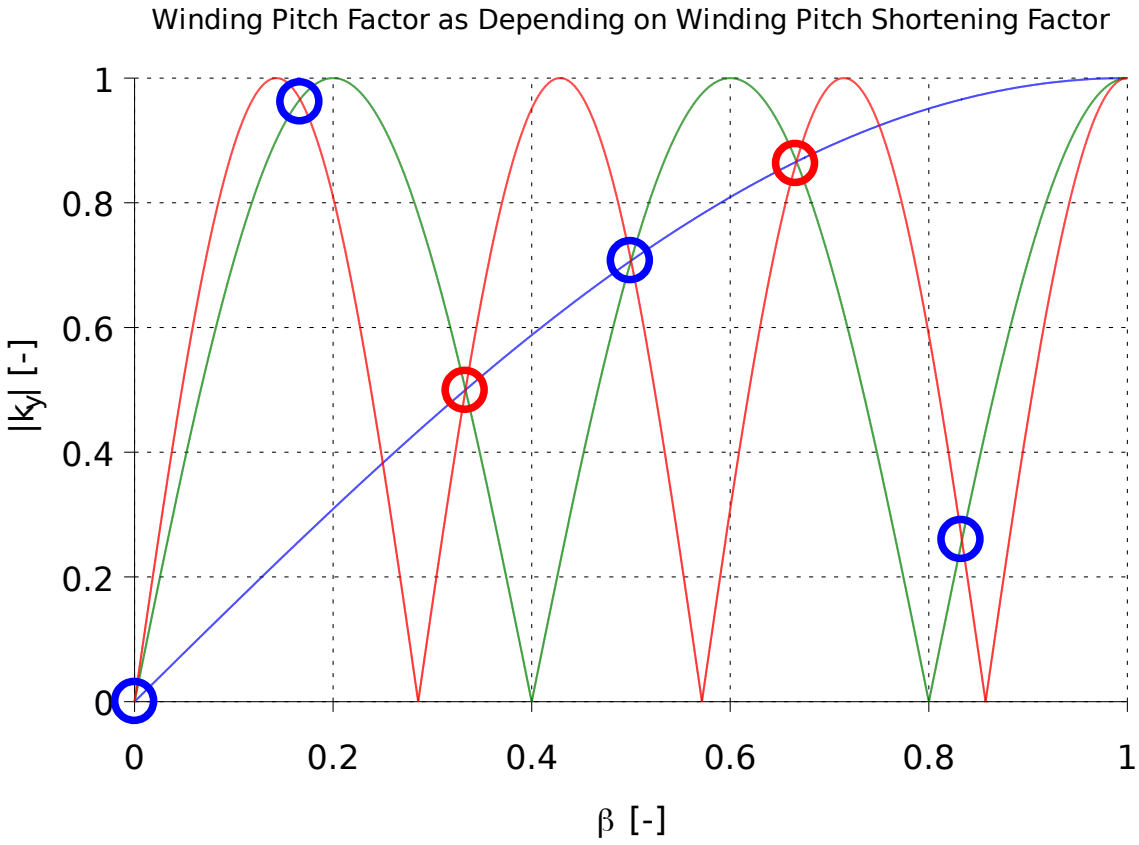
$$k_{v\nu} = k_{y\nu} k_{r\nu} = \sin\left(\nu \beta \frac{\pi}{2}\right) \cdot \frac{\sin\left(\nu \frac{\pi}{2m}\right)}{n \sin\left(\nu \frac{\pi}{2mn}\right)}$$

- Theoretically it is possible to achieve $k_v = 1$, but it is not suitable since there is no decrease of higher order harmonic components then
- It is possible only with a winding with $q = 1$ and full coil pitch

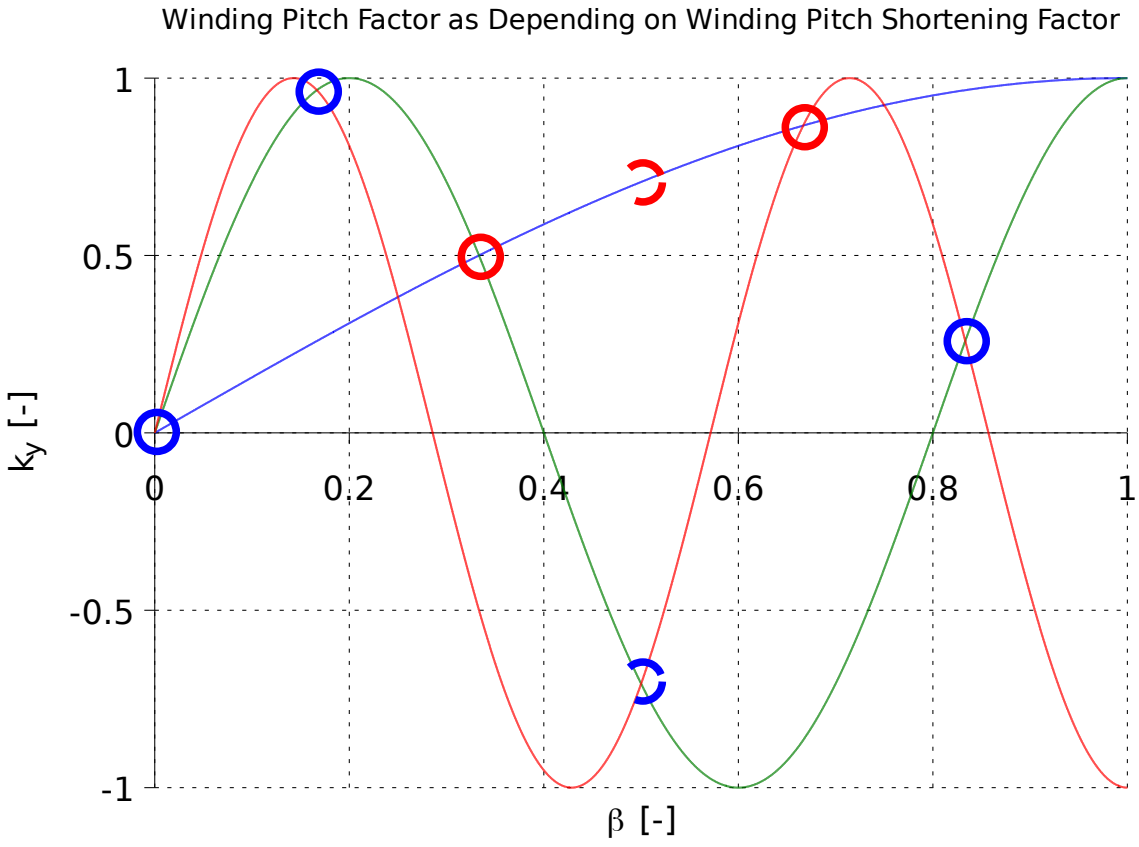
Winding Factor

- Because of these reasons the coil pitch is almost always shortened – it leads to suppression of higher order harmonic components
- The winding factor is a result of more geometric functions => it may achieve even negative values
  - This is also a reason why some optimal values of winding pitch shortening factors for 5^{th} and 7^{th} harmonic were not found

Winding Factor



Winding Factor



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Thank You for Your Attention!

Karel Hruska / +420 377 63 4429 / khruska@fel.zcu.cz